

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

GOOGLE LLC, CELLCO PARTNERSHIP D/B/A VERIZON WIRELESS, T-MOBILE USA, INC., AT&T SERVICES, INC., NOKIA OF AMERICA, CORP.,
AND ERICSSON INC.

Petitioners

v.

KT CORPORATION (Patent Owner) and
PEGASUS WIRELESS INNOVATION LLC (Exclusive Licensee)

Case No. IPR2025-00293
Patent 10,009,161

DECLARATION OF JUNE ANN MUNFORD

Declaration of June Ann Munford in Support of
Petition for *Inter Partes* Review of U.S. Patent No. 10,009,161

EXHIBIT LIST

Exhibit No.	Description
1014	X. Chen <i>et al.</i> , “A Novel CQI Calculation Scheme in LTE/LTE-A Systems,” (2011)
1024	<i>Curriculum Vitae</i> of June Ann Munford

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I, June Ann Munford, hereby state as follows:

1. I am over the age of 18, have personal knowledge of the facts set forth herein, and am competent to testify to the same.

2. I earned a Master of Library and Information Science (MLIS) from the University of Wisconsin-Milwaukee in 2009. I have over ten years of experience in the library/information science field. Beginning in 2004, I have served in various positions in the public library sector including Assistant Librarian, Youth Services Librarian and Library Director. I have attached my Curriculum Vitae as Exhibit 1024.

3. During my career in the library profession, I have been responsible for materials acquisition for multiple libraries. In that position, I have cataloged, purchased and processed incoming library works. That includes purchasing materials directly from vendors, recording publishing data from the material in question, creating detailed material records for library catalogs and physically preparing that material for circulation. In addition to my experience in acquisitions, I was also responsible for analyzing large collections of library materials, tailoring library records for optimal catalog search performance and creating lending agreements between libraries during my time as a Library Director.

4. I am fully familiar with the catalog record creation process in the library sector. In preparing a material for public availability, a library catalog record

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describing that material would be created. These records are typically written in Machine Readable Catalog (herein referred to as “MARC”) code and contain information such as a physical description of the material, metadata from the material’s publisher, and date of library acquisition. In particular, the 008 field of the MARC record is reserved for denoting the date of creation of the library record itself. As this typically occurs during the process of preparing materials for public access, it is my experience that an item’s MARC record indicates the date of an item’s public availability.

5. Typically, in creating a MARC record, a librarian would gather various bits of metadata such as book title, publisher and subject headings among others and assign each value to a relevant numerical field. For example, a book’s physical description is tracked in field 300 while title/attribution is tracked in field 245. The 008 field of the MARC record is reserved for denoting the creation of the library record itself. As this is the only date reflecting the inclusion of said materials within the library’s collection, it is my experience that an item’s 008 field accurately indicates the date of an item’s public availability.

6. I have reviewed Exhibit 1014, a paper entitled “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” by X. Chen *et al.* (2011), as published in *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing*. For purposes of my analysis in this declaration, I have been

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informed that a person of ordinary skill in the art (“POSITA”) would have had a bachelor’s degree in electrical engineering, computer engineering, or a related discipline, knowledge of the relevant 3GPP standards as of this time, and at least 2 years of experience working in a field involving wireless communications. A person with a different degree but with additional relevant experience could still qualify if the additional experience compensates for the different educational background. A person with less than 2 years of experience working in a field involving wireless communications could still qualify if the person has additional education that compensates for their lesser experience. For the reasons discussed herein, Chen (Exhibit 1014, attached, “A Novel CQI Calculation Scheme in LTE/LTE-A Systems”) was publicly available to a POSITA at least as early as November 2011 and certainly no later than December 8, 2011.

7. Attached hereto as Appendix CHEN01 is a true and correct copy of the MARC record for *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing* as held by the Rochester Institute of Technology Library. I secured this record myself from the library’s public catalog. The MARC record contained within Appendix CHEN01 accurately describes the title, publisher and ISBN number of *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing*. The ‘Available electronically’ field present on page 2 of Appendix CHEN01 indicates this library

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holding is an e-book edition of *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing* hosted on the IEEE Electronics Books database.

8. The 008 field of the MARC record in Appendix CHEN01 indicates the date of record creation. The 008 field of Appendix CHEN01 indicates the Rochester Institute of Technology Library first acquired *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing* as of May 12, 2011. Considering this information, it is my determination that *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing* and therefore “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was made available to the public shortly after May 12, 2011.

9. This May 12, 2011 acquisition pre-dates the conference itself, indicating the library purchased a copy of these proceedings pre-publication with the intent of making the conference proceedings available to the public upon formal publication. In my experience, pre-purchasing library materials in advance of publication is a common purchasing practice and expedites the process of making time-sensitive materials available to the public.

10. Attached hereto as Appendix CHEN02 is a screen capture of a webpage entitled “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” as hosted on the IEEE Xplore website. I secured these screen captures myself from

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<https://ieeexplore.ieee.org/abstract/document/6096767/citations#citations>.

Appendix CHEN02 also contains a true and correct copy of “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” I purchased from this IEEE Xplore page.

11. In comparing Appendix CHEN02 to Exhibit 1014, it is my determination that Exhibit 1014 is a true and correct copy of “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” by X. Chen, *et al.* as published in *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing*. The ‘Published in’ and ‘Date of Conference’ fields present on page 1 of Appendix CHEN02 indicates this paper was presented at the 2011 International Conference on Wireless Communications and Signal Processing at some time between November 9 – 11, 2011. The ‘Date Added to IEEE Xplore’ field present on this web page indicates the Chen paper was first added to the IEEE Xplore website as of December 8, 2011.

12. Attached hereto as Appendix CHEN03 is a screen capture of the Internet Archive Wayback Machine entry for <https://ieeexplore.ieee.org/abstract/document/6096767/citations#citations>. I secured these screen captures myself from <https://web.archive.org/web/20110718164803/http://ic-wcsp.org/index.htm>. This record was captured as of July 18, 2011.

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13. Appendix CHEN03 is an Internet Archive capture of a web page entitled About the Conference as hosted on the 2011 International Conference on Wireless Communications and Signal Processing website. This page, pre-dating the conference, describes the publishing strategy associated with the conference proceedings. Appendix CHEN03 contains the following passage: “All accepted papers at WCSP2011 will be included in IEEE Xplore and indexed in EI.” This language indicates any author who submitted a paper to this conference did so with the clear intent to publish and distribute that work via the IEEE Xplore platform. This passage also indicates that these conference proceedings will be indexed in EI, a prominent bibliographic database also known as EI Compendex. EI Compendex maintains a discovery platform and search engine to assist interested users in finding scientific literature. The inclusion of these proceedings in the EI Compendex database indicates the publisher showing a clear interest in distributing these proceedings to an audience broader than conference attendees.

14. Attached hereto as Appendix CHEN04 is a screen capture of the Internet Archive Wayback Machine entry for <http://www.ic-wcsp.org:80/Program.html>. I secured these screen captures myself from <https://web.archive.org/web/20111115211013/http://www.ic-wcsp.org:80/Program.html>. This record was captured as of November 15, 2011.

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15. Appendix CHEN04 is an Internet Archive capture of a web page entitled WCSP 2011 Program as hosted on the 2011 International Conference on Wireless Communications and Signal Processing website. Appendix CHEN04 serves as a program for the 2011 International Conference on Wireless Communications and Signal Processing itself, captured four days after the conclusion of the conference. Page 4 of Appendix CHEN04 includes a citation of “A Novel CQI Calculation Scheme in LTE/LTE-A Systems”, indicating the paper was presented to conference attendees on November 9, 2011.

16. Attached hereto as Appendix CHEN05 is a web capture of a website entitled “Radio Resource Management for Green 3GPP Long Term Evolution Cellular Networks” on the ResearchGate website. Appendix CHEN05 also includes a true and correct PDF copy of “Radio Resource Management for Green 3GPP Long Term Evolution Cellular Networks” by Mustafa Ismael Salman, *et al.* as published in *IETE Technical Review*, the paper described on the ResearchGate page. I secured these web captures myself.

17. Page 7 of Appendix CHEN05 contains a citation to “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” by X. Chen *et al.* (2011), as published in *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing*, indicating the authors of the Salman paper had access to the Chen paper during the drafting process. As the Salman

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paper was published in the May - June 2013 issue of *IETE Technical Review*, it is reasonable to assume that “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was available to the public prior to the publication of the May – June 2013 issue.

18. Attached hereto as Appendix CHEN06 is a web capture of a website entitled “Joint Carrier Aggregation and Packet Scheduling in LTE-Advanced Networks” on the IEEE Xplore website. Appendix CHEN06 also includes a true and correct PDF copy of “Joint Carrier Aggregation and Packet Scheduling in LTE-Advanced Networks” by Xiaolin Cheng, *et al.* as published in *Proceedings of the 2013 IEEE International Conference on Sensing, Communications and Networking*, the paper described on the IEEE Xplore page. I secured these web captures myself.

19. Page 13 of Appendix CHEN06 contains a citation to “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” by X. Chen *et al.* (2011), as published in *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing*, indicating the authors of the Cheng paper had access to the Chen paper during the drafting process. According to IEEE Xplore, the Cheng paper was presented at the *Proceedings of the 2013 IEEE International Conference on Sensing, Communications and Networking*, taking place from June 24 – 27, 2013. As the Cheng paper was presented in June 2013, it

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is reasonable to assume that “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was available to the public prior to June 2013.

20. Attached hereto as Appendix CHEN07 is a web capture of a website entitled “Full-Band CQI Feedback by Huffman Compression in 3GPP LTE Systems” on the International Journal of Computer Applications website.

Appendix CHEN05 also includes a true and correct PDF copy of “Full-Band CQI Feedback by Huffman Compression in 3GPP LTE Systems” by Onkar Dandekar as published in *International Journal of Computer Applications*, the paper described on the International Journal of Computer Applications website. I secured these web captures myself.

21. Page 7 of Appendix CHEN07 contains a citation to “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” by X. Chen *et al.* (2011), as published in *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing*, indicating the author of the Dandekar paper had access to the Chen paper during the drafting process. As the Dandekar paper was published in the September 2013 issue of *International Journal of Computer Applications*, it is reasonable to assume that “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was available to the public prior to the publication of the September 2013 issue.

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22. Attached hereto as Appendix CHEN08 is a web capture of a website entitled “Link Adaptation Algorithms for Channel Estimate Error Mitigation in LTE Systems” on the IEEE Xplore website. Appendix CHEN08 also includes a true and correct PDF copy of “Link Adaptation Algorithms for Channel Estimate Error Mitigation in LTE Systems” by Huiling Dai, *et al.* as published in *Proceedings of the 2012 IEEE Global Communications Conference*, the paper described on the IEEE Xplore page. I secured these web captures myself.

23. Page 8 of Appendix CHEN08 contains a citation to “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” by X. Chen *et al.* (2011), as published in *Proceedings of the 2012 IEEE Global Communications Conference*, indicating the authors of the Dai paper had access to the Chen paper during the drafting process. According to IEEE Xplore, the Dai paper was presented at the *Proceedings of the 2012 IEEE Global Communications Conference*, taking place from December 3 – 7, 2012. As the Dai paper was presented in December 2012, it is reasonable to assume that “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was available to the public prior to December 2012.

24. Attached hereto as Appendix CHEN09 is a web capture of a website entitled “A Novel Hybrid CQI Feedback Method for Throughput Improvement in 3GPP LTE Systems” on the International Journal of Engineering Trends and Technology website. Appendix CHEN09 also includes a true and correct PDF

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copy of “A Novel Hybrid CQI Feedback Method for Throughput Improvement in 3GPP LTE Systems” by Onkar Dandekar as published in *International Journal of Engineering Trends and Technology*, the paper described on the International Journal of Engineering Trends and Technology website. I secured these web captures myself.

25. Page 8 of Appendix CHEN09 contains a citation to “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” by X. Chen *et al.* (2011), as published in *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing*, indicating the author of the Dandekar paper had access to the Chen paper during the drafting process. As the Dandekar paper was published in the October 2013 issue of *International Journal of Computer Applications*, it is reasonable to assume that “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was available to the public prior to the publication of the October 2013 issue.

26. Appendix CHEN01 indicates the Rochester Institute of Technology Library first acquired a copy of *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing* and thus “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” as of May 12, 2011 with the intent of making these works available to the public soon after. Appendix CHEN04 indicates “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was

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presented to an audience to conference attendees as of November 9, 2011.

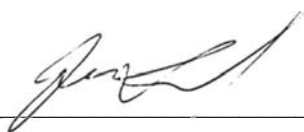
Appendix CHEN02 indicates *Proceedings of the 2011 International Conference on Wireless Communications and Signal Processing* and thus “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” were first added to the IEEE Xplore database as of December 8, 2011. Appendices CHEN04 – CHEN09 are each academic papers published or presented from December 2012 through October 2013, with each paper containing a citation to “A Novel CQI Calculation Scheme in LTE/LTE-A Systems”. As such, it is my determination “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was first made available to the public in November 2011 via attending the 2011 International Conference on Wireless Communications and Signal Processing and certainly no later than December 8, 2011. The prevalence of citations from December 2012 – October 2013 indicates “A Novel CQI Calculation Scheme in LTE/LTE-A Systems” was broadly distributed and made available to the public by the paper’s publisher from November 2011 to December 2012.

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27. In signing this Declaration, I understand that the Declaration will be filed as evidence in a contested case before the Patent Trial and Appeal Board of the United States Patent and Trademark Office. I acknowledge that I may be subject to cross-examination in the case and that cross-examination will take place within the United States. If cross-examination is required of me, I will appear for cross-examination within the United States during the time allotted for cross-examination.

28. I hereby declare that all statements made herein of my own knowledge are true and that all statements made on information and belief are believed to be true; and further that these statements were made with the knowledge that willful false statements and the like so made are punishable by fine or imprisonment, or both, under Section 1001 of Title 18 of the United States Code.

Date: 12/27/2024



June Ann Munford

A Novel CQI Calculation Scheme in LTE\LTE-A Systems

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Abstract—We propose a novel Channel Quality Indicator (CQI) calculation scheme in LTE\LTE-A systems. SNR-CQI mapping scheme, as well as SINR-CQI mapping scheme, is extensively studied in previous works. However, these kinds of CQI mapping schemes always provide imprecise results in fading channels, since all of them ignore the channel quality degeneration caused by other factors. In this paper, we further improve CQI calculation by considering the impact of multipath delay spread. The calculation scheme is presented in details. In order to guarantee the converge of CQI calculation, a Block Error Ratio (BLER) based converge algorithm is proposed. Simulations show that our calculation scheme can select CQIs more precisely, and achieve better throughput performance than traditional schemes. Furthermore, our scheme converges much faster than previous schemes.

Index Terms—CQI calculation, feedback, LTE\LTE-A.

I. INTRODUCTION

With the increasing demand of Quality of Service (QoS) in wireless communication system, more aggressive techniques are employed to improve the frequency and time efficiency. Adaptive Modulation and Coding (AMC) is one of the techniques that are applied in real systems to increase the throughput. By adaptively selecting the appropriate modulation order and coding rate, AMC can provide a much better system performance than fixed modulation and coding schemes. In order to conduct AMC operation in LTE\LTE-A systems (see [1], [2], [3]), Channel Quality Indicators (CQIs) need to be fed back by User Equipments (UEs) or Mobile Stations (MSs).

The calculation algorithms of CQI are numerous. Most of the previous works utilize the SNR-CQI mapping to determine CQIs. In [4], the SNR-CQI mapping is designed offline. Each UE estimates the channel state information (CSI), then extracts channel SNR and applies SNR-CQI mapping to determine CQIs. In this kind of CQI calculation algorithm, SNR is the only reference for CQI selection.

Based on SNR-CQI mapping algorithm, lots of enhanced schemes have been proposed. In [5], the author considers the CQI feedback in MU-MIMO systems. It is proposed that SINR-CQI mapping should be adapted instead of SNR-CQI mapping, since user interferences become a major challenge of channel quality. In [6], the authors propose a leakage-based precoding algorithm, so as to compute a more reliable CQI and minimize user interference. As a result, the computing algorithm of CQI is based on a SLNR-CQI mapping.

Unfortunately, all the above mappings are calculated in some fixed channel models (for examples, AWGN and Rayleigh channels). In different channel models, SNR-CQI mapping (as well as SINR-CQI and SLNR-CQI mappings) is different when comparing with itself. Consequently, all the above mappings are not perfectly suitable in realistic scenarios. A solution based on SNR conversion is proposed in [7]. The authors derive the conversion criterions to convert SNRs of other channel models into that of AWGN channel. Then CQIs of other channel models can be obtained by substituting the converted SNRs into AWGN channel's SNR-CQI mapping.

However, channel quality is not only decided by the quality of signal power. In [8], the authors present three kinds of factors that will cause CQI errors. Among them, mobility of UEs may be the most serious one. The impact of mobility in channel quality reflects on the size of multipath delay spread. The larger the spread is, the larger the transmission delay is, and the worst the channel quality becomes.

In order to deal with the CQI errors caused by multipath delay spread, we propose a novel CQI calculation algorithm: SNR&Delay-CQI mapping. This algorithm jointly utilizes SNR and maximum multipath delay spread (denoted as *Delay*) of instantaneous channel state, to achieve a much more precise CQI under fading channels. Moreover, we embed this SNR&Delay-CQI mapping into a BLER-based CQI converge algorithm, with the purpose of minimizing the impact of channel estimation errors. It is worth noticing that our scheme can be extended to large scale wireless networks [9] [10] [11] [12].

The rest of the paper is organized as followed. Section II provides a brief discussion on limitations of SNR-CQI mapping. Our SNR&Delay-CQI mapping is presented in details in Section III. Section IV describes the BLER-based CQI converge algorithm. Simulations can be seen in Section V. And we conclude the paper in Section VI.

II. SNR-CQI MAPPING AND ITS LIMITATION

In LTE\LTE-A system, UEs select CQIs according to the results of channel estimation. Actually, each CQI in LTE\LTE-A system is a pair of modulation order and coding rate. The detailed definition of CQI, as well as the mapping from CQI to each modulation order and coding rate pair, can be found in [3]. Each UE tries to find an optimal pair of modulation

Petitioners' Exhibit 1014

Google et al. v. KT Corporation et al.

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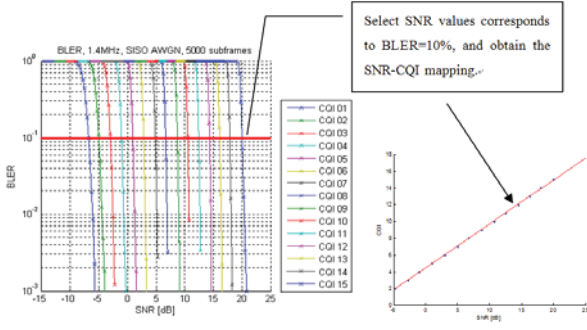


Fig. 1. SNR-CQI mapping generation in AWGN channel

order and coding rate, which provides the largest throughput when the BLER is less than 10 percent.

However, this process always costs too many computing resources for UEs. Therefore, simplifications of this optimizing process need to be adopted. Measurements and simulations should be conducted previously, so as to determine the optimal CQIs under different CSI conditions. After that, a CSI-CQI function or mapping is derived by a fitting of data. In this sense, UEs can obtain the feedback CQIs timely, as long as the channel estimations are finished.

Based on this idea, SNR-CQI mapping is proposed by many previous works. A common way to obtain a SNR-CQI mapping consists of three steps.

- In the first step, a BS employs CQI one by one in transmission. An active UE receives signals, then measures the SNR-BLER curve for each CQI, respectively. The UE preserves a group of SNR-BLER curves, each of which corresponds to a CQI.
- In the second step, UE selects the SNR value corresponding to BLER = 10% in each curve. Note that each curve corresponds to a CQI.
- In the third step, UE utilizes the SNR values selected in the second step, as well as the corresponding CQIs, to fit the desired SNR-CQI mapping.

An example of SNR-CQI mapping generation is showed in Fig. 1.

However, SNR is not the only parameter to determine a channel's quality. A SNR-CQI mapping in one channel model may fail to maintain a good performance in another. Fig. 2 presents the SNR-CQI mappings in some classic channel models. All the channel models are based on the measurements in realistic scenarios by 3GPP [3].

It is clear in Fig. 2 that one SNR value may correspond to different CQIs in different channel models. Such a difference is brought by a channel quality variation, which is a consequence of the variation of channel parameters other than SNR. Moreover, the SNR-CQI mappings plotted in Fig. 2 are achieved with the priori knowledge of channel models. In real systems, it is almost impossible to estimate the channel models in UEs. As a result, SNR-CQI mapping is incapable of achieving accurate CQI values.

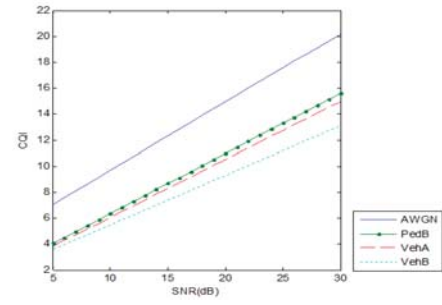


Fig. 2. SNR-CQI mappings in different channels

III. SNR&DELAY-CQI MAPPING

A. Certification for the Use of Multipath Delay Spread

Expect of SNR, multipath delay spread (denote as *Delay* for short) is another critical parameter in determining channel quality. Multipath delay spread is a measure of the multipath richness of a channel. It can be interpreted as the difference between the time of arrival of the first significant multipath component and the time of arrival of the last multipath component. In other words, it is the maximal delay of multipath transmissions. With the increase of *Delay*, more and more CQIs can not be adapted in transmissions even when SNR is high enough. Fig. 3 gives an illustration of invalid CQIs when *Delay* increases.

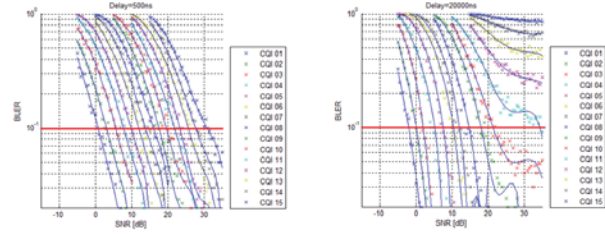


Fig. 3. Illustration of invalid CQIs when *Delay* increases. The left one presents the SNR-BLER curves for *Delay* = 500ns, and the right one stands for *Delay* = 20000ns

It can be seen from Fig. 3 that, when *Delay* is 500ns, all the 15 CQIs¹ can be used if SNR is large enough.² However, when *Delay* increases to 20000ns, only 10 CQIs can be used even maximum SNR is provided.

From the above analysis, we can conclude that multipath delay spread should be consider carefully in CQI calculation schemes.

B. Generation of SNR&Delay-CQI Mapping

In real systems, such as LTE/LTE-A systems and HSD-PA systems, there are too many factors affecting the system BLER. In order to obtain a SNR&Delay-CQI mapping,

¹Number of CQIs that are employed in LTE/LTE-A system is 15

²In real system, a SNR of 30dB is almost the largest SNR that can be achieved in optimal conditions. Correspondingly, we use 30dB as the upper value of SNR in this paper.

empirical formula should be achieved by simulations and measurements. In our work, we employ a link-level simulation platform³, which contains all the functions of LTE downlink transmissions, such as Turbo coding, linear MIMO decoding, channel estimation, AMC, etc. With the help of this platform, we adopt the following algorithm to obtain the SNR&Delay-CQI mapping in fading channels.

Algorithm 1 Generation of SNR&Delay-CQI Mapping

1. Set current *Delay* value D equals 0. Set measurement step of *Delay* as Δ_d .
2. Set current *Delay* value as $D + \Delta_d$, obtain the power delay profile of the corresponding channel [13].
3. Proceed transmissions in the channel generated in step 2, and obtain a SNR-CQI mapping as described in Section II.
4. If current *Delay* value is larger than the max value of *Delay* in measurement process, go to step 5. Otherwise, repeat step 2 and step 3.
5. Obtain a group of SNR-CQI mappings corresponding to different *Delay* values, and fit these mappings into a 3-dimension function:

$$CQI = F(SNR, Delay)$$

6. Output F .
-

C. A Simplified but Effective SNR&Delay-CQI Mapping

The process of calculating a 3-dimension function $CQI = F(SNR, Delay)$ by Algorithm 1 is complex. And the storage of such a function is relatively large in mobile devices. Here we present a simplified scheme, which changes the 3-dimension function $CQI = F(SNR, Delay)$ into a piecewise function. We will prove the effectiveness of such a simplified scheme in Section V. The cut-off points of the piecewise function in *Delay* axis defined as followed:

Definition 1: (CQI i 's cut-off point) The *Delay* cut-off point of CQI i represents the maximal multipath delay spread, under which the corresponding BLER is within system's limit while the largest SNR condition is provided.

In other words, the increase of multipath delay spread will cause a decrease of the available CQIs, since channel quality drops largely and can no long sustain high level modulations or coding rates. The turning points of available CQIs in multipath delay spread axis are defined as the cut-off points. A multipath delay spread that is larger than the cut-off point of CQI i will result in a large BLER by CQI(s) larger than i . A graphical illustration of cut-off points is presented in Fig. 4.

We propose to use the following cut-off points in LTE\LTE-A systems.

$$Q_{max} = \begin{cases} 15 & D \geq 400ns \ (D_{15}) \\ 14 & 400ns < D \leq 9500ns \ (D_{14}) \\ 13 & 9500ns < D \leq 12500ns \ (D_{13}) \\ 12 & 12500ns < D \leq 14800ns \ (D_{12}) \\ 11 & 14800ns < D \leq 18000ns \ (D_{11}) \end{cases} \quad (1)$$

³This simulation platform is developed by IWCT, Shanghai Jiao Tong University.

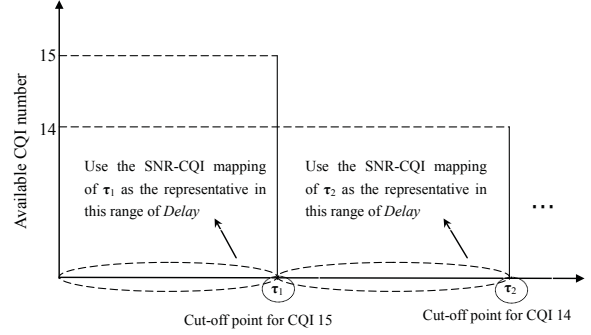


Fig. 4. A graphical interpretation of cut-off points and their meanings. A cut-off point is the maximal multipath delay spread that a certain CQI can be used with an optimal SNR condition.

where Q_{max} is the maximal CQI that can be used within two *Delay* cut-off points, and D denotes the *Delay*. D_{15} to D_{11} denote corresponding *Delay* range for short.

The corresponding piecewise function for SNR&Delay-CQI mapping is:

$$Q = \begin{cases} \min(\lfloor 0.513S - 0.215 \rfloor, 15) & D \in D_{15} \\ \min(\lfloor 0.431S + 2.148 \rfloor, 14) & D \in D_{14} \\ \min(\lfloor 0.402S + 2.152 \rfloor, 13) & D \in D_{13} \\ \min(\lfloor -0.004S^2 + 0.513S + 1.74 \rfloor, 12) & D \in D_{12} \\ \min(\lfloor -0.007S^2 + 0.527S + 1.77 \rfloor, 11) & D \in D_{11} \end{cases} \quad (2)$$

where Q represents the selected CQI, $\lfloor \cdot \rfloor$ denotes the rounding-down calculation, and S is the channel SNR.

It is worth pointing out that although the above results are achieved based on the simulations, they can be applied in most of the scenarios in LTE systems. First of all, all the simulations are conducted under typical LTE/LTE-A scenarios. Secondly, any CSI-CQI mapping is a rough estimation, which can be refined by the following converge algorithm. Moreover, the above scheme can be reapplied in other scenarios or systems with similar simulations and measurements.

IV. BLER-BASED CQI CONVERGE ALGORITHM

There are multiple factors that will decrease the performance of SNR&Delay-CQI mapping described in Section III. The accuracy of CQI calculation will be disturbed by the times and granularity of measurement, as well as the selection of simulation channels. As a result, UEs may select inappropriate CQIs over and over again. In order to guarantee a relatively good accuracy of CQI calculation, a BLER-based CQI converge algorithm is proposed. The SNR&Delay-CQI mapping is nested inside the body of BLER-based CQI converge algorithm. Every selected CQI will be re-evaluated by BLER-based CQI converge algorithm, so as to maintain a BLER that fits the system's requirement.

If channel quality decreases, the feedback CQI should decrease, or at least remain the same. Therefore, we employ a CQI-decreasing function to make sure that feedback CQIs converge. The cut-off points decreased in (1) are used in

such a function. The CQI-decreasing function is presented as followed.

$$Q_{conv} = Q_{pre} - \Delta Q \quad (3)$$

and
 $\Delta Q =$

$$\begin{cases} [18.69\beta - 18.22\Delta\beta] & D \in D_{15} \\ [13.38\beta - 14.31\Delta\beta] & D \in D_{14} \\ [-93.55\beta^2 + 110.41\beta - 35.23\Delta\beta] & D \in D_{13} \\ [-123.67\beta^2 + 146.63\beta - 45.54\Delta\beta + 0.32] & D \in D_{12} \\ [-0.52\beta^2 + 35.59\beta - 34.64\Delta\beta - 0.1] & D \in D_{11} \end{cases} \quad (4)$$

where Q_{conv} denotes the converged CQI, Q_{pre} is the CQI fed back in previous period, ΔQ denotes the decreasing value to obtain a converged CQI value, β represents current BLER, and $\Delta\beta$ is the subtraction between BLER in the last period and BLER in the current period.

Based on the above function, the BLER-based CQI converge algorithm is presented in Algorithm 2.

Algorithm 2 BLER-based CQI Converge Algorithm

Input: Feedback CQI Q_{pre} , BLER β , SNR S_{pre} and Delay D_{pre} in the last transmission period, system threshold of BLER δ , current SNR S and Delay D .

Output: Refined CQI Q .

1. Initiate two intermediate variables $Q_1 = Q_2 = 15$.
 2. If $\beta \leq \delta$, go to step 5. Otherwise, go to step 3.
 3. If $S > S_{pre}$ and $D < D_{pre}$, go to step 5. Otherwise, go to step 4.
 4. Calculate converged CQI by equation(3), and save it in Q_1 .
 5. Calculate mapping CQI by equation(2), and save it in Q_2 .
 6. Output $Q = \min(Q_1, Q_2)$.
-

By employing Algorithm 2, a refined CQI that can guarantee a BLER under system's threshold can be achieved conveniently.

V. SIMULATIONS AND DISCUSSIONS

In this section, we provide some simulation results to verify our SNR&Delay-CQI mapping and BLER-based CQI converge algorithm. In our simulations, we assume that the initial CQI in simulations is 15, so as to illustrate the converge process of CQIs. Channel models in [13] are adopted.

We denote our scheme as Scheme 1, which utilizes both SNR&Delay-CQI mapping and BLER-based CQI converge algorithm. The SNR-CQI mapping scheme proposed in [4], [7], etc, can not guarantee a converge on feedback CQIs. Therefore, we combine the SNR-CQI mapping and our BLER-based CQI converge algorithm to form Scheme 2. Scheme 3 represents the scheme that only employs a traditional dichotomous BLER-based CQI converge algorithm [1].

A. Comparison of CQI Converge Time

In order to compare the converge time for each scheme, we assume that the channels remain unchanged during simulation time. This setting is reasonable in slow fading channels. However, the simulation results can still provide a certification

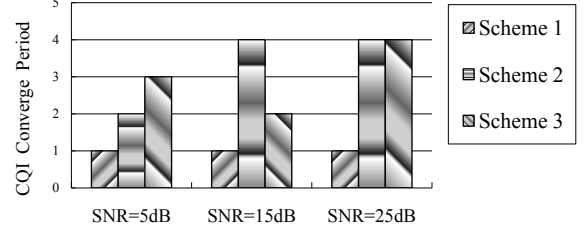


Fig. 5. Comparison of converge time in *PedB* channel

in fast fading channels (We will discuss in the following paragraphs).

Fig. 5 shows the comparison of CQI converge time in *PedB* channel [13]. *PedB* channel is a channel model characterizing the channel of pedestrians. The speed of mobile UEs is relatively small.

It is demonstrated in Fig. 5 that our scheme can converge at the final CQI with only 1 feedback period. Recall that we set the initial CQI as 15 in simulations, a converge period of 1 indicates that our scheme always selects a converged CQI in each feedback period. Other schemes consume up to 4 feedback periods to obtain a converged CQI. This means that other schemes require several feedback periods of interaction to finish CQI selection. This further illustrates that the scheduling overhead of our scheme is much less than that of the other two. Moreover, if the variation of channel is fast, our scheme can provide a real-time CQI calculation, while other schemes fail to catch up with the channel's variation.

Fig. 6 shows the comparison of CQI converge time in *VehB* channel [13]. *VehB* channel is a channel model characterizing the channel of vehicles. The multipath delay spread is much larger than that of *PedB* channel.

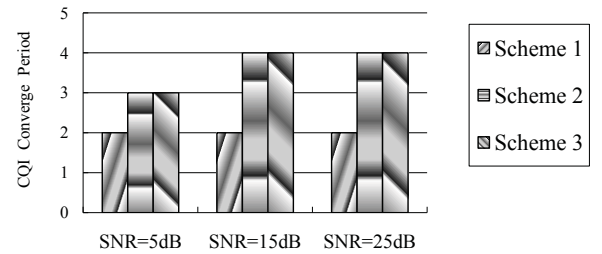


Fig. 6. Comparison of converge time in *VehB* channel

It can be seen that, with the increase of multipath delay spread, the channel quality decreases largely. As a result, it takes 2 feedback period for our scheme to calculate a converged CQI. The decrease in performance of our scheme is a consequence of more complex channel conditions in channels with large multipath delay spread. This only happens in the communications of high speed users (such as users in highways or subways). Although our scheme consumes more

feedback periods in *VehB* channel than in *PedB* channel, it still outperforms the other two schemes.

B. Comparison of Throughput

When comparing the throughput of the three schemes, we adopt the same assumption described in the beginning of Section V-A. The simulated SNR values are 5dB, 15dB and 25dB.

Fig. 7 presents the comparison of average throughput in *PedB* channel.

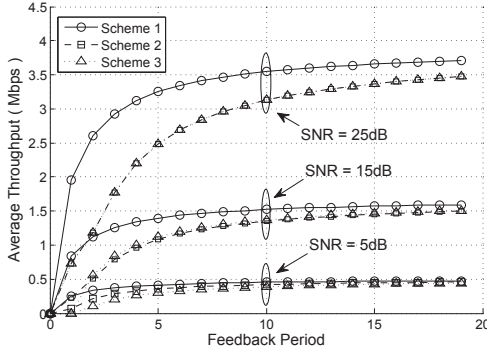


Fig. 7. Comparison of average throughput in *PedB*

Recall the assumption that initial CQI equals 15, the resulting throughput in the first transmission period (before a new CQI is fed back to BS) is almost zero, since the channel quality is far too poor to sustain the high modulation order and coding rate denoted by CQI 15. Consequently, the curves of average throughput starts from zero. However, it is still obvious from Fig. 7 that our scheme can always achieve a better throughput performance than other schemes. Moreover, our scheme reaches to the ultimate throughput much more quickly, which indicates that our scheme calculates CQIs more accurately and rapidly.

Fig. 8 shows the comparison of average throughput in *VehB* channel. It presents an interesting phenomenon: the achievable throughput (after a certain feedback periods) by different schemes are different. Our scheme provides the largest achievable throughput. It is well-known that downlink throughput in an AMC system is directly determined by the accuracy of CQI calculation. This phenomenon indicates that our scheme can select the optimal CQI, while other schemes only converge to a sub-optimal CQI. Hence, other schemes can not achieve the optimal throughput as our scheme.

VI. CONCLUSION

In this paper, we propose a novel CQI calculation scheme based on channel estimation. Unlike schemes proposed in previous works, our scheme not only considers the effect of SNR, but also takes multipath delay spread into account. A SNR&Delay-CQI mapping algorithm is designed to implement this idea. Furthermore, we nests this algorithm into a BLER-based CQI converge algorithm, so as to guarantee the

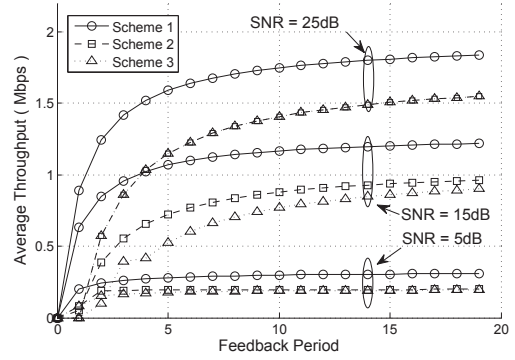


Fig. 8. Comparison of average throughput in *VehB*

converge of CQI calculation. Simulation results show that our scheme can select CQIs much more precisely and rapidly than previous schemes. Moreover, systems implementing our scheme can achieve a better average throughput. The design is based on LTE/LTE-A systems, but it can be applied directly on other systems.

VII. ACKNOWLEDGMENT

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APPENDIX CHEN01

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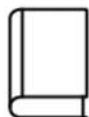
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A novel CQI calculation scheme in LTE\LTE-A systems

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III. SNR&Delay-CQI Mapping

IV. BLER-Based CQI Converge Algorithm

V. Simulations and Discussions

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Abstract:

We propose a novel Channel Quality Indicator (CQI) calculation scheme in LTE\LTE-A systems. SNR-CQI mapping scheme, as well as SINR-CQI mapping scheme, is extensively studied in previous works. However, these kinds of CQI mapping schemes always provide imprecise results in fading channels, since all of them ignore the channel quality degeneration caused by other factors. In this paper, we further improve CQI calculation by considering the impact of multipath delay spread. The calculation scheme is presented in details. In order to guarantee the converge of CQI calculation, a Block Error Ratio (BLER) based converge algorithm is proposed. Simulations show that our calculation scheme can select CQIs more precisely, and achieve better throughput performance than traditional schemes. Furthermore, our scheme converges much faster than previous schemes.

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I. Introduction

With the increasing demand of Quality of Service (QoS) in wireless communication system, more aggressive techniques are employed to improve the frequency and time efficiency. Adaptive Modulation and Coding(AMC) is one of the techniques that are applied in real systems to increase the throughput. By adaptively selecting modulation order and coding rate, AMC can provide a much better system performance than fixed modulation and coding schemes. In order to conduct AMC operation in LTE\LTE-A systems (see [1], [2], [3]), Channel Quality Indicators (CQIs)

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A Novel CQI Calculation Scheme in LTE\LTE-A Systems

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Abstract—We propose a novel Channel Quality Indicator (CQI) calculation scheme in LTE\LTE-A systems. SNR-CQI mapping scheme, as well as SINR-CQI mapping scheme, is extensively studied in previous works. However, these kinds of CQI mapping schemes always provide imprecise results in fading channels, since all of them ignore the channel quality degeneration caused by other factors. In this paper, we further improve CQI calculation by considering the impact of multipath delay spread. The calculation scheme is presented in details. In order to guarantee the converge of CQI calculation, a Block Error Ratio (BLER) based converge algorithm is proposed. Simulations show that our calculation scheme can select CQIs more precisely, and achieve better throughput performance than traditional schemes. Furthermore, our scheme converges much faster than previous schemes.

Index Terms—CQI calculation, feedback, LTE\LTE-A.

I. INTRODUCTION

With the increasing demand of Quality of Service (QoS) in wireless communication system, more aggressive techniques are employed to improve the frequency and time efficiency. Adaptive Modulation and Coding (AMC) is one of the techniques that are applied in real systems to increase the throughput. By adaptively selecting the appropriate modulation order and coding rate, AMC can provide a much better system performance than fixed modulation and coding schemes. In order to conduct AMC operation in LTE\LTE-A systems (see [1], [2], [3]), Channel Quality Indicators (CQIs) need to be fed back by User Equipments (UEs) or Mobile Stations (MSs).

The calculation algorithms of CQI are numerous. Most of the previous works utilize the SNR-CQI mapping to determine CQIs. In [4], the SNR-CQI mapping is designed offline. Each UE estimates the channel state information (CSI), then extracts channel SNR and applies SNR-CQI mapping to determine CQIs. In this kind of CQI calculation algorithm, SNR is the only reference for CQI selection.

Based on SNR-CQI mapping algorithm, lots of enhanced schemes have been proposed. In [5], the author considers the CQI feedback in MU-MIMO systems. It is proposed that SINR-CQI mapping should be adapted instead of SNR-CQI mapping, since user interferences become a major challenge of channel quality. In [6], the authors propose a leakage-based precoding algorithm, so as to compute a more reliable CQI and minimize user interference. As a result, the computing algorithm of CQI is based on a SLNR-CQI mapping.

Unfortunately, all the above mappings are calculated in some fixed channel models (for examples, AWGN and Rayleigh channels). In different channel models, SNR-CQI mapping (as well as SINR-CQI and SLNR-CQI mappings) is different when comparing with itself. Consequently, all the above mappings are not perfectly suitable in realistic scenarios. A solution based on SNR conversion is proposed in [7]. The authors derive the conversion criterions to convert SNRs of other channel models into that of AWGN channel. Then CQIs of other channel models can be obtained by substituting the converted SNRs into AWGN channel's SNR-CQI mapping.

However, channel quality is not only decided by the quality of signal power. In [8], the authors present three kinds of factors that will cause CQI errors. Among them, mobility of UEs may be the most serious one. The impact of mobility in channel quality reflects on the size of multipath delay spread. The larger the spread is, the larger the transmission delay is, and the worst the channel quality becomes.

In order to deal with the CQI errors caused by multipath delay spread, we propose a novel CQI calculation algorithm: SNR&Delay-CQI mapping. This algorithm jointly utilizes SNR and maximum multipath delay spread (denoted as *Delay*) of instantaneous channel state, to achieve a much more precise CQI under fading channels. Moreover, we embed this SNR&Delay-CQI mapping into a BLER-based CQI converge algorithm, with the purpose of minimizing the impact of channel estimation errors. It is worth noticing that our scheme can be extended to large scale wireless networks [9] [10] [11] [12].

The rest of the paper is organized as followed. Section II provides a brief discussion on limitations of SNR-CQI mapping. Our SNR&Delay-CQI mapping is presented in details in Section III. Section IV describes the BLER-based CQI converge algorithm. Simulations can be seen in Section V. And we conclude the paper in Section VI.

II. SNR-CQI MAPPING AND ITS LIMITATION

In LTE\LTE-A system, UEs select CQIs according to the results of channel estimation. Actually, each CQI in LTE\LTE-A system is a pair of modulation order and coding rate. The detailed definition of CQI, as well as the mapping from CQI to each modulation order and coding rate pair, can be found in [3]. Each UE tries to find an optimal pair of modulation

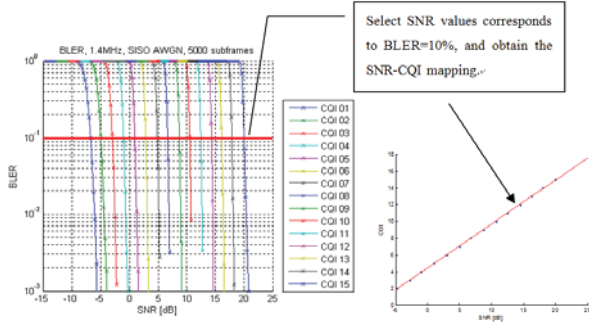


Fig. 1. SNR-CQI mapping generation in AWGN channel

order and coding rate, which provides the largest throughput when the BLER is less than 10 percent.

However, this process always costs too many computing resources for UEs. Therefore, simplifications of this optimizing process need to be adopted. Measurements and simulations should be conducted previously, so as to determine the optimal CQIs under different CSI conditions. After that, a CSI-CQI function or mapping is derived by a fitting of data. In this sense, UEs can obtain the feedback CQIs timely, as long as the channel estimations are finished.

Based on this idea, SNR-CQI mapping is proposed by many previous works. A common way to obtain a SNR-CQI mapping consists of three steps.

- In the first step, a BS employs CQI one by one in transmission. An active UE receives signals, then measures the SNR-BLER curve for each CQI, respectively. The UE preserves a group of SNR-BLER curves, each of which corresponds to a CQI.
- In the second step, UE selects the SNR value corresponding to BLER= 10% in each curve. Note that each curve corresponds to a CQI.
- In the third step, UE utilizes the SNR values selected in the second step, as well as the corresponding CQIs, to fit the desired SNR-CQI mapping.

An example of SNR-CQI mapping generation is showed in Fig. 1.

However, SNR is not the only parameter to determine a channel's quality. A SNR-CQI mapping in one channel model may fail to maintain a good performance in another. Fig. 2 presents the SNR-CQI mappings in some classic channel models. All the channel models are based on the measurements in realistic scenarios by 3GPP [3].

It is clear in Fig. 2 that one SNR value may correspond to different CQIs in different channel models. Such a difference is brought by a channel quality variation, which is a consequence of the variation of channel parameters other than SNR. Moreover, the SNR-CQI mappings plotted in Fig.2 are achieved with the priori knowledge of channel models. In real systems, it is almost impossible to estimate the channel models in UEs. As a result, SNR-CQI mapping is incapable of achieving accurate CQI values.

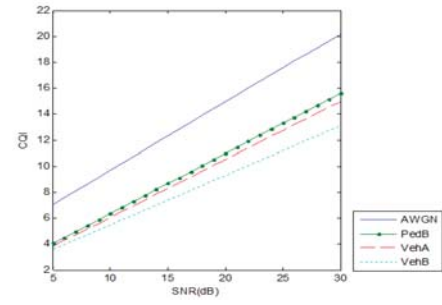


Fig. 2. SNR-CQI mappings in different channels

III. SNR&DELAY-CQI MAPPING

A. Certification for the Use of Multipath Delay Spread

Expect of SNR, multipath delay spread (denote as *Delay* for short) is another critical parameter in determining channel quality. Multipath delay spread is a measure of the multipath richness of a channel. It can be interpreted as the difference between the time of arrival of the first significant multipath component and the time of arrival of the last multipath component. In other words, it is the maximal delay of multipath transmissions. With the increase of *Delay*, more and more CQIs can not be adapted in transmissions even when SNR is high enough. Fig. 3 gives an illustration of invalid CQIs when *Delay* increases.

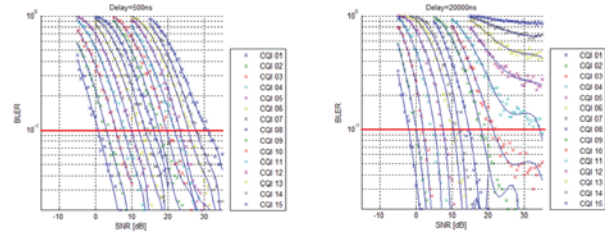


Fig. 3. Illustration of invalid CQIs when *Delay* increases. The left one presents the SNR-BLER curves for *Delay*= 500ns, and the right one stands for *Delay*= 20000ns

It can be seen from Fig. 3 that, when *Delay* is 500ns, all the 15 CQIs¹ can be used if SNR is large enough.² However, when *Delay* increases to 20000ns, only 10 CQIs can be used even maximum SNR is provided.

From the above analysis, we can conclude that multipath delay spread should be consider carefully in CQI calculation schemes.

B. Generation of SNR&Delay-CQI Mapping

In real systems, such as LTE\LTE-A systems and HSD-PA systems, there are too many factors affecting the system BLER. In order to obtain a SNR&Delay-CQI mapping,

¹Number of CQIs that are employed in LTE\LTE-A system is 15

²In real system, a SNR of 30dB is almost the largest SNR that can be achieved in optimal conditions. Correspondingly, we use 30dB as the upper value of SNR in this paper.

empirical formula should be achieved by simulations and measurements. In our work, we employ a link-level simulation platform³, which contains all the functions of LTE downlink transmissions, such as Turbo coding, linear MIMO decoding, channel estimation, AMC, etc. With the help of this platform, we adopt the following algorithm to obtain the SNR&Delay-CQI mapping in fading channels.

Algorithm 1 Generation of SNR&Delay-CQI Mapping

1. Set current *Delay* value D equals 0. Set measurement step of *Delay* as Δ_d .
2. Set current *Delay* value as $D + \Delta_d$, obtain the power delay profile of the corresponding channel [13].
3. Proceed transmissions in the channel generated in step 2, and obtain a SNR-CQI mapping as described in Section II.
4. If current *Delay* value is larger than the max value of *Delay* in measurement process, go to step 5. Otherwise, repeat step 2 and step 3.
5. Obtain a group of SNR-CQI mappings corresponding to different *Delay* values, and fit these mappings into a 3-dimension function:

$$CQI = F(SNR, Delay)$$

6. Output F .
-

C. A Simplified but Effective SNR&Delay-CQI Mapping

The process of calculating a 3-dimension function $CQI = F(SNR, Delay)$ by Algorithm 1 is complex. And the storage of such a function is relatively large in mobile devices. Here we present a simplified scheme, which changes the 3-dimension function $CQI = F(SNR, Delay)$ into a piecewise function. We will prove the effectiveness of such a simplified scheme in Section V. The cut-off points of the piecewise function in *Delay* axis defined as followed:

Definition 1: (CQI i 's cut-off point) The *Delay* cut-off point of CQI i represents the maximal multipath delay spread, under which the corresponding BLER is within system's limit while the largest SNR condition is provided.

In other words, the increase of multipath delay spread will cause a decrease of the available CQIs, since channel quality drops largely and can no long sustain high level modulations or coding rates. The turning points of available CQIs in multipath delay spread axis are defined as the cut-off points. A multipath delay spread that is larger than the cut-off point of CQI i will result in a large BLER by CQI(s) larger than i . A graphical illustration of cut-off points is presented in Fig. 4.

We propose to use the following cut-off points in LTE\LTE-A systems.

$$Q_{max} = \begin{cases} 15 & D \geq 400ns \ (D_{15}) \\ 14 & 400ns < D \leq 9500ns \ (D_{14}) \\ 13 & 9500ns < D \leq 12500ns \ (D_{13}) \\ 12 & 12500ns < D \leq 14800ns \ (D_{12}) \\ 11 & 14800ns < D \leq 18000ns \ (D_{11}) \end{cases} \quad (1)$$

³This simulation platform is developed by IWCT, Shanghai Jiao Tong University.

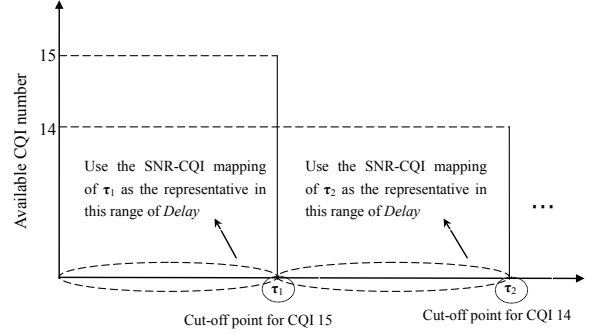


Fig. 4. A graphical interpretation of cut-off points and their meanings. A cut-off point is the maximal multipath delay spread that a certain CQI can be used with an optimal SNR condition.

where Q_{max} is the maximal CQI that can be used within two *Delay* cut-off points, and D denotes the *Delay*. D_{15} to D_{11} denote corresponding *Delay* range for short.

The corresponding piecewise function for SNR&Delay-CQI mapping is:

$$Q = \begin{cases} \min(\lfloor 0.513S - 0.215 \rfloor, 15) & D \in D_{15} \\ \min(\lfloor 0.431S + 2.148 \rfloor, 14) & D \in D_{14} \\ \min(\lfloor 0.402S + 2.152 \rfloor, 13) & D \in D_{13} \\ \min(\lfloor -0.004S^2 + 0.513S + 1.74 \rfloor, 12) & D \in D_{12} \\ \min(\lfloor -0.007S^2 + 0.527S + 1.77 \rfloor, 11) & D \in D_{11} \end{cases} \quad (2)$$

where Q represents the selected CQI, $\lfloor \cdot \rfloor$ denotes the rounding-down calculation, and S is the channel SNR.

It is worth pointing out that although the above results are achieved based on the simulations, they can be applied in most of the scenarios in LTE systems. First of all, all the simulations are conducted under typical LTE/LTE-A scenarios. Secondly, any CSI-CQI mapping is a rough estimation, which can be refined by the following converge algorithm. Moreover, the above scheme can be reapplied in other scenarios or systems with similar simulations and measurements.

IV. BLER-BASED CQI CONVERGE ALGORITHM

There are multiple factors that will decrease the performance of SNR&Delay-CQI mapping described in Section III. The accuracy of CQI calculation will be disturbed by the times and granularity of measurement, as well as the selection of simulation channels. As a result, UEs may select inappropriate CQIs over and over again. In order to guarantee a relatively good accuracy of CQI calculation, a BLER-based CQI converge algorithm is proposed. The SNR&Delay-CQI mapping is nested inside the body of BLER-based CQI converge algorithm. Every selected CQI will be re-evaluated by BLER-based CQI converge algorithm, so as to maintain a BLER that fits the system's requirement.

If channel quality decreases, the feedback CQI should decrease, or at least remain the same. Therefore, we employ a CQI-decreasing function to make sure that feedback CQIs converge. The cut-off points decreased in (1) are used in

such a function. The CQI-decreasing function is presented as followed.

$$Q_{conv} = Q_{pre} - \Delta Q \quad (3)$$

and
 $\Delta Q =$

$$\begin{cases} [18.69\beta - 18.22\Delta\beta] & D \in D_{15} \\ [13.38\beta - 14.31\Delta\beta] & D \in D_{14} \\ [-93.55\beta^2 + 110.41\beta - 35.23\Delta\beta] & D \in D_{13} \\ [-123.67\beta^2 + 146.63\beta - 45.54\Delta\beta + 0.32] & D \in D_{12} \\ [-0.52\beta^2 + 35.59\beta - 34.64\Delta\beta - 0.1] & D \in D_{11} \end{cases} \quad (4)$$

where Q_{conv} denotes the converged CQI, Q_{pre} is the CQI fed back in previous period, ΔQ denotes the decreasing value to obtain a converged CQI value, β represents current BLER, and $\Delta\beta$ is the subtraction between BLER in the last period and BLER in the current period.

Based on the above function, the BLER-based CQI converge algorithm is presented in Algorithm 2.

Algorithm 2 BLER-based CQI Converge Algorithm

Input: Feedback CQI Q_{pre} , BLER β , SNR S_{pre} and Delay D_{pre} in the last transmission period, system threshold of BLER δ , current SNR S and Delay D .

Output: Refined CQI Q .

1. Initiate two intermediate variables $Q_1 = Q_2 = 15$.
 2. If $\beta \leq \delta$, go to step 5. Otherwise, go to step 3.
 3. If $S > S_{pre}$ and $D < D_{pre}$, go to step 5. Otherwise, go to step 4.
 4. Calculate converged CQI by equation(3), and save it in Q_1 .
 5. Calculate mapping CQI by equation(2), and save it in Q_2 .
 6. Output $Q = \min(Q_1, Q_2)$.
-

By employing Algorithm 2, a refined CQI that can guarantee a BLER under system's threshold can be achieved conveniently.

V. SIMULATIONS AND DISCUSSIONS

In this section, we provide some simulation results to verify our SNR&Delay-CQI mapping and BLER-based CQI converge algorithm. In our simulations, we assume that the initial CQI in simulations is 15, so as to illustrate the converge process of CQIs. Channel models in [13] are adopted.

We denote our scheme as Scheme 1, which utilizes both SNR&Delay-CQI mapping and BLER-based CQI converge algorithm. The SNR-CQI mapping scheme proposed in [4], [7], etc, can not guarantee a converge on feedback CQIs. Therefore, we combine the SNR-CQI mapping and our BLER-based CQI converge algorithm to form Scheme 2. Scheme 3 represents the scheme that only employs a traditional dichotomous BLER-based CQI converge algorithm [1].

A. Comparison of CQI Converge Time

In order to compare the converge time for each scheme, we assume that the channels remain unchanged during simulation time. This setting is reasonable in slow fading channels. However, the simulation results can still provide a certification

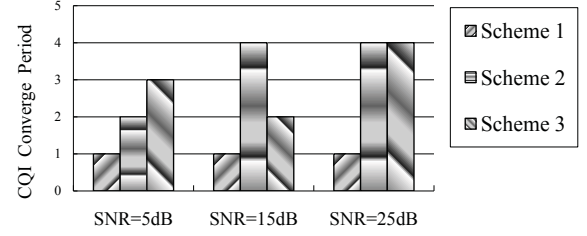


Fig. 5. Comparison of converge time in *PedB* channel

in fast fading channels (We will discuss in the following paragraphs).

Fig. 5 shows the comparison of CQI converge time in *PedB* channel [13]. *PedB* channel is a channel model characterizing the channel of pedestrians. The speed of mobile UEs is relatively small.

It is demonstrated in Fig. 5 that our scheme can converge at the final CQI with only 1 feedback period. Recall that we set the initial CQI as 15 in simulations, a converge period of 1 indicates that our scheme always selects a converged CQI in each feedback period. Other schemes consume up to 4 feedback periods to obtain a converged CQI. This means that other schemes require several feedback periods of interaction to finish CQI selection. This further illustrates that the scheduling overhead of our scheme is much less than that of the other two. Moreover, if the variation of channel is fast, our scheme can provide a real-time CQI calculation, while other schemes fail to catch up with the channel's variation.

Fig. 6 shows the comparison of CQI converge time in *VehB* channel [13]. *VehB* channel is a channel model characterizing the channel of vehicles. The multipath delay spread is much larger than that of *PedB* channel.

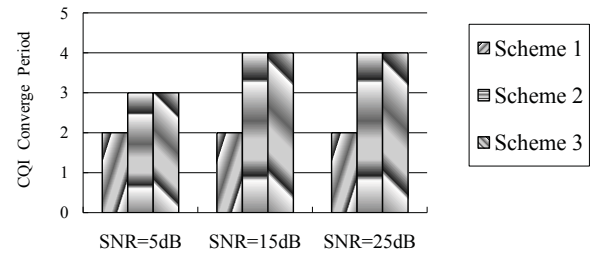


Fig. 6. Comparison of converge time in *VehB* channel

It can be seen that, with the increase of multipath delay spread, the channel quality decreases largely. As a result, it takes 2 feedback period for our scheme to calculate a converged CQI. The decrease in performance of our scheme is a consequence of more complex channel conditions in channels with large multipath delay spread. This only happens in the communications of high speed users (such as users in highways or subways). Although our scheme consumes more

feedback periods in *VehB* channel than in *PedB* channel, it still outperforms the other two schemes.

B. Comparison of Throughput

When comparing the throughput of the three schemes, we adopt the same assumption described in the beginning of Section V-A. The simulated SNR values are 5dB, 15dB and 25dB.

Fig. 7 presents the comparison of average throughput in *PedB* channel.

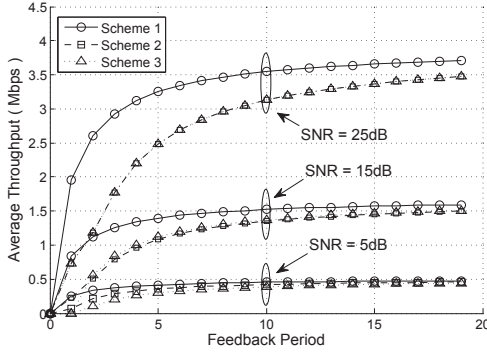


Fig. 7. Comparison of average throughput in *PedB*

Recall the assumption that initial CQI equals 15, the resulting throughput in the first transmission period (before a new CQI is fed back to BS) is almost zero, since the channel quality is far too poor to sustain the high modulation order and coding rate denoted by CQI 15. Consequently, the curves of average throughput starts from zero. However, it is still obvious from Fig. 7 that our scheme can always achieve a better throughput performance than other schemes. Moreover, our scheme reaches to the ultimate throughput much more quickly, which indicates that our scheme calculates CQIs more accurately and rapidly.

Fig. 8 shows the comparison of average throughput in *VehB* channel. It presents an interesting phenomenon: the achievable throughput (after a certain feedback periods) by different schemes are different. Our scheme provides the largest achievable throughput. It is well-known that downlink throughput in an AMC system is directly determined by the accuracy of CQI calculation. This phenomenon indicates that our scheme can select the optimal CQI, while other schemes only converge to a sub-optimal CQI. Hence, other schemes can not achieve the optimal throughput as our scheme.

VI. CONCLUSION

In this paper, we propose a novel CQI calculation scheme based on channel estimation. Unlike schemes proposed in previous works, our scheme not only considers the effect of SNR, but also takes multipath delay spread into account. A SNR&Delay-CQI mapping algorithm is designed to implement this idea. Furthermore, we nests this algorithm into a BLER-based CQI converge algorithm, so as to guarantee the

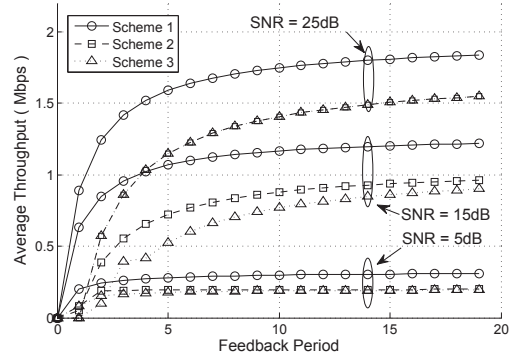


Fig. 8. Comparison of average throughput in *VehB*

converge of CQI calculation. Simulation results show that our scheme can select CQIs much more precisely and rapidly than previous schemes. Moreover, systems implementing our scheme can achieve a better average throughput. The design is based on LTE/LTE-A systems, but it can be applied directly on other systems.

VII. ACKNOWLEDGMENT

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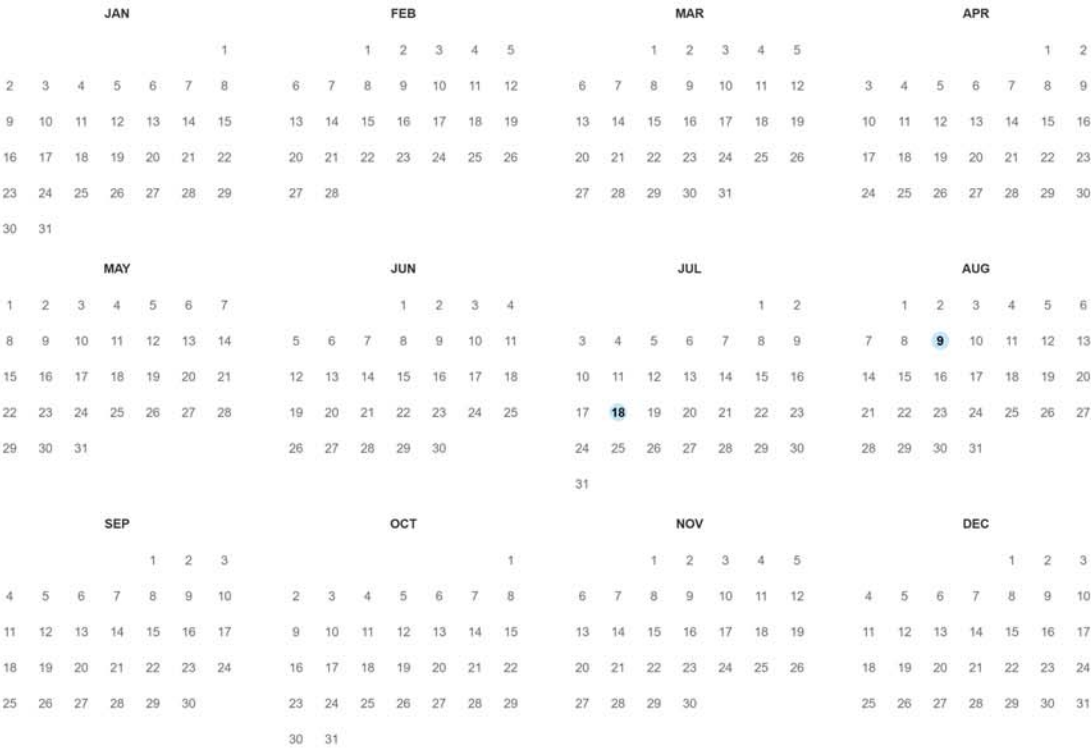
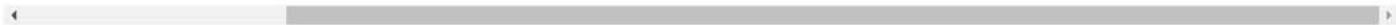
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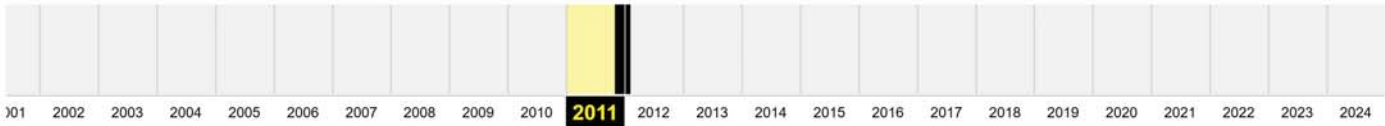
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09:50-10:40	Keynote Speech 2	Scientific Lecture Hall	Chip-Level Space-Time Coding: Its Opportunities and Challenges (by Prof. Hsiao-Hwa Chen,National Cheng Kung University)
10:40-11:10	Coffee Break		
11:10-12:00	Keynote Speech 3	Scientific Lecture Hall	Impulse radio UWB with Time Reversal (by Prof. Maria-Gabriella Di Benedetto,University of Rome)
12:00-13:00	Lunch Buffet	Nanjing Hotel	
13:30-15:30	Oral 1	Hall1 Nanjing Hotel	Signal Processing for Communications
	Oral 2	Hall2 Nanjing Hotel	B3G and 4G Technology (No.1)
	Oral 3	Hall3 Nanjing Hotel	Invited Session on Interference Management Techniques in Wireless Networks
	Oral 4	Hall4 Nanjing Hotel	Cognitive Radio and Cognitive Wireless Network (No.1)
	Oral 5	Hall5 Nanjing Hotel	Cooperative Communications (No.1)
	Oral 6	Hall6 Nanjing Hotel	Image & Video Signal Processing (No.1)
	Oral 7	Hall7 Nanjing Hotel	Information Theory and Coding (No.1)
	Oral 8	Hall8 Nanjing Hotel	MIMO Technology and Space-time Coding (No.1)
15:30-16:00	Coffee Break		
	Oral 9	Hall1 Nanjing Hotel	OFDM Technology (No.1)
	Oral 10	Hall2 Nanjing Hotel	Signal Processing Applications (No.1)
		Hall3	

16:00-18:00	Oral 11	Nanjing Hotel	Special Session on Cognitive Radio
	Oral 12	Hall4 Nanjing Hotel	Wireless Ad Hoc and Sensor Networks (No.1)
	Oral 13	Hall5 Nanjing Hotel	Invited Session on Smart Grid: From Elementary to Evolutionary Technologies in Networking,Security,Optimization,Applications
	Oral 14	Hall6 Nanjing Hotel	Channel Measurement,Modeling and Evaluation Blind Signal Processing
	Oral 15	Hall7 Nanjing Hotel	Invited Session on Applications of Optimization Theory in Wireless Communications
	Oral 16	Hall8 Nanjing Hotel	Cooperative Communications (No.2)
18:00-20:00	Supper Buffet	Nanjing Hotel	
November 10,2011(Thur)			
09:00-09:50	Keynote Speech 4	Scientific Lecture Hall	Interference in wireless networks: To suppress or to decode? (by Prof. Xiaodong Wang, Columbia University)
09:50-10:40	Keynote Speech 5	Scientific Lecture Hall	An Overview of the Network Coding Theory (by Prof. Zhen Zhang ,University of Southern California)
10:40-11:10	Coffee Break		
11:10-12:00	Keynote Speech 6	Scientific Lecture Hall	Applications for Wireless Visual Sensor Networks - the Digital Zoo (by Prof. Haibo Li,Umeå universitet)
12:00-13:00	Lunch Buffet	Nanjing Hotel	
13:30-15:30	Oral 17	Hall1 Nanjing Hotel	B3G and 4G Technology (No.2)
	Oral 18	Hall2 Nanjing Hotel	Cooperative Communications (No.3)
	Oral 19	Hall3 Nanjing Hotel	Wireless Ad Hoc and Sensor Networks (No.2)
	Oral 20	Hall4 Nanjing Hotel	Image & Video Signal Processing (No.2)
	Oral 21	Hall5 Nanjing Hotel	Invited Session on Multimedia Communication Technology
	Oral 22	Hall6 Nanjing Hotel	Antennas and Propagation MIMO Technology and Space-time Coding (No.2)
	Oral 23	Hall7 Nanjing Hotel	Array & Multi-channel Signal Processing Signal Processing Applications (No.2)
	Oral 24	Hall8 Nanjing Hotel	Cognitive Radio and Cognitive Wireless Network (No.2) Information Theory and Coding (No.2)
15:30-16:00	Coffee Break		
16:00-18:00	Oral 25	Hall1 Nanjing Hotel	Wireless Ad Hoc and Sensor Networks (No.3) Wireless Mesh Network
	Oral 26	Hall2 Nanjing Hotel	Radio Resource Allocation Digital Circuits & Systems in Wireless Communications
	Oral 27	Hall3 Nanjing Hotel	Analog Circuits & Systems in Wireless Communications Wireless Communications System Architectures and Applications
	Oral 28	Hall4 Nanjing Hotel	Space and Satellite Communications Wireless Transmission Technologies
	Oral 29	Hall5 Nanjing Hotel	Adaptive Signal Processing,Biomedical Signal Processing Image & Video Signal Processing (No.3)
	Oral 30	Hall6	Speech and Audio Signal Processing

		Nanjing Hotel	
	Oral 31	Hall7	Estimation and Detection
		Nanjing Hotel	Wireless Network Coding
	Oral 32	Hall8	OFDM Technology (No.2)
		Nanjing Hotel	Ultra-Wideband Communications
			Cross-layer Design
18:30-20:30	Banquet	Nanjing Hotel	

Shuttle service from Nanjing Hotel to Nanjing University of Posts & Telecommunications (NUPT) will be provided for free during the conference.

Oral1:Signal Processing for Communications

13:30-15:30,Wednesday,Nov. 9

- 40Gbps Multi-Connection TCP/IP Offload Engine
Yong Ji,Qingsheng Hu
- Implementation of MVDR detector using cascaded modular structure
Zhongjie Li
- Performance Analysis of Relay Selection for Two-Way Cooperative Relay Networks
Ji BaoFeng,Song Kang,Yongming Huang,Yang Luxi
- Two-way Relay Channel Estimation Based on Compressive Sensing
Wenwen Yuan,Baoyu Zheng,Wenjing Yue,Lei Wang
- Quadrature Compressive Sampling for Radar Echo Signals
Feng Xi,Shengyao Chen,Zhong Liu
- Estimating the Frequencies of Harmonics in Multiplicative and Additive Noise Based on Subspace Rotational Invariance
Shiyong Yang,Tao Jiang
- A Sparse Reconstruction Algorithm with Hierarchical Bayesian Analysis for Wideband Spectrum Detection
Xiaorong Xu,JianWu Zhang,Baoyu Zheng,Junrong Yan
- MAP equalization in Indoor Visible Light
Xiu-Xiu Xie,Jun-Bo Wang,Ling-Ling Cao,Ming Sheng,Min Feng

Oral2: B3G and 4G Technology (No.1)

13:30-15:30,Wednesday,Nov. 9

- Weakness in 802.11w and an improved mechanism on protection of management frame
Wang Weijia,Haihang Wang
- Inter-piconet Interference Mitigation Schemes for Converged BTLE and Cellular Network
Ying Hu,Guizhu Wang,Lianhai Shan
- Performance Analysis of Time Division Broadcast Protocol with Incremental Relaying
Kun Xu,Yuanyuan Gao,Xiaoxin Yi
- Downlink Performance Analysis of Distributed Antenna Systems
Yuxi Liu,Ju Liu,Weidong Guo,He Chen,Dong Zheng,Guowei Zhang
- Performance Analysis of Selection Decode-and-Forward Relay Networks in Generalized Fading Channels
Kaihua Wang,Chunxiao Cai,Cai Yueming
- A Low-Complexity Adaptive Transmission Scheme Based on the Dual-Codebook of 3GPP LTE-Advanced
Minxia Hu,Shi Jin,Xiqi Gao
- A Correlated-Equilibrium-based Subcarrier Allocation Scheme for Interference Minimization in Multi-cell OFDMA Systems
Jianchao Zheng,Cai Yueming,Dan Wu
- A Novel CQI Calculation Scheme in LTE/LTE-A Systems
Xi Chen,Haike Yi,HanWen Luo,Hui Yu,Hailong Wang
- Joint Optimization on Load Balancing and Network Load in 3GPP LTE Multi-cell Networks
Zhihang Li,Hao Wang,Zhiwen Pan,Nan Liu,Xiaohu You
- Design of LDPC Code Strategy for Orthogonal Modulation
Haiyang Hu,Yukui Pei,Ning Ge

Oral3: Invited Session on Interference Management Techniques in Wireless Networks

13:30-15:30,Wednesday,Nov. 9

- Designs and Performance Analysis on ML-decoders in a Two User's Interference Channel

Haiquan Wang, Zhijin Zhao

- A Feedback Rate Control Game using Sequential Second Price Auction for Channel State Information and Inter-cell Interference in Wireless Networks

Tianyu Wang, Lingyang Song, Zhu Han, Zhongshan Zhang, Bingli Jiao

- Price of Anarchy of Congestion Games with Player-Specific Constants

Lok Man Law, Jianwei Huang, Mingyan Liu

- Distributed Power Control with Limited Message Passing for Nonconcave Utility Maximization

Liping Qian, Ying Jun (Angela) Zhang

- Coordinated Beamforming with Relaxed Zero Forcing

Gilwon Lee, Juho Park, Youngchul Sung, Masahiro Yukawa

- On Design of Asymmetric Interference Alignment and Cancellation Scheme in MIMO X Network

Lu Yang, Wei Zhang

Oral4: Cognitive Radio and Cognitive Wireless Network (No.1)

13:30-15:30, Wednesday, Nov. 9

- Downlink Power Control in Cognitive Femtocell Networks

Daolong Sun, Xinning Zhu, Zhimin Zeng, Shaohua Wan

- Improving Primary Throughput by Cognitive Relay Beamforming with Best-Relay Selection

Xinrong Guan, Cai Yueming, Weiwei Yang

- Resource Allocation Technique for Downlink Beamformed Cognitive Radio Network

Kishore Babu Chandrababu, Abdel hamid Soliman, Mohammad Patwary

- An Access Control Algorithm in Cognitive Radio System

Zhang Guobin

- From Reconfigurable SDR to Cognitive Femto-Cell: A Practical Platform

Le Zhao, Shiyang Chen, Xiaoying Gan

- User cooperation communication based on cognitive radio in DAS

Liping Huang, Dongming Wang, Xiangyang Wang

- Analysis of Cognitive Radio Spectrum Access for Emergency Communication System

Peng Han, Hua Tian, Wei Xie

- Maximum-minimum Eigenvalue Detection-based Method to Mitigate the Effect of the PUEA in Cognitive Radio Networks

Fayu Liu, Hui Fang Chen, Lei Xie, Kuang Wang

- Spectrum Sensing Using Non-asymptotic Behavior of Eigenvalues

Lei Wang, Baoyu Zheng, Jing Wu Cui, Wenjing Yue

- Reasoning Through Fuzzy Logical for Reconfiguration in Cognitive Radio Network

Qian He, Zhiyong Feng, Ping Zhang

Oral5: Cooperative Communications (No.1)

13:30-15:30, Wednesday, Nov. 9

- Augment Delay Tolerant Networking Routing to extend wireless network coverage

Mei Haibo

- Outage Performance Analysis and Optimal Power Allocation of Opportunistic Cooperation Communications without Direct-Link

Xiaojie Chen, Youyun Xu, Dongmei Zhang

- Outage Performance Analysis for Cooperative Networks with Randomly Distributed Nodes

Haichuan Ding, Shuo Li, Chengwen Xing, Fei Zesong

- Gaussian Two-hop Relay Channel with Linear Relaying

Zhixiang Deng, Bao-Yun Wang, Fei Lang, Yayan Ma

- Performance Analysis of Two-way Relay Systems Based on Partial Channel State Information

Rui Zhao, Canhui Cai, Yongming Huang

- An Energy-efficient Cooperative MAC Protocol with Piggybacking for Wireless Sensor Networks

Xurong Pi, Cai Yueming

- Performance Analysis of Distributed Space-Time Coded Cooperative Multicast

Hui Tian, Wei Xie, Youyun Xu, Lianguo Wu, Maoqiang Zuo

- Cooperative Scheme Using STNC for Uplink SC-FDMA and Downlink OFDMA System

Xiaochen Xia, Youyun Xu, Kui Xu

- Energy-Efficient Multi-User relay networks

Huan Yu, Ruogui Xiao, Yunzhou Li, Jing Wang

- A Limited Feedback Strategy for Cooperative Multicell MISO Systems

Fengfeng Shi, Wei Xu, Chunming Zhao

Oral6: Image & Video Signal Processing (No.1)

13:30-15:30, Wednesday, Nov. 9

- Processing Piecewise Autoregressive Model Image Interpolation Algorithm on GPU with CUDA
Kuiying Yin
- K-cluster Based Reconstruction for Compressive
Mai Xu, Jianhua Lu
- Detect and Autofocus the Moving Target by Its Range Walk in Time Domain
Yake Li
- Application of Digital Image Processing on Non-destructive Testing of Fusion Joints of Polyethylene Piping by Ultrasonic Technique
Babak Rostami, Behzad Saeedi Razavi
- Improved SAI Method using Non-local Spatial Constraint for Image Interpolation
Jueping Bian, Zongliang Gan, Mengcheng Zhang, Xiuchang Zhu
- An Adaptive Image Denoising Method for Mixture Gaussian Noise
Yiwen Qiu, Zongliang Gan, Yaqiong Fan, Xiuchang Zhu
- Structural Similarity Optimal MB Layer Rate Control for H.264
Ziguan Cui, Zongliang Gan, Xiuchang Zhu
- A camera self-calibration method based on dual constraints of multi-view images
Feng Liu, Weiwei Han
- A Comparison of Image Registration Techniques for Joining Sequential Images
Prakash Duraisamy

Oral7: Information Theory and Coding (No.1)

13:30-15:30, Wednesday, Nov. 9

- The Investigation of Mapping schemes for LDPC-Coded Modulated Systems
Ying Wang, Kangming Jiang, Kaisui Zhang, Bojian Wen
- Achievable Secrecy Rate of The Relay-eavesdropper Channel with Generalized Feedback
Yayan Ma, Jing Bao, Junxi Zhao, Bao-Yun Wang
- Diversity and Multiplexing Tradeoff in the Uplink of Cellular Systems with Linear MMSE Receiver
Xiaoshi Song, Changchuan Yin, Dan Pu Liu
- Polar codes and Its Application in Speech communication
Sheng-mei Zhao
- Construction of Irregular Quasi-Cyclic LDPC Codes Based on Euclidean Geometries
Xueqin Jiang, Moon Ho Lee
- A High-throughput Reconfigurable Viterbi Decoder
Rongchun Li, Yong Dou, Jie Zhou, Guoqing Lei
- On the Capacity Region of the Semi-deterministic Z Channel
Wuling Liu, Nan Liu, Zhiwen Pan
- Improved Interleaving Scheme for DVB-S2 BICM System
Kangming Jiang, Ying Wang
- Unequal Error Protected JPEG 2000 Broadcast Scheme with Progressive Fountain Codes
Zhao Chen, Mai Xu, Liuguo Yin, Jianhua Lu

Oral8: MIMO Technology and Space-time Coding (No.1)

13:30-15:30, Wednesday, Nov. 9

- Investigations on Gains of Transmit and Receiver Diversities for Uplink DFT-Precoded OFDMA
Lianjun Deng, Teruo Kawamura, Hidekazu Taoka, Mamoru Sawahashi
- Non-orthogonal Pilot Design and Analysis for CoMP Systems
Xiujun Zhang, Xiang Chen, Shidong Zhou, Jing Wang
- The Achievable Secrecy Rate of MISO Wiretap Channels
Haiyang Zhang, Bao-Yun Wang
- Adaptive Feedback Scheme on Multicell Multiuser MISO System
Rui Zhang
- Design of MAI Constrained Decision Feedback Equalizer for MIMO CDMA System
Khalid Mahmood, Syed Muhammad Asad, Muhammad Moinuddin, Shashi Paul
- Proportional Fair Scheduling Schemes for Highly Transmit Correlated Channels
Qiang Sun, Jue Wang, Yuan Zhang, Shi Jin, Xiqi Gao
- Phase Noise Mitigation in High Frequency Band SC-MIMO Systems
Hui Xie, Gui Lin, Jian Xiong
- Joint Power Control and Beamforming for Peer-to-Peer MIMO Relay Systems
Muhammad Khandaker, Yue Rong
- Performance Evaluation of Limited Feedback Transmit Precoding via Phase Rotation in Correlated MIMO Channel
Sho Furuichi, Kenta Umebayashi, Yasuo Suzuki
- On Quasi-Orthogonal Space-Time Block Codes for Dual-Polarized MIMO Channels
Yabo Li, Zhike Huang, Haiquan Wang, Xiang-Gen Xia

Oral9: OFDM Technology (No.1)

16:00-18:00, Wednesday, Nov. 9

- Statistical Distributions of OFDM Signals on Multi-Path Fading Channel
Renhui Xu, Ming Chen, Chang Tian, Xuming Lu, Chunjuan Diao
- A Carrier Frequency Offset Estimation Algorithm for OFDM Systems
Pengcheng Zhu
- Pilot Tone Selection in OFDM Amplified-and-forward Relay System
Linfeng An
- A Two-stage-game-based Power Control Scheme for OFDMA-relay Channels under Physical Layer Security Requirement
Zhao Hou, Dan Wu, Cai Yueming
- A Differential Successive Multiuser Ranging Detection for OFDMA Systems
Chieh Lung Lin
- Cauchy-Rayleigh Scattering Cluster Based Spatial-Temporal-Spectral Correlation Properties with MIMO-OFDM Channel Model
Xin Li, Torbjorn Ekman
- CDM Based Reference Signal Structure Using Oversampling for OFDM Downlink
Masahiro Tabata, Teruo Kawamura, Hidekazu Taoka, Mamoru Sawahashi
- Distribution of PAPR in LOFDM Systems Based on Extreme Value Theory
Kui Xu, Dongmei Zhang, Youyun Xu, Zhenxing Lv, Wenwen Liang
- Multicast or Broadcast in multiuser OFDM systems
José Saavedra, Pierre Duhamel

Oral10: Signal Processing Applications (No.1)

16:00-18:00, Wednesday, Nov. 9

- A Predictive Deadbeat Control in Shunt Active Power Filter
Zhihua Bao, Zongchen Wang, Shibing Zhang
- Modified spread-transform dither modulation
Yifeng Zhang
- An Efficient Algorithm for Indoor Location Based on RFID
Jing Chen, Gengmin Li, Xuejun Zhang, Tuanfa Qin
- Compressive Parametric GLRT detector for Airborne MIMO Radar
Siva Karteek Bolisetti, Khawza Ahmed, Mohammad Patwary, Mohamed Abdel-Maguid
- Two Blind Algorithms of MMSE Filter Based on Second-Order Statistics in MIMO Systems with Multiple Interferences
Fan He, Rueywen Liu, Xu Wang, Tao Yang, Bo Hu
- Estimability of Quantized Linear systems
Ying Shen, Hui Zhang
- A Smart Tracking-based Jamming Scheme for Signals with Periodic Synchronization Sequences
Yuan Chen, Fei He, Jian Yan, Xiang Chen, Yuntao Gu
- High-speed LMS equalizer for Spread Spectrum System Based on FPGA
Liu Bingchao, Li Fang, Daoben Li
- An Efficient Algorithm for TDOA/FDOA Estimation Based on Approximate Coherent Accumulative of Short-Time CAF
Wei Zhang

Oral11: Special Session on Cognitive Radio

16:00-18:00, Wednesday, Nov. 9

- Multiuser Power Allocation for OFDM-Based Cognitive Radio Network
Lili Wang, Wenjun Xu, Kai Niu, Zhiqiang He, Jiaru Lin, Baoyu Tian
- A distributed network selection mechanism for WCDMA/OFDMA heterogeneous networks
Ning Li, Wenjun Xu, Jiaru Lin
- Code Aided CPO Estimation Based on Particle Filtering
Peng Chen
- Capacity of Cognitive Radio under Outage Constraint with Partial Channel Knowledge
Liu Yang, Ding Xu, Zhiyong Feng, Qian Li, Ping Zhang
- Connectivity Guaranteed Cluster Header Selection Scheme Based on Spectra Analysis of Graph
Fenglin Xie, Zhiyong Feng, Zhiqing Wei
- Cognitive Network Channel Allocation Strategy with Queuing Delay and Game Analysis
Jun Liu, Xiufeng Xie
- Joint Access and Power Control in Cognitive Femtocell Networks
Qian Li, Zhiyong Feng, Wei Li, Liu Yang, Ping Zhang
- Spatial-Temporal Opportunity Detection in Spectrum-Heterogeneous Cognitive Radio Networks: Non-Cooperative Case

Guoru Ding, Qihui Wu

- Variable Bandwidth Spectrum Access for Secondary User in Cognitive Radio Network
Yu Fu, Qinyu Zhang, Wang Ye, Xin Guan
- Graph-based Spectrum Sharing for Multiuser OFDM Cognitive Radio Networks
Qiu Tao
- Capacity Analysis for Secondary User in Cognitive Radio Network
Wang Ye, Qinyu Zhang

Oral12: Wireless Ad Hoc and Sensor Networks (No.1)

16:00-18:00, Wednesday, Nov. 9

- An Improved AODV Routing Protocol for VANETs
Ben Ding, Zehua Chen, Yan Wang, Hui Yu
- An Energy-Efficient Distributed Compressed Sensing Architecture for Wireless Sensor Networks Based on a Distributed Wavelet Compression Algorithm
Haifeng Hu, Zhen Yang
- Improving Energy-Efficiency in Building Automation with Event-Driven Radio
Yan Zhang
- A 0.18 μ m CMOS Up-Conversion Mixer for Wireless Sensor Networks Application
Chenjian Wu
- A Weighted Energy Efficient Clustering (WEEC) for Wireless Sensor Networks
Negin Behboudi, Ehsan Arvacheh, Abdolreza Abhari
- A Capacity-Aware Cross-Layer QoS Optimization Scheme for Wireless Multimedia Networks
Hai-tao Zhao, Rui Zhang, Rongfang Song, Zhang Hui, Yu-ning Dong, Feng Tian
- A Cross-layer Protocol of Wireless Sensor Networks for Tailings Reservoir On-line Monitoring
Feng Jin, Da Zhang, Ligang Wang
- A New IVC Based on Ad Hoc and its Design Simulations
Guo Chen, Huang Xuejun, Hongbo Zhu
- Designing an Energy Efficient Prediction-based Algorithm for Target Tracking in Wireless Sensor Networks
Fatemeh Deldar, Mohammad Hossien Yaghmaee

Oral13: Invited Session on Smart Grid: From Elementary to Evolutionary Technologies in Networking, Security, Optimization, Applications

16:00-18:00, Wednesday, Nov. 9

- A technical approach to achieve smart grid advantages using energy management systems
Yousuke Nozaki, Tetsuya Tominaga, Noboru Iwasaki, Akira Takeuchi
- A Survey of Game Theoretic Approaches in Smart Grid
Zubair Fadlullah, Yousuke Nozaki, Nei Kato
- Energy Efficient Communication Network Design for Demand Response in Smart Grid
Lei Zheng, Simon Parkinson, Dan Wang, Lin Cai, Curran Crawford
- A Stochastic Petri Nets Approach to Dependability Analysis of Control Center Networks in Smart Grid
Rongfei Zeng, Yixin Jiang, Chuang Lin, Sherman Shen

Oral14: Channel Measurement, Modeling and Evaluation, Blind Signal Processing

16:00-18:00, Wednesday, Nov. 9

- Abnormal ECG signal detection based on Compressed Sampling in Wearable ECG sensor
Kun Mean Hou
- Autocorrelation Based Detection of DSSS Signal for Cognitive Radio System
Zhipeng Deng, Lianfeng Shen, Nan Bao, Bailong Su, Jintao Lin, Dayang Wang
- Channel Estimation and Adaptive Transmission in Variable Symbol Rate Systems
Jingning Wang, Dongliang Wang, Hang Zhang
- Improved Compressed Sensing-based UWB Channel Estimation
Chunyu Jian, Xinrong Ye, Wei-Ping Zhu
- Compressed Channel Estimation based on Optimized Measurement Matrix
Xiaochao Xiao, Baoyu Zheng, Chenhao Wang
- An Improved Adaptive Channel Estimation Method for Multiuser Multiantenna OFDM Systems
Yue-Xing Gao, Jie Yang, Qing-Min Meng
- Overall Outage Probability of Two-Way Amplify-and-Forward Relaying in Nakagami-m Fading Channels
Xiaoming Xu, Cai Yueming, Chunxiao Cai
- Compressed MIMO Channel Estimation and Efficient Pilot Pattern over Doppler Sparse Environment
Dongmei Wang, Xiaoyun Hou
- Soft Input Channel Estimation for Two-Way Cooperative-OFDM

Wei Wu

- A Joint Design of Code and Training Sequence for Frequency-Selective Block Fading Channels with Partial CSI

Po-Ning Chen, Chia-Lung Wu, Mikael Skoglund

Oral15: Invited Session on Applications of Optimization Theory in Wireless Communications

16:00-18:00, Wednesday, Nov. 9

- Bi-directional Communication with Eigenmode Sharing
Mai Xu, Zhiguo Ding, Baoguo Xu
- Robust Transceiver Beamforming in MIMO Cognitive Radio via Second-Order Cone Programming
Huiqin Du, Tharmalingam Ratnarajah
- Robust Linear Transceiver Design for Multi-Hop Non-Regenerative MIMO Relaying Systems
Chengwen Xing, Fei Zesong, Shaodan Ma, Jingming Kuang, Yik-Chung Wu
- Source and Relay Matrices Optimization for Multiuser Multi-Hop MIMO Relay Systems
Yue Rong
- A New Approach to Weighted Sum-Rate Maximization for the K-User Gaussian Interference Channel
Liang Liu, Rui Zhang, Kee Chaing Chua
- Simplified Alternating Optimization for Robust MMSE MIMO Transceiver
Jiaheng Wang, Mats Bengtsson
- Beamformer Designs for Zero-forcing Dirty Paper Coding
Le-Nam Tran, Markku Juntti, Mats Bengtsson, Björn Ottersten
- On the Performance of Kronecker MIMO Channel Models: A Semi-definite Relaxation Approach
Naftiseh Shariati, Mats Bengtsson
- Yet another entropy power inequality with an application
Miquel Payaró, Maria Gregori, Daniel Palomar

Oral16: Cooperative Communications (No.2)

16:00-18:00, Wednesday, Nov. 9

- Optimizing bit-interleaved coded modulation for half-duplex relay based on protograph codes
Sun Xiaojun, Ming Jiang, Wei Xu, Chunming Zhao
- Low SNR Capacity of Multi-Base Station Cooperative Transmission
Jun Zhang, Bin Jiang, Shi Jin, Xiqi Gao
- Cooperative ARQ in Wireless Sensor Networks: Outage Behavior and Throughput Efficiency
Hualiang Chen, Cai Yueming, Weiwei Yang
- Probability Constraint Robust Downlink Collaborative Beamforming
Dong Zheng, Ju Liu, He Chen, Hongji Xu, Lina Zheng
- Outage Probability of Two-Way Amplify-and-Forward Relaying System with Interference-Limited relay
Junchao Shen, Nan Sha, Cai Yueming
- Joint MMSE Precoding Design in Multi-user Two-Way MIMO Relay Systems
Haike Yi, Jun Zou, Hanwen Luo, Hui Yu, Jipeng Ma
- Performance Analysis of Incremental Relaying Based on Partial Selection in Multi-Source Multi-Relay Networks
Weidong Guo, Ju Liu, Yuxi Liu, Lina Zheng, Dong Zheng
- On the Number of Relays for Orthogonalize-and-Forward Relaying
Yue Yang, Xudong Wang, Xiaodong Cai
- Physical Layer Network Coding Based on Dual Relay Selection
Lianju Wu, Xiaoyun Hou
- A Simple Downlink Diversity Transmit Scheme for Cooperative Base Stations
Min Lin, Jian Ouyang
- Security Game between Source and Friendly Relay
Maorui Zhang, Bao-Yun Wang

Oral17: B3G and 4G Technology (No.2)

13:30-15:30, Thursday, Nov. 10

- An efficient CFO estimation algorithm for the downlink of 3GPP-LTE
Feng Wang, Yu Zhu
- A Novel Channel Estimation Method for TD-HSPA+ System in Rapidly Time-Varying Environments
Qiang Gu, Xiaodong Xu
- An Efficient Adaptive Receiver for MIMO-OFDM Systems

Hong Shen, Hua Zhang, Chunming Zhao

- Design of Simplified Overlapped Code Division Multiplexing System

Peng Sun, Daoben Li, Li Fang

- A Time-Difference-of-Arrival Location Method Based on Residual Sorting and Weighted Matrix amended

Jian Geng, Linghua Zhang

- Frequency Synchronization Scheme for LTE Downlink in Cell Handover of HST Environment

Lihua Yang

- The Uplink Capacity of SA-MIMO System under Single-User Scenario

Jian-xin Dai, Ming Chen, Pei-Jung Chung

- Accurate Channel Estimation and Wavelet-based Interference Estimation Methods and Application in Downlink Beamforming for LTE Systems

Ruijuan Sun, Ke Deng, Pengcheng Mu, Hui-Ming Wang

- A novel energy saving strategy for LTE HetNet

Chengzhe Liu, Zhiwen Pan, Nan Liu, Xiaohu You

- Investigations on Best Combining Scheme of Diversity Branches in Joint MLD for PUCCH in LTE Uplink

Hideyuki Numata, Teruo Kawamura, Mamoru Sawahashi

Oral18: Cooperative Communications (No.3)

13:30-15:30, Thursday, Nov. 10

- Hybrid Forward Scheme with Generalized Selective Combining

Qiang Huo, Tianxi Liu, Lingyang Song, Bingli Jiao

- Opportunistic Relaying for Two-Way Relay Transmission with Analog Network Coding

Xiaodong Ji, Baoyu Zheng, Lei Wang, Xing Gao

- Multi-hop Relay Pairs Transmission Scheme Based on Fountain Code

Liu Hui Feng, Lei Weijia, Xianzhong Xie

- Feedback-Aided Pilot Placement for Two-Way Cooperative-OFDM

Wei Wu

- Cooperative Transmit Diversity Based on Physical Layer Network Coding

Xin Yi Zhong, Youyun Xu, Kui Xu

- Outage-Optimal Relay Selection in Wireless Sensor Networks Using Fuzzy Comprehensive Evaluation

Wendong Yang, Cai Yueming

- Outage Performance for Parallel Relay-Assisted Free-Space Optical Communications in Strong Turbulence With Pointing Errors

Min Feng, Jun-Bo Wang, Ming Sheng, Ling-Ling Cao, Xiu-Xiu Xie

- A Method for Cooperative Relay Selection

Xin Huang, Enchang Sun, Yanhua Zhang

- Wideband Dynamic Base Station Selection for Downlink Coordinated Multipoint System

Shulei Gong, Xiaohu You, Pengcheng Zhu

- An improved distributed iterative beamforming algorithm with cooperative base stations

Jiamin Li, Dongming Wang, Pengcheng Zhu, Xiaohu You, Lan Tang

- Projection-based Power Allocation Scheme for Joint Transmission System

Chunyan Yan, Ke Deng, Hui-Ming Wang

- Multiple Symbol Differential Detection of MPSK with Cooperative Diversity Reception

Yajun Zhang, Yuanyuan Gao, Shibin Su, Guozhen Zang

Oral19: Wireless Ad Hoc and Sensor Networks (No.2)

13:30-15:30, Thursday, Nov. 10

- A Spanning Routing Tree Protocol Based on State Diffusion for Mobile Sensor Networks

Wei Xing, Kuntai Li, Yongchao Wang, Wen Zhou

- A Clustering Routing Algorithm of WSN based on Uneven Nodes Deployment

Yan Gu

- A New Energy-Efficient Scheduling Scheme for Multiple Target Coverage in Wireless Sensor Networks

S. M. Kawser Amir, Md. nurul Shaon, Mohammad Matin

- A New Uni-Scheduling Algorithm in S-MAC based Wireless Sensor Networks

Dheeman Saha, Mohammad Matin

- Detecting Selective Forwarding attacks in WSNs using Watermark

Chao Xu

- Integration of Wireless Sensor Network into Existing Public Network using DSL and Development of Web Presenter

Yu Sun, Stevan Berber

- A multi-path transmission algorithm for Layered scalable coding

Zhang Dengyin

- Accurate and Computation-Efficient Localization for Mobile Sensor Networks

Yunlong Wang, Ze Wang

- Dynamic Updating Based Key Management Algorithm for Wireless Sensor Networks

Y. Rao, Jinhua Wang

- A Low-Voltage CMOS Programmable Gain Amplifier for WSN Application

Libin Huang, Zhiquan Li

Oral20: Image & Video Signal Processing (No.2)

13:30-15:30, Thursday, Nov. 10

- Stereoscopic Visualization of Monocular Images in Photo Collections
Shahrouz Yousefi, Farid Abedan Kondori, Haibo Li
- Robust Correction of D Geo-Metadata in Photo Collections by Forming a Photo Grid
Shahrouz Yousefi, Farid Abedan Kondori, Haibo Li
- A video watermarking algorithm based on three dimensional wavelet transform
Cao Lin, Jiang Wei
- Map Updation using Image Registration for Different Sensors by Camera Calibration
Prakash Duraisamy, Ye Yu
- 3D Head Pose Estimation using the Kinect
Farid Abedan Kondori, Shahrouz Yousefi, Haibo Li, Samuel Sonning, Sabina Sonning
- A Zero-watermarking Image Authentication Scheme Using Zernike Moment and Extreme Learning Machine
Guangyong Gao, Guoping Jiang
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XiaoLiang Dong, Sheng-mei Zhao, Baoyu Zheng

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- A Mobile Health Monitoring Solution for Weight Control
Ivo Lopes, Bruno Silva, Joel Rodrigues, Jaime Lloret, Mario Proença Jr.
- Adaptive Reconstruction of Human Motion on Wireless Body Sensor Networks
Shih-Yeh Chen, Wei-Tsong Lee, Han-Chieh Chao, Yueh-Min Huang, Chin-Feng Lai
- Real Time Services for Future Cloud Computing Enabled Vehicle Networks
Jin Wang
- Real-time Video Surveillance for Large Scenes
Hanyu Liu, Chong Tang, Shaoen Wu, Honggang Wang
- A Game based Routing algorithm for Congestion Control of Multimedia transmission in VANETs
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- A New Robust Beamforming Method Against Signal Steering Vector Errors And Moving Jammers
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- Finite-Difference Frequency-Domain Analysis of Wave Propagation in 2-D Frequency-Dependent Periodic Structures
Amin Gul Hanif, Toru Uno, Takuji Arima
- RF Link Budget Analysis in Urban Propagation Microcell Environment for Mobile Radio Communication Systems Link Planning
Ardavan Rahimian, Farhad Mehran
- An Asymmetric Scan Time Synchronization Algorithm for TDMA Directional Antennas Networks
Qiang Zuo, Youyun Xu, Ma Wenfeng, Mo Li
- A Joint Design of Transmit Antenna Selection and Multiuser Scheduling for Multiuser MIMO systems Employing Block Diagonalization Precoding Scheme
Feng Wang
- A Multi-user MIMO Resource Scheduling Scheme for Carrier Aggregation Scenario

Lei Na,Guo Caili,Feng Chunyan,Chen Yu

- Layer reduced K-best sphere decoding
Xinyu Mao,Shubo Ren,Haige Xiang
- A Unified Mathematical Model for Spatial Scrambling Based Secure Wireless Transmission and Its Wiretap Method
Feilong Wu,Wenjie Wang,Hui-Ming Wang,Qinye Yin
- Chernoff Upper Bound of PEP for Distributed Space-Time Coding Relay Systems in Nakagami-m Fading Channels
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- Time Synchronization Error and PRF in Pulse Jamming Against ISAR
Shi rui Peng,Xin Li
- Direction-of-Arrival Estimation Based on Modified Bayesian Compressive Sensing Method
Lei Sun
- Moving Target Detection Based on Long Coherent Processing Interval for Vehicle-borne Low Frequency SAR System
Zhimin Zhou,Hong Zhou,Xiaotao Huang,Pengzheng Lei,Chang Yulin,Tong Jin
- Rician K-factor analysis of In-Cabin Distributed MIMO System Measurements
Yuejian Zhou
- Source Analysis and Separation Using Spatial Filtering and Time Frequency Distribution in Array Signal Processing Under Complicated Environment
Wen-yan Liu,Xiaotao Huang,Tong Jin
- Practical Beam Broadening for Space-borne SAR Using Phase-Only Pattern Synthesis
Xiangneng Zeng
- Relative navigation using pulsar signals
Zhang Hua,Xu Luping,Li Woheng
- Flaw Classification in Ultrasonic Guided Waves Signal Using Wavelet Transform and PNN Classifier
Xiaohui Zhang,Guangmin Sun,Haomiao Liu,Qite Wang

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- Enhanced Dynamic Spectrum Sharing for Multi-Cell Heterogeneous Networks
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- On the Periodic Scheduling of Spectrum Sensing for Cognitive Radio
Renhui Xu,Ming Chen,Chang Tian,Xuming Lu,Chunjuan Diao
- A Node Grouping Algorithm for Joint Relay Selection and Resource Allocation in Cooperative Cognitive Radio Networks
Chuan Ma,Guanding Yu,Jietao Zhang
- A QoS constrained cognitive routing algorithm for ad hoc networks based on directional antenna
Feng Ping,Yongfei Ding,Bo Liu,Jianmin Wu,Gui Lin,Haibo Zhou
- A self-awareness routing scheme with power control for underlay spectrum sharing networks
Yongfei Ding,Jianmin Wu,Haibo Zhou,Ping Feng,Bo Liu,Lin Gui
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Yin Long,Jiang Zhu,Fangwei Li
- Cognitive Radio Spectrum Sharing using Improved Quantum Genetic Algorithm
Fei Li,Dongpo Zhu,Feng Tian,Haibo Li
- An Improved Interference Mitigation Scheme Based on Interference Subspace Alignment
He Shiwen,Yongming Huang,Yang Luxi
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- An Improved Distributed Bayesian Algorithm for Fault-Tolerant Detection in Electromagnetic Spectrum Monitoring Sensor Networks
Yu Zhang,Hangsheng Zhao,Qiongli Liu
- A 1V Active-RC Complex Filter for Wireless Sensor Networks Application
Zeng Yi,Zhiqun Li
- Adaptive Mobility-Assisted Data Collection in Wireless Sensor Networks
Liang He,Jun Tao,Jianping Pan,Jingdong Xu
- Understanding the Indoor Interference between IEEE 802.15.4 and IEEE 802.11b/g via Measurements
Yanchao Mao,Zenghua Zhao,Xin Jia
- Hierarchical Heterogeneous Wireless Sensor Network Management System
Junjiao Ye,Zenghua Zhao,Hao Li,Hao Chen
- Fault Tolerant Routing in Three-dimensional Underwater Acoustic Sensor Networks
Ming Xu,Guangzhong Liu
- Utilizing Weighted Rating of Multiple Attributes Scheme to Enhance Handoff Efficiency in Heterogeneous Wireless Networks
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Xing Yang,Tiankui Zhang,Feng Chunyan,Zhongfeng Li
- Energy-Efficient Resource Allocation in Multi-user OFDMA systems
Hu Ying,Yongming Huang,Yang Luxi
- Resources Allocation in Mobile Communications on Aircraft
Chao Zhang,Keke Pang
- A Decentralized Downlink Dynamic ICIC Method for Multi-cell OFDMA System
Shujun Wang,Yuan Zhang,Guangguo Bi
- A Novel Resource Allocation Algorithm in Uplink Multi-cell OFDMA Networks Based on Game Theory
An Wang,Cai Yueming,Zhao Hou
- An Energy Optimization Scheme Based on Rate Guarantee in Emergency Mesh Network
Liang Changqing,Zhao Su
- A Cross-band Cooperation Architecture for Spectrum Efficiency Improvement
Yi Li,Yifei Zhao,Shidong Zhou,Yuan Gao,Xiang Chen,Chunhui Zhou
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Zhiyuan Shi,Man Liu,Lianfen Huang
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Dongjun Shen,Zhiqun Li
- Joint Design of Physical Layer Network Coding and Channel Decoding Based on Trellis Coded Modulation in two-way relay channel
Zhicheng Chen,Baoyu Zheng,Xiaodong Ji,Wei Liang zhang
- Differential Six-port Modulator
Owais Owais,Joakim Öst,Shaofang Gong
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- Research on Decreasing Resource Consumption in Wireless O2O Services Operation
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Jian Guo, Shubo Ren, Ying Si, Jianjun Wu
- Analysis of Channel Correlation Characteristics in GEO Mobile Satellite Communications
Xiaoyan Xu, Shubo Ren, Jianjun Wu, Haige Xiang
- Terrestrial Mobile Networks for Air-to-Ground Communications of the General Aviation
Chao Zhang
- Performance Analysis of Adaptive Modulation System over Mobile Satellite Channels
Junhui Zhao, Shengchun Guan, Yi Gong
- Analysis of Cell Spectral Efficiency of Infrastructure Relay-Enhanced Cellular System
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- Broadcasting Efficient Opportunistic Network Coding for Multisource-Multidestination Scenarios
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- A MDCT-based Click Noise Reduction Method for MPEG-4 AAC Codec
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- Impact of Channel Estimation Errors in Amplify-and-forward Two-way Relaying System
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- A Novel Transmit Beamforming Scheme for BER Improvement in EIRP Constrained UWB Systems
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APPENDIX CHEN05

Article PDF Available

Radio Resource Management for Green 3GPP Long Term Evolution Cellular Networks: Review and Trade-offs

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Abstract and Figures

Conventional design of cellular systems aims to maximize the system capacity and spectral efficiency due to sustainable growth of data rate requirements. As the energy consumption becomes relatively high, energy-efficient design for cellular systems is highly required to save energy as well as reducing the undesirable carbon dioxide emitted by these systems. However, reducing the energy consumption will degrade other system performances such as the data rate and quality of service. Therefore, joint optimization for overall system performances should be achieved. In this paper, the energy-efficient radio resource management (RRM) for Long Term Evolution (LTE) systems is addressed. After a brief introduction to LTE radio resource block and LTE frame, different types of energy efficiency metrics are defined to give a better understanding to the energy efficiency perspectives. The energy-efficient approaches related to link adaptation and RRM are explained. The state-of-the-art energy-efficient schedulers are also discussed, and a comprehensive comparison between them is adopted in this paper. Moreover, many trade-offs, challenges, and open issues are addressed to optimize the system performances.



The amount Power : TEEER The LTE BLER curves
of CO 2... consumpti... formulas downlink... in SISO...

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Radio Resource Management for Green 3GPP Long Term Evolution Cellular Networks: Review and Trade-offs

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Abstract

Conventional design of cellular systems aims to maximize the system capacity and spectral efficiency due to sustainable growth of data rate requirements. As the energy consumption becomes relatively high, energy-efficient design for cellular systems is highly required to save energy as well as reducing the undesirable carbon dioxide emitted by these systems. However, reducing the energy consumption will degrade other system performances such as the data rate and quality of service. Therefore, joint optimization for overall system performances should be achieved. In this paper, the energy-efficient radio resource management (RRM) for Long Term Evolution (LTE) systems is addressed. After a brief introduction to LTE radio resource block and LTE frame, different types of energy efficiency metrics are defined to give a better understanding to the energy efficiency perspectives. The energy-efficient approaches related to link adaptation and RRM are explained. The state-of-the-art energy-efficient schedulers are also discussed, and a comprehensive comparison between them is adopted in this paper. Moreover, many trade-offs, challenges, and open issues are addressed to optimize the system performances.

Keywords

Adaptive modulation and coding, Energy efficiency, Green communication, Link adaptation, Multi-input-multi-output, Orthogonal frequency division multiple access, Resource allocation, 3GPP long term evolution.

1. Introduction

Escalation of wireless and cellular systems continues to stir up new research avenues that enable these systems to meet the growing demands and to work under various limitations. "Green Radio Technology" [1,2] is among areas which have been adopted recently to overcome the limitations in the radio spectrum as well as reducing the energy consumed by the wireless systems.

The limitation in radio spectrum comes from the fact that the spectrum is fixed and it is not free. The more wireless applications and technologies used, the more bandwidth required. Wireless data traffic has increased in recent years due to the variety of applications and smart software and devices. It has also increased due to the presence of many social networking applications through the internet, such as Facebook and Twitter. Moreover, it has been expected that this growth will continue increasing exponentially, especially with the exploitation of the 3GPP Long Term Evolution (LTE)-Advanced cellular networks, which should support up to 1 Gbps in the downlink transmission. Therefore, the radio spectrum resources should be utilized as efficiently as possible to overcome the bandwidth limitations.

On the other hand, the continuous growth in wireless data traffic results in the increase of energy consumed by wireless networks, which leads to undesirable increase in carbon dioxide (CO_2) emission. For example, the total energy consumed by a network of 20,000 3G base stations is about 58 MW, resulting in an annual cost of \$62 million and a carbon footprint of 11 tons for each cell site [3]. The CO_2 emission is considered as the chief greenhouse gas that resulted from wireless networks and other human activities, and causes the global warming and climate changes. Stephen Ruth in [4] has investigated several leading approaches that have been used to reduce the CO_2 emitted by information and communications technology. Although there are serious efforts to reduce the amount of CO_2 emission per mobile subscriber, as shown in Figure 1 [5], cleaner and efficient solutions for wireless communications is urgently required.

The cellular network power consumption can be classified into five categories as shown in Figure 2 [6]. These categories give us an insight into the possible research avenues for reducing energy consumption in cellular network. It is obviously noticed that the major amount of the cellular network power is consumed by the base stations. However, the power consumed by transmission

process is also momentous due to the sustainable growth of data rate requirements. Therefore, in this paper, we will address the energy-efficient approaches that can reduce the energy consumption in the core transmission. Unlike most of the review articles available in the literature related to green communications [6,7], this paper discusses exclusively the energy-efficient link adaptation and resource scheduling techniques related to 3GPP LTE systems.

In energy-efficient link adaptation, we carry out a detailed survey on adaptive modulation and coding (AMC), power control and multi-input-multi-output (MIMO) antenna, and highlight the research opportunities that make these techniques green. Although the link adaptation needs more control signaling, it is shown that adapting some or all of these link properties will help the system to maximize its energy efficiency. Moreover, link adaptation alongside with the gain of multiuser diversity will give the cellular systems more flexibility to make a proper decision in allocating the

radio resources among users. Therefore, energy-efficient radio resource management (RRM) is also discussed in this paper. A comparison between the state-of-the-art energy-efficient resource schedulers is carried out. Furthermore, many types of trade-offs between the energy efficiency, spectral efficiency, fairness, and delay are investigated to meet the 3GPP LTE requirements.

The rest of the paper is organized as follows. In Section 2, a brief overview to LTE radio resource block (RB) and frame structure is introduced. Then, the energy efficiency with the related radio transmission metrics is defined in Section 3. In Section 4, a review of the energy-efficient cellular transmission by using energy-efficient link adaptation strategies is provided. Section 5 will cover various energy-efficient resource allocation procedures and algorithms proposed in the literature. Finally, conclusions and recommendations for future work are discussed in Section 6.

2. LTE Radio Resource Management

RRM is essential for LTE cellular networks because of the scarceness of radio resources which should be shared by multiple users. The RRM involves many strategies to utilize the limited power and bandwidth resources in an efficient way whereby a reliable transmission is satisfied. Furthermore, the radio resources can be managed to achieve a spectral-efficient transmission with high throughput and low latency, which is highly required for LTE networks. The RRM is usually categorized into two parts, scheduling and resource allocation. The scheduler normally decides which user to be served and determines the number of packets that should be scheduled in the current frame. However, the resource allocator decides which RB is assigned to the selected user, and determines the number of RBs required for satisfying the user requirements. The resource allocator assigns RBs to user with the best channel condition and/or according to their QoS requirements in order to improve the overall system performances. RB is a block of 12 subcarriers in the frequency domain and 7 (or 6) symbols in time domain. Hence, there is a grid of 84 resource elements per RB, each can be represented by 2, 4, or 6 bits depending on the type of used modulation as shown in Figure 3 [8]. In the frequency domain, the LTE transmission bandwidth can be chosen between 1.4 to 20 MHz due to the non-utilized spectrum, and thus, there will be different numbers of RBs to be allocated



Figure 1: The amount of CO_2 emitted per subscriber [5].

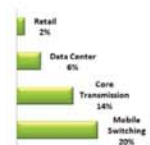




Figure 2: Power consumption of a typical wireless cellular network.

to the users according to the used channel bandwidth as shown in Table 1. In the time domain, the 10 ms LTE

Table 1: LTE channel bandwidth

Channel bandwidth (MHz)	1.4	3	5	10	15	20
Transmission bandwidth (MHz)	1.08	2.7	4.5	9	13.5	18

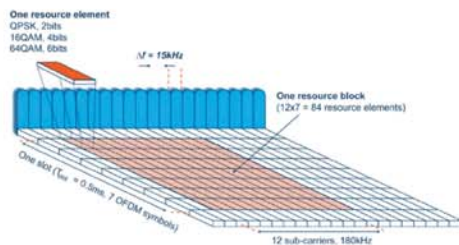


Figure 3: The LTE downlink physical resource based on OFDM.

frame is divided into 10 subframes with each consisting of two 0.5 ms time slots. The 0.5 ms time slot represents the time duration of each RB. Further information on LTE frame structure can be found on [8].

3. Energy Efficiency Metrics

In general, "The more energy-efficient the communication system is, the less energy it needs to achieve the same task" [9]. However, energy efficiency can be defined in different ways according to the purpose of designed system. And accordingly, the energy efficiency metrics can be addressed. Rather than the definition, the energy efficiency metrics should reflect how green the wireless system is. Therefore, the energy efficiency metrics can be classified into three categories [10], component-level, equipment-level, and system-level metrics.

The component-level metrics include low-level energy efficiency rating for individual parts inside the wireless equipments; antenna system, baseband processor, etc. In the equipment level, metrics should reflect the energy efficiency of whole base station or wireless access point [11]. Finally, system (network) level metrics would consider the energy efficiency for the entire network. This level metrics can be classified according to the classes of wireless network such as cellular, wireless local area network, ad-hoc, and satellite networks. In this paper, we will discuss some of these metrics which are related to data transmission of LTE cellular systems.

3.1 Transmission Energy Efficiency

The number of bits transmitted per joule of energy reflects how energy-efficient the transmission link between the base station and the user equipment is. This metric represents the transmission rate energy efficiency which is given by [12]

$$U(R) = \frac{R}{P(R)} = \frac{R}{P_t + P_c} \quad (1)$$

where, P_t is the circuit power consumption, P_c is the transmit power, and R is the achievable data rate.

3.2 Energy Consumption Rate

Energy consumption rate (ECR) is a framework for measuring the energy efficiency of network and telecom devices [13]. This metric is considered as a valid differentiator between the networking and telecom equipments. For example, equipment with lower ECR consumes less energy to drive the same amount of payload. The ECR can be defined as the consumed energy divided by the effective full-duplex throughput as given by

$$ECR = \frac{E}{T} \quad (2)$$

where, E represents the energy consumption in watts, and T denotes the effective system throughput in bits per second. In LTE systems, it is highly required to determine the ECR corresponding to various base station equipments. The basic power consumption models of different base stations have been discussed in details in [14]. As shown in Figure 4, the basic equipments in base station are rectifier, power amplifier, baseband signal processing unit, feeder, antenna, and cooling systems. Moreover, the base station site may also incorporate other supports and/or supplementary cabinets that are not included with the base station main equipments, and it should be considered in the calculation of the ECR. Each of these equipments has different activity levels of power consumptions due to different load conditions, i.e. in LTE cellular networks, three activity levels are defined corresponding to the busy hour, medium term load, and low load [15].

3.3 Energy Reduction Gain

In order to compare between the performances of two systems, a useful metric called Energy Consumption Gain (ECG) can be used to show difference in energy consumption between the baseline and the new cellular system. In contrast, the energy reduction gain (ERG) [6] can be used to show the percentage in saving energy gain between two systems, and it can be calculated as

$$ERG = 1 - \frac{1}{ECG} \quad (3)$$

ERG can determine the saving in energy consumption when there are two different systems having to deliver the same amount of data through the same duration of time. However, such metrics give relative measurements, and therefore, the energy-related calculations were not done in a fair manner.

3.4 Telecommunications Equipment Energy Efficiency Rating

Telecommunications equipment energy efficiency rating (TEEER) is an equipment-level metric that calculates the energy efficiency of individual pieces of cellular network equipments at various utilization levels. TEEER is proposed by Alliance for telecommunications industry solutions [16] to calculate the energy efficiency rating for specific products. Prior to calculate TEEER, the equipment under test (EUT) should be examined under three levels of utilizations which are 100%, 50%, and 25% for full-load, medium, and low utilizations, respectively. At each level, a corresponding required power should be provided to the EUT over a period of 15 minutes for stability purposes, and the value is recorded. Then, the total power consumption for this EUT can be represented by a weighting formula as

$$P_{avg} = (0.35 \times P_{max}) + (0.4 \times P_{50}) + (0.25 \times P_{25}) \quad (4)$$

where, P_{max} , P_{50} , and P_{25} are the measured input powers with the EUT while operating at maximum load, 50% of maximum load, and no activity mode, respectively. However, the weighting values may not be the same for all operators. According to the calculated value of

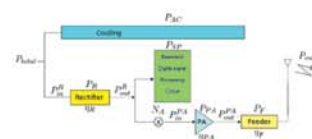


Figure 4: Power flow in the base station.

Table 2: TEEER formulas

Equipment type	TEEER formula
Soft Switch	$-\log(P_{Total} / \text{BHCA})$
Media Gateway	$-\log(P_{Total} / \text{Throughput})$
Video Multiplexer	$-\log(P_{Total} / \text{BHCA})$
Access	$(\text{Access Lines} / P_{Total}) \times 1$
Power	$(P_{Out} / P_{In} / \text{Total}) \times 10$
Power Amplifier (Wireless)	$(\text{Total RF Output Power} / \text{Total Input Power}) \times 10$
Mechanized Distributing Frames	$-\log(P_{Total} / \# \text{ of input connections})$

will then select a user with good channel gain, and determine the required number of RBs for this user at a given transmission time interval. Thus, the required number of RBs for each user can be determined according to the used modulation order, level of transmitted power, and/or the number of transmitting antennas. Both, resource scheduling and link adaptation rely upon the available channel state information at the eNodeB. However, the adaptation in both link properties and resource scheduling is crucial for 3GPP LTE cellular systems to maximize the system performances. In this section, several energy-efficient link adaptation techniques such as AMC, power control, and adaptive transceiving antenna are discussed.

4.1 Adaptive Modulation and Coding

The most appealing feature of AMC is that it can adjust the transmission data rate and energy efficiency dynamically according to the channel condition. It is well-known that the low order modulation scheme is robust against higher level of interference; however, it provides lower

P_{max} above, the TEEER can be calculated for different equipments according to the formulas shown in Table 2. TEEER metric is applicable for broadband, networks, and customer-premise equipments.

4. Energy-efficient Link Adaptation

The link adaptation is a fundamental procedure that is related to adaptive resource scheduling [17]. It is used to adapt the link properties such as modulation and coding scheme (MCS), and MIMO rank and precoding according to the channel state. The resource scheduler

bit rate. Therefore, low-order modulation is recommended when signal-to-interference-noise ratio (SINR) is low. Conversely, when the SINR is relatively high, the high modulation order will be the suitable candidate. The Channel Quality Indicator (CQI) plays an important role in determining the channel quality, and thus, the coding and modulation level can be recognized accordingly. In LTE cellular systems, it is important to know that the CQI reported by the UE is not a SINR direct indicator, but a 4-bit integer which shows the highest MCS that can be decoded by the user with a block error rate (BLER) not more than 10% [18].

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The type of the receiver and number of antennas should be taken into account in the estimation process of the CQI value. By using this procedure, the UE can help the eNodeB in choosing the suitable MCS for data transmission. The LTE link level simulator presented by [19] shows the BLER-SINR curves which give the BLER value as shown in Figure 5. According to these curves, the MCS can be chosen adaptively to maintain the BLER lower than 10% as shown in Figure 6.

Most of the AMC techniques in the literature have been proposed to maximize the spectral efficiency. However, changing the constellation size has also been used to maximize the energy efficiency. In [20], the authors proposed a modulation scaling for saving energy. They proposed an energy aware packet scheduling system, and emphasized the analogy between the modulation scaling and voltage scaling. They proved that the modulation scaling exhibits benefits similar to that of voltage scaling, and, to some extent, it outperforms the voltage scaling in energy-aware systems.

In addition to change of the constellation size, the authors in [21] have ensured that the transmission time and the circuit energy should be taken into account in the energy consumption analysis. They have examined the MQAM and minimum frequency shift keying (MFSK) under the delay and peak-power constraints. It has been shown that there will be an energy saving of up to 80% when the transmission time is optimized, especially in short distance transmission.

Furthermore, coding in MQAM and MFSK is also examined in [21]. Trellis-coded modulation with MQAM has been studied and it outperformed the uncoded MQAM. However, in MFSK, coding can only reduce the consumed energy in large distance transmission.

For orthogonal frequency division multiple access (OFDMA)-based wireless networks, the authors in [12] and [22] have also proved that the adaptive modulation can help to optimize the energy efficiency. Although both works have considered the circuit power consumption in their analysis, different circuit power model has been adopted by each of them. In [12], the authors considered that the total power consumed by the base station is the transmitted power plus the circuit power consumption, without taking into account their relation to the used bandwidth. However, the authors in [22] have adopted the following circuit power model:

$$P_c = W(p_{cs} + p_{ci}^s) + P_{cc}^s \quad (5)$$

where, W represents the bandwidth used for transmission, and p_{cs} and p_{ci}^s are the transmitted and circuit power

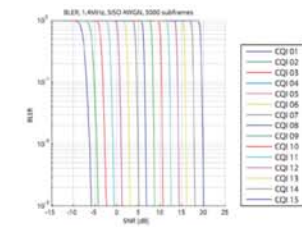


Figure 5: BLER curves in SISO AWGN simulations for all 15 CQI values. From CQI 1 (leftmost) to CQI 15 (rightmost).

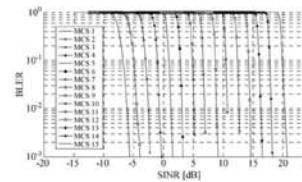


Figure 6: BLER-SINR curves for 1.4MHz with corresponding MCSs.

consumed for signal processing per unit bandwidth, respectively, which are both proportional to the transmission bandwidth. P_{cc} is the static power consumption that does not have any defined relation to the transmission bandwidth, i.e. the power supply and cooling systems. The latter model seems closer to the practical situation, and, by considering it in their analysis, the authors found that the modulation order should be adapted according to the channel condition to maximize the energy efficiency. As shown in Figure 7, it is clear that the system with adaptive modulation can transmit higher number of bits per Joule compared to other systems with fixed modulation order.

4.2 Power Control

Beside AMC, energy-efficient link adaptation can be obtained by adjusting other transmission parameters such as the transmitted power. Controlling the level of transmitted power can maximize the spectral efficiency [23,24], and at the same time can manage the intra-cell and inter-cell interference [25,26]. Thus, energy efficiency can also be optimized in the cellular networks by using energy-efficient power control tech-

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niques [27-29]. In [27] and [28], the game theory was proposed to solve the power optimization problem which aimed to maximize the number of bits per joule in a single-carrier, non-cooperative game scenario. For a multicarrier scenario, the authors in [29] modeled a non-cooperative game scenario whereby each user decides how much power can be transmitted over each carrier to maximize the energy efficiency. More details about other game-theoretic approaches used for energy-efficient power control can be found in [30].

The works shown previously optimize either the spectral efficiency or energy efficiency apart from showing the trade-off between them. Nevertheless, the authors in [31] address this trade-off by developing energy-efficient power optimization for a multi-cell interference limited environment. In order to understand this trade-off, the interference level can be defined as follows:

$$\alpha = \frac{\delta^2}{g}, \quad (6)$$

where, α is the interference coefficient, g is the channel gain per user, and δ^2 is the interference channel gain. The increase in α may represent higher interfering scenario. Then, the energy efficiency over the entire network will become as [31]

$$\eta(\psi) = \sum_{n=1}^N \frac{10 \log \left(1 + \frac{p_n g}{p_i + p_c} \right)}{p_i + p_c}$$

$$\frac{N \log \left(1 + \frac{p_n}{(N-1)\alpha p_i + (\delta^2/g)} \right)}{p_i + p_c} \quad (7)$$

and the network spectral efficiency will become as

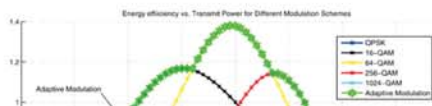
$$r(\psi) = N \log \left(1 + \frac{p_i}{(N-1)\alpha p_i + (\delta^2/g)} \right) \quad (8)$$

where, N is the number of users, δ^2 represents the average noise power per a block of subcarriers assigned to user n . As shown in Figure 8, the energy efficiency is more sensitive to power optimization than the spectral efficiency, i.e. for $\alpha > 0$ scenario, any increase in the level of transmitted power beyond the energy-efficient optimal point will significantly hurt the energy efficiency while it slightly improves the spectral efficiency.

4.3 Adaptive Transceiving Antenna

MIMO is a well-known strategy which can be used to increase the spectral efficiency of wireless systems. In 3GPP LTE, both an alamouti-based Space-Frequency Block Coding (SFBC) and spatial multiplexing (SM) are proposed [32].

To further improve the cell edge throughput and the coverage, coordinated multipoint (CoMP) has been proposed in 3GPP LTE-Advanced [33]. Although MIMO techniques showed a significant improvement in spec-



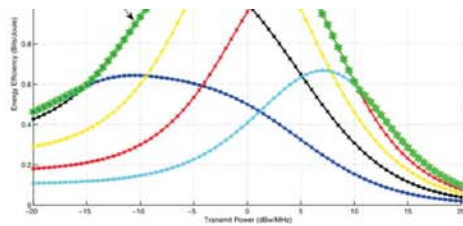


Figure 7: The energy efficiency performance versus the transmit power for different modulation schemes [22].

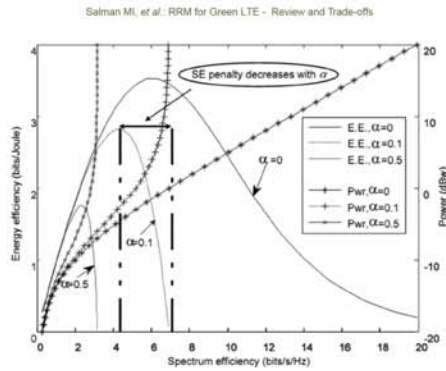


Figure 8: Tradeoff of energy efficiency and spectral efficiency with different interfering scenarios [31].

tral efficiency, energy efficiency can also be increased. MIMO can enhance both the spectral and energy efficiencies by providing diversity and SM gains. This assumption is true if the circuit power consumption is not considered in the calculation of energy efficiency. In other words, MIMO systems are not always more energy-efficient than SISO systems. Therefore, the authors in [34] have discussed the trade-off between the circuit power consumption and the transmission power in terms of energy required per bit. It is shown that the MIMO systems are less energy-efficient than SISO for short ranges unless the adaptive modulation is used to balance the circuit and transmit power consumption. In [35], a number of MIMO precoding techniques, which can be potentially applied to LTE, are examined in terms of their combined spectral and power-saving efficiency. These techniques are SFBC, Random Beamforming, Layered Random Beamforming, SU-MIMO, and MU-MIMO. The authors proposed a cost metric which is the aggregated power required for achieving a specific spectral efficiency, and they proved that MU-MIMO is the most power-efficient scheme. In addition to that, MU-MIMO is preferred in low mobility scenarios as the inter-user interference is small as shown in Figure 9. When the moving speed is high, on the other hand, the inter-user interference with MU-MIMO becomes more tangible, and therefore, the SU-MIMO will be the suitable scheme as shown in Figure 10. According to these facts, the authors in [36] proposed an adaptive switching technique to switch between the transmitting antenna modes according

to the speed (value of interference) and the distance from base station. This switching technique proved a significant improvement in energy efficiency over the entire system. However, the energy efficiency for MIMO channels is fully analyzed in [37-39].

Although there was an extensive research on energy efficient link adaptation schemes, there are still more issues need to be considered to improve the energy efficiency. First, a near-exact power consumption modeling needs to be constructed for different network scenarios. Accordingly, the optimal energy efficient link properties can be obtained. For energy-efficient MIMO schemes, utilizing the spatial resources to maximize the energy efficiency and to mitigate the interference in a multi-cell environment is still an open issue. Furthermore, the closed-loop MIMO schemes were also proposed to enhance the spectral efficiency. However, the enhancement of closed-loop over open-loop SM MIMO schemes on the energy efficiency needs more investigation.

5. Energy-efficient Resource Allocation

Due to the high data rate requirements, OFDMA is proposed to represent the physical layer of LTE cellular systems. The bandwidth and power resources should be allocated to the users according to the designed system requirements. Most of the resource optimization problems that have been covered in the literature are to utilize the system bandwidth efficiently in order to maximize the sum of data rate capacity, which is known as "rate adaptive" [40-50]. Another resource optimization

tion problem is known as "margin adaptive," which aims to achieve the minimum power consumption that guarantees the QoS requirements for all users [51-58]. A comprehensive overview of rate-adaptive and margin-adaptive for OFDMA resource allocation has been covered in [59,60].

However, the orthogonal frequency division multiplexing (OFDM) system, which is a basic element in OFDMA, addresses a big challenge from power consumption point of view. It requires RF power amplifier with high peak-to-average-power ratio as well as the complex electronic components including the fast Fourier transform

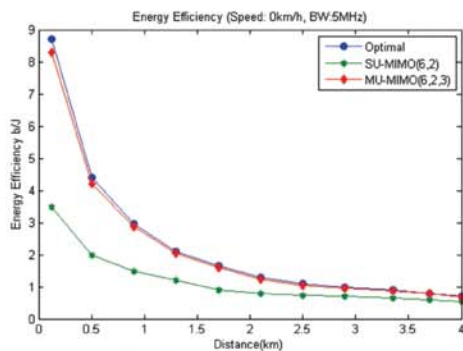


Figure 9: Energy efficiency in low speed mobility for MIMO switching mode.

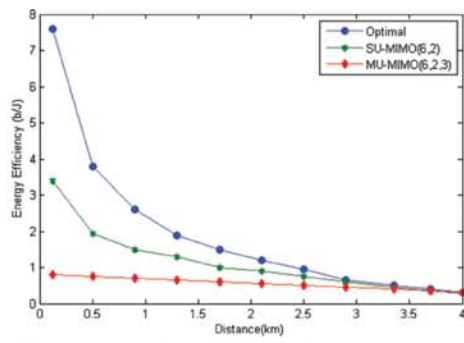


Figure 10: Energy efficiency in high speed mobility for MIMO switching mode.

and forward error correction which are not energy-efficient. Therefore, energy-efficient resource allocation has been adopted recently to accommodate the green wireless communications requirements. Energy-efficient resource allocation is a process by which the RBs, or subcarriers, would be allocated to users such that the bits transmitted per joule will be maximized over the entire network as given by

$$\max_{P, R} \frac{\sum_{j=1}^J \log_2 \left(1 + \frac{P_j |h_j| g_j |k|}{\delta^2} \right) x_{j,k} |k|}{P_j + \sum_{k=1}^K p_{j,k} |k|} \quad (9)$$

s.t.

$$\sum_{j=1}^J \log_2 \left(1 + \frac{P_j |h_j| g_j |k|}{\delta^2} \right) x_{j,k} |k| \geq R_k^{\min}, \forall k,$$

$$\sum_{j=1}^J x_{j,k} |k| \leq 1, \forall k,$$

where, J is the number of users, N is the number of RBs, δ^2 represents the average noise power per RB, p_j is the amount of transmitted power, and g_k is the average channel gain. The first constraint (10) guarantees the QoS requirements, while the second constraint (11) assures that the RB would be allocated to one user exclusively.

The initial work in this area has been done by authors in [12,61]. The authors proposed an energy-efficient resource scheduling algorithm for flat and selective fading OFDM channels. According to (9), the optimal energy efficiency (OptEE) is obtained by using an energy-efficient scheduler as shown in Figure 11. The OptEE has proposed that each user adapts the modulation order according to its channel condition by using AMC. Then, according to the used MCS, the number of RBs is assigned to each user. Each user, however,

can choose the best RB which maximizes the energy efficiency over the entire system. Therefore, the OptEE scheduler achieves the best energy efficiency compared to rate adaptive scheduler with the fixed transmitted power of 33 dbm as shown in Figure 11a.

Although this approach can maximize the energy efficiency, it is not fair for users whose channel gain is low. In other words, the users with good channel gain will consume most of the RBs available greedily. Therefore, the proportional fairness alongside with the energy-efficient transmission (PropEE) algorithm has been applied to achieve fair resource allocation among users while achieving near-optimal energy efficiency [12]. While the energy efficiency can be optimized by using an energy-efficient resource scheduling, there will be a certain degradation in data throughput as shown in Figure 11b. Therefore, a trade-off between the energy efficiency and throughput should be defined according to the required QoS [62].

A latest work that considered the trade-off between energy efficiency and fairness for OFDMA systems is proposed by the authors in [63]. The authors have formulated the energy-efficient resource allocation by using game theory optimization. Normally, the resource allocation game considers the users as the players of the game. Each user can select the transmit power strategy due to his observation. Once the RB is included in the allocation process, the user is very unlikely to choose the best RB due to incongruity with the exclusive RB allocation. Therefore, by considering the RBs as non-cooperative players, the authors in [63] used energy-efficient correlated equilibrium (CE) to help the RBs to choose the most satisfying users. In other words, the CE is achieved when no user would want to deviate from the recommended RB. In order to implement the CE in [63], a linear programming optimization and a distributed algorithm based on the regret-matching procedure is used. Although this technique addresses high

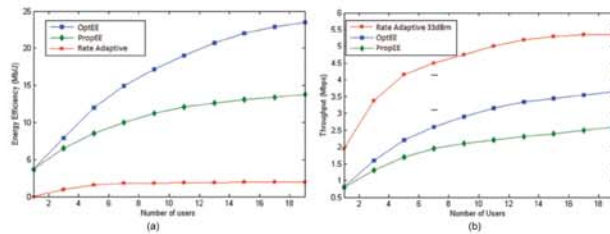


Figure 11: Comparison between OptEE, PropEE, and RA schedulers.

complexity compared to the energy-efficient scheduler with proportional fairness, it is a plausible concept which ensures Pareto optimality and fairness for any number of RBs and users.

Bandwidth Expansion Mode (BEM) is another approach that has been proposed in the design of energy-efficient resource allocation for LTE systems [64]. This approach can be used to save energy when the network is not fully loaded, whereby more RBs are not utilized by any user. In this case, the authors in [64] have suggested to trade-off the non-utilized bandwidth for the transmitted power by allocating more RBs to the users and switching back to lower modulation index, and hence lower transmitted power can be obtained. By considering the advantage of link adaptation, multi-user diversity, and allocation of spare spectrum, this algorithm has showed 79 to 86% energy reduction over a conventional non-energy aware scheduler throughout the day. Beside AMC, antenna adaptation is also examined with BEM algorithm by [64]. It has been revealed that MIMO with low modulation order is more energy-efficient than SISO with high modulation order. However, SISO is preferred for LTE when low spectral efficiency is required.

While more signaling overhead is required by BEM, the time compression mode (TCoM) that is complementary

number of allocated RBs to a user to save energy when the energy consumption is dominated by the signaling overhead. In this case, the authors in [65] proposed an energy-efficient score-based scheduler alongside with BEM and TCoM that should work together to reduce the energy consumption, while not compromising the fairness and data throughput. By using TCoM, the underutilized RBs are grouped together and turned off to conserve energy that would otherwise be wasted in control channel transmissions. The fully utilized RBs, on the other hand, are grouped together and a higher modulation order is used. A significant energy saving of 38% has been achieved by combining TCoM with BEM and EESBS compared to the frequency selective proportional fair which is proposed by [66]. A comprehensive summary for the aforementioned resource schedulers is shown in Table 3.

Although some researches on energy-efficient resource allocation have been done, there are many trends and challenges that need more exploration. For the time being, the energy-efficient RB allocation should consider the interference management and handoff strategies in a multi-cell environment, i.e. reducing transmitted power would save more energy and reduce the interference while sacrificing the cell-edge user performances. Moreover, the relay-cooperative cellular networks can also enhance the energy efficiency in addition to increas-

to BEM is another resource allocation approach proposed by authors in [65] to reduce the consumed energy by the signaling overhead. It allows the scheduler to reduce the

ing in coverage area. However, the energy-efficient joint optimization of RBs along with the cooperative relays is still not cleared. Nevertheless, the resource allocation

Table 3: Energy-efficient resource schedulers, comparison

Scheduler	OptEE	PropEE	BEM	TCoM	EECE
Author (s)	Miao et al.-2008 [12,61]	Miao et al.-2008 [12,61]	Han et al.-2011 [64]	Videv et al.-2012 [65]	Wu et al.-2012 [63]
Objective	To optimize the overall bits transmitted per Joule of energy in a network	To optimize both energy efficiency and fairness in a network	To maximize the EE with guaranteed QoS	To optimize energy efficiency, throughput and fairness	To balance the tradeoff between the total energy efficiency and the fairness
Solution	Energy-efficient resource scheduler	Energy-efficient scheduler with fairness	Power efficient link adaptation, exploitation of multi-user diversity and trading BW for energy efficiency	Trading BW for energy efficiency, controlling the overhead signals to save energy	Energy-efficient resource allocation scheme by using the correlated equilibrium (CE)
Methodology	Sorting-Search algorithm, and link adaptation (AMC)	Combined sorting-search algorithm, AMC, and proportional fairness	Allocating the spare (non-utilized) RBs, and switch to lower MCS	bandwidth expanded mode (BEM), and Time compression mode (TCoM)	Game theory, linear programming method and a distributed algorithm based on the regret matching procedure
Trade-off	Energy efficiency vs. Throughput (bps-J- bps)	Energy efficiency vs. Throughput (bps-J- bps)	Power vs. Bandwidth	Power vs. bandwidth, Energy efficiency vs. overhead	Energy efficiency vs. fairness
Enhancement	Highest energy efficiency can be obtained compared to PropEE, Round Robin energy-efficient scheduler RREE	Better energy efficiency than round robin energy-efficient scheduling and fairness guaranteed among users	Significant energy saving (up to 86%) over a conventional non-energy aware scheduler without losses in throughput when the network is not fully loaded	Energy saving of 38% over a frequency selective proportional fair (FSPF)	Good convergence, Pareto optimality and fairness

AMC - Adaptive modulation and coding; MCS - Modulation and coding scheme; PropEE - Energy efficient with proportional fairness; RREE - Round robin energy efficient scheduler; EE - Energy efficiency; QoS - Quality of service; BW - Bandwidth; RBs - Resource blocks

process would affect the end-to-end service delay, and hence, another possible trade-off between the energy efficiency and service delay is addressed as discussed in [67,68].

6. Conclusion and Suggestions for Future Work

There is an imperative need to improve the energy efficiency in the overall communication networks due to the negative impact of emitted CO₂ on the environment. The radio transmission is among the main contributors of energy consumption inside the cellular systems. In this paper, the optimization of radio transmission is addressed by using the energy-efficient approaches, such as link adaptation and resource allocation. In link adaptation, we outlined the methodologies used in the literature to maximize the energy efficiency, such as AMC, MIMO, and power control. Beside the link adaptation, the RRM is addressed. It shows a considerable improvement in system performance when it works together with link adaptation. Furthermore, other system performances, such as the spectral efficiency and QoS, are investigated alongside with the energy efficiency by considering the trade-off between them. Nevertheless, many challenges still exist and require more investigation. For instance, the effect of inter-cell interference on energy efficiency in a MIMO-OFDM multi-cell scenario needs further study. Besides, the energy-efficient resource allocation with cooperative relay has not been considered in most of the previous work. The OFDM-relay technology is proposed for LTE-Advanced cellular systems to improve the cell-edge throughput. Therefore, the number of relays along with the other radio resources should be optimized to maximize the energy efficiency as well as improving cell coverage area.

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... We consider a single-frequency band FDD transmission mode in the downlink. In addition, this work also considers a block fading structure in which $\tau \in \mathbb{Z}^+$, where the channel with the LCT block is assumed as in the A-LTE mobile networks [45]. In the training phase, the downlink channel is employed per each coherence block, where the BS can transmit a training sequence in the downlink with a power of p tr and a length τ tr

Maximizing the Downlink Data Rates in Massive Multiple Input Multiple Output with Frequency Division Duplex Transmission Mode Using Power Allocation Optimizatio...

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... According to typical wireless networks, the coherence block length that is available for transmission resources consists of time and frequency symbols. These symbols represent the intervals of time and frequency during which the channel responses remain mostly constant [47][48][49][50]. Extension to orthogonal frequency-division multiple (OFDM) could be considered in the future [51,52]. ...

Downlink Training Sequence Design Based on Waterfilling Solution for Low-Latency FDD Massive MIMO Communications Systems

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... Content may change prior to final publication. efficient designs and operations for future 6G networks with an aim to reduce the undesirable carbon dioxide (CO₂) emission per mobile subscriber becomes essential [309]. In addition, finding suitable designs for realizing economically sustainable future wireless communications systems that achieve both spectral and energy efficiencies with low hardware cost are crucial [88], [310]. ...

6G Wireless Communications Networks: A Comprehensive Survey

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... In this study, we consider a scenario of a single-cell block-fading model over which the channel coefficients are timely invariant. In particular, in the typical cellular networks, the time and frequency resource blocks are allocated to different user equipments (UEs) simultaneously [24][25][26][27][28]. In a block-fading model, the channels are considered to be frequency flat, which remain unchanged during a constant period of time that corresponds to a channel coherence time of T [29]. ...

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... The available energy in each coherence block can be freely distributed between the training transmission and the data transmission as typically considered in the currently deployed mobile networks, i.e., the advanced-long-term evolution (A-LTE) [52], [53]. To estimate the DL channel in training-phase, the BS sends TS of length τ p enumerated in symbols per coherence block. ...

Sum Rate Maximization Versus MSE Minimization in FDD Massive MIMO Systems with Short Coherence Time

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... The instantaneous estimation of channel responses is referred to as CSI knowledge. As discussed earlier, the accuracy of CSI estimation is essential for efficient precoding design [57] and resource allocation [58]. To obtain the CSI estimation of the DL channel, known deterministic

sequences of length T_{tr} are transmitted by the BTS in the DL to the UEs during the training transmission phase. ...

A Partial CSI Estimation Approach for Downlink FDD massive-MIMO System with Different Base Transceiver Station Topologies

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... Figure 1 shows the BS with MaMi system and demonstrates the DL and UL transmissions within each coherence block length. In particular, the available coherence block length consists of resource transmission in time T_c and frequency B_c plane, which represents the time and the frequency intervals over which the channel responses are approximately constant, as considered in the current long term evolution (LTE) wireless networks [35, 36]. According to the Nyquist-Shannon sampling theorem, the coherence block length is given as $\tau = T_c \times B_c$

Downlink Training Design for FDD Massive MIMO Systems in the Presence of Colored Noise

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... Worldwide interoperability for microwave access (Wi-MAX), third generation partnership project (3GPP), long-term evolution (LTE) and long-term evolution-advanced (LTE-A) [1,2] are being considered as the potential candidates for 4G/5G broadband access. Due to orthogonality between subcarriers and by exploiting multiuser (MU) diversity along with adaptive resource allocation, OFDMA can provide the required performance in terms of power and spectral efficiency [3][4][5][6] [7]. Del Castillo et al. [8] describes the OFDMA resource allocation problem in broadband wireless access IEEE 802.16 network. ...

Parallel Resource Allocation and Subcarrier Assignment for Downlink OFDMA

Article Jul 2018

Satyendra Singh Yadav · Paulo Alexandre Crisóstomo Lopes · Sarat Kumar Patra

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... Cell selection entails the procedure through which UE is attached to either PeNB or MeNB using the received signal strength assigned to resources for traffic offloading. Cell selection can thus achieve traffic load balancing and throughput maximization of the UE by using the available resource allocated [11]. Some major cell selection schemes are: ...

Improving load balancing in various user distribution LTE advanced HetNets through a hybrid channel-gain access-aware cell selection scheme

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Energy-aware clustering for multi-cell joint transmission in LTE networks

June 2013

Efstathios Katranaras · Muhammad Ali Imran · Mehrdad Dianati

This paper investigates the energy-aware clustering of cooperating base stations in the downlink of cellular networks. The focus of this work is on static clustering deployments for LTE systems when joint signal precoding is employed at multiple base stations. We demonstrate that properly planned clustering can provide the desired balance between network spectral and energy efficiency. To this ... [\[Show full abstract\]](#)

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Energy efficient transmission for LTE cellular system

July 2012

Mustafa Ismael Salman · Chee Kyun Ng · Nor Kamariah Noordin · [...] · Aduwati Sali

With the introduction of Long Term Evolution (LTE) cellular networks, the spectral efficiency should be maximized according to the required high data rate. However, any increase in spectral efficiency will lead to an undesirable increase in power consumption, and thus lower energy efficiency will be obtained. Therefore, a new problem in radio resource allocation is addressed to manage the ... [\[Show full abstract\]](#)

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CQI-MCS Mapping for Green LTE Downlink Transmission

December 2013 · Proceedings of the Asia-Pacific Advanced Network

Mustafa Ismael Salman · Chee Kyun Ng · Nor Kamariah Noordin · [...] · Aduwati Sali

Maximizing the data rate and spectral efficiency are the main targets in LTE cellular systems. However, any increase in data rate or spectral efficiency will result in an undesirable increase in energy consumption. Hence, both energy efficiency (EE) and spectral efficiency (SE) necessitate to be optimized. In this paper, a multi-objective optimization framework is formulated to prove the tradeoff ... [\[Show full abstract\]](#)

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Adaptive radio resource allocation in OFDMA systems: A survey of the state-of-the-art approaches

April 2009 · Wireless Communications and Mobile Computing

Surachai Chiochan · Ekram Hossain

Orthogonal frequency division multiplexing (OFDM)-based orthogonal frequency division multiple access (OFDMA) has emerged as a promising transmission technology for next generation wireless systems. In a multiuser scenario, adaptive radio resource allocation can significantly improve the performance of OFDMA systems. In this article, an overview of the major state-of-the-art approaches to ... [\[Show full abstract\]](#)

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Article

A self-configured link adaptation for green LTE downlink transmission

March 2014 · Transactions on Emerging Telecommunications Technologies

Mustafa Ismael Salman · Chee Kyun Ng · Nor Kamariah Noordin · [...] · Aduwati Sali

Green deployment for cellular eNodeBs has been proposed recently to save power and reduce the huge amount of carbon dioxide (CO₂) emitted by traditional power-hungry base stations. Green eNodeBs should also be subjected to restrictions on high data rate and quality of service (QoS), which both entail a high level of power consumption. In this regard, this paper addresses the trade-off between ... [\[Show full abstract\]](#)

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Joint carrier aggregation and packet scheduling in LTE-advanced networks

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Abstract

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I. Introduction

II. System Model

III. Problem Formulation

IV. Joint Carrier Aggregation and Packet Scheduling

V. Performance Evaluation

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Abstract:

LTE is the next generation of all-IP mobile communication system designed and developed by 3GPP. It offers unprecedented data transmission speed and low latency to support a variety of applications and services. However, compared to wireline networks, efficient QoS provisioning for diversified applications in wireless access networks such as LTE is challenging due to unreliable and resource-constrained radio interface. In this paper, we investigate an important problem of downlink resource allocation in recently enhanced LTE-Advanced systems where a newly added feature carrier aggregation provides more flexibility in radio resource management in addition to the existing resource block level packet scheduling. The resource allocation problem can be formulated as a complex combinatorial problem with multiple constraints and is solved every time slot. We decompose this highly complex optimization problem and construct a two-tier resource allocation framework which incorporates dynamic component carrier assignment and backlog based scheduling schemes with intelligent link adaptation. An efficient algorithm is developed to dynamically allocate component carriers to users to achieve load balancing. We also present novel backlog based scheduling policies and weighted-CQI based link adaptation scheme to obtain significantly better throughput and delay fairness. Performance of the proposed schemes is evaluated against the static round-robin component carrier assignment, the well-known proportional fairness scheduling rule and the existing link adaptation scheme. Extensive simulation results demonstrate that our schemes offer both better throughput and delay performance as well as user fairness.

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I. Introduction

The major attraction of the next generation (4G) wireless systems such as Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) is the availability of high data rate and low end-to-end latency. LTE has been designed and developed by 3GPP [1] as an all-IP network with simplified radio access and core network architecture. On air interface, LTE features OFDMA and MIMO technologies, which significantly improve the data transmission speed along with lower latency. LTE can provide a peak rate of 100 Mbps in downlink and 100 Mbps in uplink, which is compared to previous cellular systems. In the core network, an all-IP infrastructure with support of IMS (IP Multimedia System) facilitates the addition of a variety of services and applications, including data, voice, video and location. However, it is challenging to provide the required level of

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Joint Carrier Aggregation and Packet Scheduling in LTE-Advanced Networks

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Abstract—LTE is the next generation of all-IP mobile communication system designed and developed by 3GPP. It offers unprecedented data transmission speed and low latency to support a variety of applications and services. However, compared to wireline networks, efficient QoS provisioning for diversified applications in wireless access networks such as LTE is challenging due to unreliable and resource-constrained radio interface. In this paper, we investigate an important problem of downlink resource allocation in recently enhanced LTE-Advanced systems where a newly added feature carrier aggregation provides more flexibility in radio resource management in addition to the existing resource block level packet scheduling. The resource allocation problem can be formulated as a complex combinatorial problem with multiple constraints and is solved every time slot. We decompose this highly complex optimization problem and construct a two-tier resource allocation framework which incorporates dynamic component carrier assignment and backlog based scheduling schemes with intelligent link adaptation. An efficient algorithm is developed to dynamically allocate component carriers to users to achieve load balancing. We also present novel backlog based scheduling policies and weighted-CQI based link adaptation scheme to obtain significantly better throughput and delay fairness. Performance of the proposed schemes is evaluated against the static round-robin component carrier assignment, the well-known proportional fairness scheduling rule and the existing link adaptation scheme. Extensive simulation results demonstrate that our schemes offer both better throughput and delay performance as well as user fairness.

I. INTRODUCTION

The major attraction of the next generation (4G) wireless systems such as Third Generation Partnership Project (3GPP) Long Term Evolution (LTE) is the availability of high data rate and low end-to-end latency. LTE has been designed and developed by 3GPP [1] as an all-IP network with simplified radio access and core network architecture. On air interface, LTE features OFDMA and MIMO technologies, which significantly improve the data transmission speed along with lower latency. LTE can provide a peak rate of 300Mbps, a significant increase in spectrum efficiency compared to previous cellular systems. In the core network, an all-IP infrastructure with support of IMS (IP Multimedia System) facilitates the addition of a variety of services and applications, including data, voice, video and location. However, it is challenging to provide the required level of quality of service (QoS) and maintain the designed system performance due to the constraints of limited radio resources, unreliable radio propagation channel, and high user demands.

Resource allocation and scheduling have been important as-

pects of QoS support in wireless networks, and have attracted an increasing attention from the research community. Wireless scheduling has two particular characteristics which distinguish it from conventional wireline scheduling [2]: (1) The radio channel is inherently unreliable and error-prone. Also, errors can be bursty in nature which results into unsuccessful packets transmissions during the burst. The implication is that a good scheduling algorithm needs to be adaptive to changing channel quality. (2) Channel state varies randomly in time on both slow and fast time scale. In fast channel variations (due to fast fading), states of different channels can asynchronously switch from “good” to “bad” within a few milliseconds and vice-versa. A good scheduling algorithm should exploit this condition by giving higher preference to a user whose channel is currently better. Slow channel variations mean that the average channel state depends on user’s location and other factors. Therefore some users may have to demand more radio resources than others even if their data rate requirements are the same.

In OFDMA based LTE networks, data is transmitted on a large number of parallel, narrow-band sub-carriers. During each time slot, multiple users can be allocated a set of sub-carriers (termed resource blocks in LTE) to enable concurrent transmissions. Thus efficient scheduling of radio resources is crucial to achieve high network performance.

In a resource allocation period, each resource block is associated with different channel quality in terms of SINR (signal-to-interference and noise ratio), which is sent back on a feedback channel known as CQI (Channel Quality Indicator) from mobile terminals. Based on the CQI, appropriate modulation and coding schemes can be applied to improve the transmission reliability and rate (known as AMC or adaptive modulation and coding). In this way, the available channel rate or the size of transport block on resource blocks can be determined.

Carrier aggregation introduced in LTE-Advanced (Release 10) [1] is designed to expand the transmission bandwidth by combining multiple carriers in the same or different bands. With this new feature, resource allocation module will have more flexibility when scheduling radio resources for users. However, different assignments of carriers will have significant impact on network performance. For instance, distributing users across available carriers efficiently is important to achieve improved network load balancing and higher utilization. Carriers on different bands may have diversified channel

characteristics such as path loss patterns and fading variations, so carrier allocation will be a key part of RF planning.

In this paper, we study the radio resource management (RRM) problem in LTE-Advanced systems by jointly considering both carrier aggregation and packet scheduling. The joint resource allocation is formulated as a complex combinatorial problem. We propose efficient algorithms to address the issues presented in the problem. Specifically, we propose a dynamic component carrier allocation algorithm which utilizes aggregated head-of-line delay of users associated with a carrier as the metric. The algorithm focuses on the user backlog accumulated on a carrier to achieve load balancing as well as better throughput and delay performance. For the resource block level allocation, we propose the backlog based scheduling schemes which are channel-aware and targeted on reducing user backlog (queue length or head-of-line delay). The backlog based schemes have been studied from a mostly theoretical point of view for restricted cases and unrealistic assumptions on arrival processes and channel characteristics. Our goal is to study and propose efficient backlog based scheduling algorithms with realistic settings and scenarios in LTE networks. The proposed resource allocation schemes are enhanced using an intelligent link adaptation mechanism which takes the weighted CQI of all allocated resource blocks for a user as input and determines the MCS (Modulation and Coding Scheme) mode. The weighted-CQI based link adaptation helps in achieving correct balance between transmission rate and error rate.

The rest of the paper is organized as follows. In Section II, we describe the detailed system model. In Section III, we formulate the combinatorial optimization problem for downlink resource allocation. Section IV proposes our dynamic carrier allocation and backlog based scheduling schemes and intelligent link adaptation mechanism. Performance of the proposed schemes is evaluated in Section V. Related work is discussed in Section VI. Section VII concludes the paper.

II. SYSTEM MODEL

A. LTE Downlink Model

The LTE downlink transmission scheme [3] provides scalable bandwidth from 1.4MHz to 20MHz. It is based on conventional OFDM using a cyclic prefix, with a sub-carrier spacing $\Delta f = 15\text{kHz}$ and a cyclic-prefix (CP) duration $T_{CP} \approx 4.7/16.7\mu\text{s}$ (short/long CP). A radio frame is 10ms in duration, and divided into 10 equally sized sub-frames (each being 1ms long). Each sub-frame is called an *Transmission Time Interval* (TTI), and further divided into 2 slots (0.5ms each). Each slot has 6 or 7 OFDM symbols. The basic transmission parameters are specified in more detail in Table I. The sub-carrier spacing is constant regardless of the transmission bandwidth. Multiple sub-frames can be concatenated into longer TTI to improve support for lower data rates and QoS optimization.

The transmitted downlink signal consists of N_{BW} sub-carriers for a duration of T_{slot} . It can be represented by a resource grid as depicted in Figure 1. Each box within the

TABLE I
LTE DOWNLINK PHYSICAL PARAMETERS

Bandwidth (MHz)	1.4	3	5	10	15	20
Radio frame duration	10 ms					
Sub-carrier spacing	15 KHz					
RB bandwidth	180 KHz					
Number of RBs	6	15	25	50	75	100

grid represents a single sub-carrier for one symbol period and is referred to as a *resource element*. A *physical resource block* (PRB or RB) is defined as one slot in the time domain (0.5ms) and 12 consecutive sub-carriers (180KHz) in the frequency domain. A resource block is the smallest element of resource allocation assigned by the base station scheduler. The resource block model is demonstrated in Figure 1.

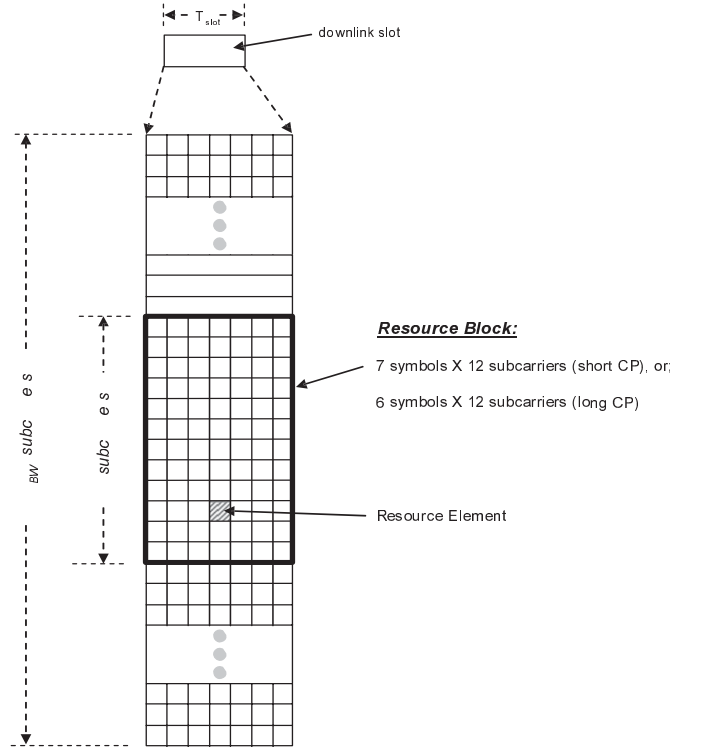


Fig. 1. LTE Downlink Resource Grid

B. Carrier Aggregation

It is unlikely that spectral efficiency of LTE can be improved much beyond its current performance limit to meet the requirement of 1Gbps set by IMT-Advanced. Therefore the only way to achieve significantly higher data rates is to increase the channel bandwidth. Carrier aggregation (CA) [1] is one of the most notable key features of LTE-Advanced which has been standardized in 3GPP as part of LTE Release 10. It allows scalable expansion of effective bandwidth delivered to a user terminal through concurrent utilization of radio resources across multiple carriers. These carriers may be of different bandwidths, and may be in the same or different bands to provide maximum flexibility in utilizing the scarce radio spectrum available to operators. In the carrier

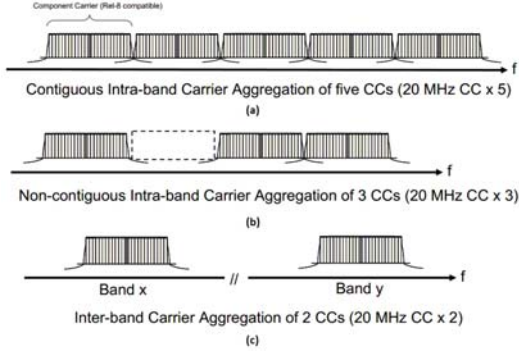


Fig. 2. Types of Carrier Aggregation

aggregation, up to 5 component carriers can be aggregated. The term “component carrier” (CC) in this context refers to any of the bandwidths defined in LTE. The creation of wider bandwidths has three options: intra-band contiguous aggregation, intra-band non-contiguous aggregation, or inter-band non-contiguous aggregation.

Intra-band contiguous CA provides a contiguous bandwidth wider than 20MHz (Figure 2(a)). It may be a unlikely scenario given current frequency allocations of operators, but can be common when new spectrum bands are allocated in the future. Intra-band non-contiguous CA combines multiple CCs belonging to the same band but in a non-contiguous manner (Figure 2(b)). This option can be used in scenarios where spectrum allocation is non-contiguous within a single band. Inter-band non-contiguous CA (Figure 2(c)) is the most general mode where multiple CCs belong to different bands. It can potentially improve mobility robustness by exploiting different radio propagation characteristics of different bands, but may require additional complexity in the RF front-end.

Data aggregation schemes across component carriers can be achieved at the MAC layer where the transmission blocks (TBs) from different component carriers can be built in a way that is transparent to the upper layers (RLC and PDCP) (Figure 3) [1]. Each component carrier has its own transmission configuration parameters as well as an independent HARQ entity in order to support more flexible and efficient data transmissions and guaranteed backward compatibility at the expense of complex control signaling.

C. Channel Models

1) *Friis Path Loss Model*: The major attenuation of signal strength on a wireless link comes from the large-scale path which can be modeled using the Friis transmission equation [4][5]. The ratio of the power available at the input of the receiving antenna P_r to the output power of the transmitting antenna P_t ,

$$P_r = P_t + G_t + G_r + 20 \cdot \log_{10} \left(\frac{\lambda}{4\pi R} \right)$$

where G_t and G_r are the antenna gains of the transmitting and receiving antennas respectively, λ is the wavelength, and R is the distance between the antennas. It is clear that frequency

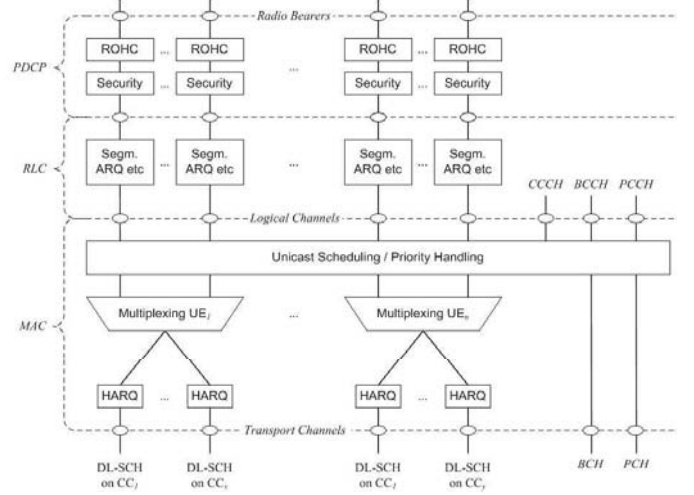


Fig. 3. Downlink Protocol Stack with Carrier Aggregation

plays an important role in the path loss model: signals in a band with higher frequency attenuate faster, so the band will have a smaller coverage. This fact is well known but its impact on component carrier assignment is significant.

2) *Rayleigh Fading Model*: Fading adds fast variations upon path loss. Rayleigh fading [6] is a statistical model for modeling the effect of multi-path propagation on a radio signal. Rayleigh fading model assumes that the magnitude of a signal that has passed through such a transmission channel will vary or fade randomly according to a Rayleigh distribution. The MATLAB functions `rayleighchan` and `pwelch` are used to generate the fading traces for simulation [5] [7].

3) *PHY Error Model*: The PHY error model of NS3 simulator used in the paper is designed according to the standard link-to-system mapping (LSM) techniques [5] [7]. It is aligned with the standard system simulation methodology of OFDMA radio transmission technology. It is based on the mapping of link layer performance obtained using link level simulators to system simulators. In particular, the link layer simulator is used for generating the performance of a single link from a PHY layer perspective (usually in terms of block error rate (BLER) based on SINR), under specific static conditions. NS3 uses the Vienna LTE Simulator [8] to extract the link layer performance and build the PHY error model.

D. Link Adaptation

Adaptive modulation and coding (AMC) has been adopted in LTE to enhance the system throughput. It has been widely proven to be a powerful technique for improving the spectral and energy efficiency and increasing the data rate over a fading channel [9]. AMC is one of the most important techniques of link adaptation. Its objective is to maximize the data rate by adjusting transmission parameters according to channel variation. AMC operates on channel conditions identified by the channel quality indicator (CQI) obtained using SINR estimation.

By using AMC, the combination of different constellation of modulation and different rate of error-control codes are

chosen based on the time-varying channel conditions. When channel quality is good (high CQI), AMC schemes with larger constellation sizes and higher channel coding rate can be applied to effectively achieve high transmission rate. When channel quality is poor (low CQI), transmission rate is reduced to ensure transmission quality. Thus it can realize optimal allocation of system resources and maximize throughput.

E. Scheduler in LTE

Since LTE is based on OFDM, it is possible to distribute available transmission radio resources in the frequency domain to different mobile terminals. The resource allocation can be changed dynamically. The MAC scheduler in the eNodeB (base station) assigns both uplink and downlink radio resources. The scheduling decision covers not only the resource block assignment but also the modulation and coding scheme to be used and the antenna techniques.

3GPP does not specify the MAC scheduler, but leaves its design and implementation to vendors. This added flexibility changes the system performance significantly with the use of different scheduling algorithms. Depending on the implementation, the scheduler can base its scheduling decision on the QoS class and the queuing delay of data, on the instantaneous channel conditions, or on fairness indicators. The channel conditions in a wide-band system vary in both time domain and frequency domain. With sufficiently detailed channel-quality information (such as CQI) to eNodeB, the scheduler can perform channel-dependent scheduling in the time and frequency domains, and improve the system capacity.

Carrier Aggregation offers another level of flexibility for the scheduler to allocate the radio resources. This functionality is to configure a set of CCs for each user. The CC assignment is an important apparatus for optimizing system performance, as well as limiting the power consumption of users. The power a UE requires increases with the number of CCs it is assigned (more bandwidth and signals to process). For optimal system performance, it is desirable to have approximately equal load on different CCs.

III. PROBLEM FORMULATION

We consider a single-cell (one base station or eNodeB) scenario where the downlink bandwidth is configured with C component carriers which totally have M resource blocks (RBs) (similar notations to ones used in [10]). The base station serves N active users. We denote the set of component carriers as $\mathcal{C} = \{c | c = 1, 2, \dots, C\}$, and all RBs as $\mathcal{M} = \{m | m = 1, 2, \dots, M\}$, and the set of all users by $\mathcal{N} = \{n | n = 1, 2, \dots, N\}$. C_n of C component carriers may be configured for user n . During each scheduling slot, the base station can allocate M_n RBs (RBs are not necessarily contiguous) from C_n component carriers to user n . Each RB is assigned to at most one user. We denote the power set of $\mathcal{M}$ as $\mathcal{P}$. Each p in $\mathcal{P}$ identifies a set of RBs. We have $x_i^p = 1$ if and only if p is allocated to user i . In the framework defined by the problem, two levels of resource allocations are involved: component carrier assignment and resource block

scheduling. The former runs at a coarse granularity, and the major objective is to load balance across multiple component carriers. The latter runs at each scheduling interval (one TTI) in order to be channel adaptive and achieve better throughput and delay performance. It is evident that two levels are closely related and impact each other.

The resource allocation problem of multiple component carriers and resource blocks within a carrier for multiple users can be formulated as a combinatorial optimization problem. The objective is to maximize the total size of transport blocks (TBS) built for each user at each scheduling interval. The variables are different assignments of component carriers and schedules of resource blocks for users. The constraints are all available component carriers and resource blocks, available AMC modes, and the delay requirements for users. The component carrier allocation is implicitly embedded in the problem formulation which is done at a configurable interval.

Given a set of component carriers $\mathcal{C}$, resource blocks $\mathcal{M}$, a set of active users $\mathcal{N}$ and a set of available AMC schemes $\mathcal{A}$ during a scheduling period in a cell:

$$\text{Maximize: } \min_{i \in \mathcal{N}} \sum_{k \in \mathcal{C}} TBS_{UE(i)}^k \quad (1)$$

subject to:

$$\forall \text{ RB } m \in \mathcal{M} : \sum_{m \in p, i \in \mathcal{N}} x_i^p \leq 1 \quad (2)$$

$$\forall \text{ user } i \in \mathcal{N} : \sum_{p \in \mathcal{P}} x_i^p \leq 1 \quad (3)$$

$$\forall \text{ user } i \in \mathcal{N}, p \in \mathcal{P} : x_i^p \in \{0, 1\} \quad (4)$$

$$\forall \text{ RB } m \in \mathcal{M} : \text{AMC}_{RB_m} \in \mathcal{A} \quad (5)$$

$$\forall \text{ user } i \in \mathcal{N} : \text{delay}_i \leq \text{DELAYBOUND}_i \quad (6)$$

Constraint (2) requires each RB be assigned to at most one user. Constraint (3) ensures each user get no more than one set of RBs.

IV. JOINT CARRIER AGGREGATION AND PACKET SCHEDULING

A. Dynamic Component Carrier Assignment

Carrier aggregation in LTE-Advanced will significantly boost the transmission speed on air interface. Efficient assignment of component carriers (CCs) to UEs to achieve higher network utilization and performance is an important issue that needs to be carefully addressed. In the existing carrier aggregation schemes, CCs are allocated statically when UEs attach to the network and the allocation does not change with time. In our proposed approach, we take channel conditions, network load and other impacting factors into account, and dynamically allocate component carriers for UEs.

In our scheme, the metric to determine the load of a component carrier is the aggregated value of queuing head-of-line (HOL) delay of UEs which are allocated the carrier. This metric can properly quantify and indicate the loading of a particular CC and implicitly factor in the channel conditions. It can help achieve network load balancing and high utilization.

In our scheme, we assume that there are M CCs and each UE can be allocated at most $N(< M)$ CCs. eNodeB periodically runs the dynamic assignment algorithm to reallocate CCs to UEs. The detailed procedure is presented in Algorithm 1. The frequency of running CC reallocation is a configurable parameter on eNodeB.

Algorithm 1 Dynamic CC Reallocation

Require: N out of M to be assigned to each of K UEs.

```

1: Clear the CC assignments for all UEs.
2: Reset  $\text{AggregHOLPerCC}[1...M]$ .
3: Calculate HOL delay of all UEs.
4: Sort HOL delay in a descending order into  $\text{HOL}(1...K)$ .
5: for  $\text{UE}(k)$ ,  $k = 1...K$  from  $\text{HOL}(1...K)$  do
6:   for  $i = 1...N$  do
7:      $\text{LeastHOL} = \text{INF}$ ;
8:      $\text{LeastHOLFlag} = \text{FALSE}$ ;
9:     for  $j = 1...M$  do
10:      if  $\text{AggregHOLPerCC}[j] == 0$  then
11:        Assign CC  $j$  to  $\text{UE}(k)$ ;
12:         $\text{AggregHOLPerCC}[j] = \text{HOL}(k)$ ;
13:         $\text{LeastHOLFlag} = \text{TRUE}$ ;
14:        break.
15:      else
16:        if ( $\text{LeastHOL} > \text{AggregHOLPerCC}[j]$ )
17:          and (CC  $j$  not assigned to  $\text{UE}(k)$ ) then
18:             $\text{LeastHOL} = \text{AggregHOLPerCC}[j]$ ;
19:             $\text{LeastHOLCCId} = j$ .
20:        end if
21:      end if
22:    end for
23:    if  $\text{LeastHOLFlag} == \text{FALSE}$  then
24:      Assign CC  $\text{LeastHOLCCId}$  to  $\text{UE}(k)$ ;
25:       $\text{AggregHOLPerCC}[\text{LeastHOLCCId}] =$ 
26:         $\text{AggregHOLPerCC}[\text{LeastHOLCCId}] +$ 
27:         $\text{LeastHOL}$ .
28:    end if
29:  end for
30: end for

```

B. Backlog Based Resource Block Scheduling

At a finer granularity, scheduling resource blocks is another important issue. A number of backlog based policies (e.g., [11][12]) have been proposed in literature for multi-channel systems and shown to be optimal under specific restriction on arrival processes and channel conditions. However, their empirical performance in realistic scenarios (LTE systems in particular) is not known. We study and apply two types of backlog based algorithms (Algorithms 2 and 3): Queue Side Greedy and Server Side Greedy. Here queue implies the packet queue at eNodeB for UEs and server means the available resource blocks.

In both algorithms, backlog can be in terms of either head-of-line (HOL) delay or queue length. In some cases, good queue length performance does not necessarily translate to

good delay performance. Simply maintaining low queue length is insufficient in order to guarantee low waiting-time in the queue. For example, a packet that is present in a queue with low queue length may have to wait for a long time to get served if fewer packets are offered to this queue for several time-slots. In our simulations, we will focus the Algorithm 2 (QSG) which has better performance.

Algorithm 2 Queue Side Greedy (QSG) RB Scheduling

Require: M resource blocks to be allocated to N UEs.

```

1: for  $k = 1...M$  do
2:   Choose the UE  $i$  with the largest backlog;
3:   For UE  $i$ , choose the resource block  $j$  with the best
4:     channel rate;
5:   Allocate the resource block  $j$  to UE  $i$  and mark it as
6:     allocated;
7:   Update the backlog for UE  $i$ .
8: end for

```

Algorithm 3 Server Side Greedy (SSG) RB Scheduling

Require: M resource blocks to be allocated to N UEs.

```

1: for resource blocks  $i = 1...M$  do
2:   Choose the UE  $j$  with the largest metric;
3:   Metric = backlog  $\times$  channel rate of resource block  $i$  for
4:     UE  $j$ ;
5:   Allocate the resource block  $i$  to UE  $j$ ;
6:   Update the backlog for UE  $j$ .
7: end for

```

In both algorithms, updating the backlog information for UE after one iteration is the key which is not done in conventional scheduling schemes. Backlog is a good indicator for the system load and the priority of UE to be scheduled. Both throughput and delay is taken into account with this metric.

C. Intelligent Link Adaptation

Channel awareness is indispensable for any efficient resource allocation schemes. In LTE, CQI is an important mechanism to obtain the feedback on channel quality and achieve link adaptation. In the existing implementation, the default link adaptation approach is that after all resource blocks are allocated to UEs by the scheduler, the resource blocks for a UE are built into one single transport block and modulated with MCS corresponding to the lowest CQI of the resource blocks of this UE. This approach is safe and conservative, but it may be inefficient and potentially lower the number of bytes that could be transmitted with the transport block. When a resource block is assigned to UE, the scheduler considers its CQI individually which may not be optimal in terms of all CQIs of resource blocks assigned to this UE. A function $\mathcal{F}$ can be designed to take a set of CQIs as input and output a single CQI which can be applied to all allocated resource blocks and achieve an optimal MCS and transport block size. Function $\mathcal{F}$ can be sophisticated or simple (like the default one: Min CQI).

Our basic idea is to incorporate the CQI tradeoff when allocating resource blocks and do the scheduling and link

adaptation collectively (Algorithm 4). When a resource block with a particular CQI value is available to a UE, we check if the CQI value of this resource block can collectively enhance the overall transport block (TB) size with the resource blocks already allocated to this UE. If this CQI value is very low, then it will degrade the MCS mode of the transport block built with other resource blocks. In such a case, this resource block may be scheduled to other UE which may have better channel condition (better CQI) on it. In our case, function $\mathcal{F}$ is the weighted CQI average. Once the scheduling during a TTI is finished, the final MCS mode built into the transport block is also determined by the weighted average CQI.

Algorithm 4 Intelligent Link Adaptation

```

1: UE( $i$ ) allocated resource blocks PRB( $j$ ) ( $j = 1 \dots K$ );
2: The next resource block PRB( $K + 1$ ) allocated to UE( $i$ );
3:  $\text{oldAvgCQI} = \sum_{j=1}^K (CQI_{PRB_j})^2 / \sum_{j=1}^K CQI_{PRB_j}$ ;
4:  $\text{oldMCS} = \text{GetMCSFromCQI}(\text{oldAvgCQI})$ ;
5:  $\text{oldTBSize} = \text{GetTBSizeFromMCS}(\text{oldMCS})$ ;
6:  $\text{newAvgCQI} = \sum_{j=1}^{K+1} (CQI_{PRB_j})^2 / \sum_{j=1}^{K+1} CQI_{PRB_j}$ ;
7:  $\text{newMCS} = \text{GetMCSFromCQI}(\text{newAvgCQI})$ ;
8:  $\text{newTBSize} = \text{GetTBSizeFromMCS}(\text{newMCS})$ ;
9: if  $\text{newTBSize} > \text{oldTBSize}$  then
10:   Accept PRB( $K + 1$ ) and allocate to UE( $i$ );
11: else
12:   Reject PRB( $K + 1$ ) and leave it to other UEs.
13: end if

```

V. PERFORMANCE EVALUATION

In this section we examine the performance of our proposed resource allocation schemes. We use the NS3 [5] as the system simulator. Table II lists the basic LTE parameters settings used in the simulations.

TABLE II
NS3 PARAMETER SETTINGS

Parameter	Setting
Number of eNodeBs	1
Number of UEs	10
Antenna Model	1x1 Isotropic
Path loss model	Friis transmission equation
Fading model	Rayleigh fading trace
PHY error model	LSM based mapping
Bandwidths	3MHz, 5MHz, 10MHz, 20MHz
Component Carrier Bands	0.7GHz, 0.9GHz, 1.8GHz, 2.025GHz, 2.6GHz
eNodeB TX power	30dBm
UE TX power	10dBm
Noise spectrum density	-174 dBm/Hz
Traffic	Video over UDP

A. Comparison with Static Component Carrier Assignment

The LTE module in NS3 only supports Release 8 LTE, so we extend the model and add the carrier aggregation feature. We compare our dynamic CC assignment scheme with the static round-robin allocation which assigns CCs for UE when it attaches to the network in a round-robin fashion. Our simulations are conducted in a grid scenario with one eNodeB

and ten UEs as shown in Figure 4. eNodeB is colocated with UE1. The space between UEs are 1500m. A UDP video session with a rate of 1000KB/s runs on the downlink between eNodeB and each UE. The total simulation time is 10 seconds. Five CCs are available and each UE can have at most three CCs assigned. The bandwidth is 5MHz (25 PRBs), so one UE can have a maximum aggregated 15MHz bandwidth (75 PRBs).



Fig. 4. A 10-UE Grid Scenario

In Figure 5 the aggregated throughput is compared: dynamic reallocation achieves higher aggregated throughput which translates to better network utilization. It is evident in Figure 6 that the average delay performance of dynamic scheme is better than the static assignment. The average delay keeps increasing with the static round-robin assignment.

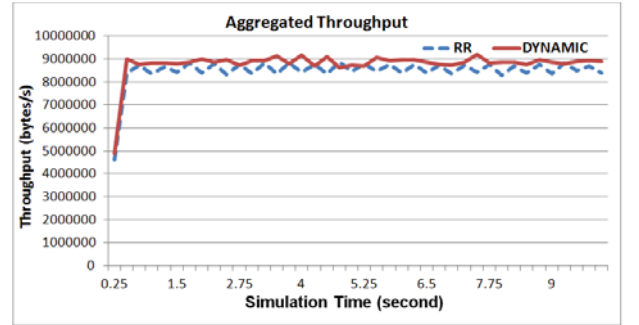


Fig. 5. Aggregated Throughput of 10 UEs

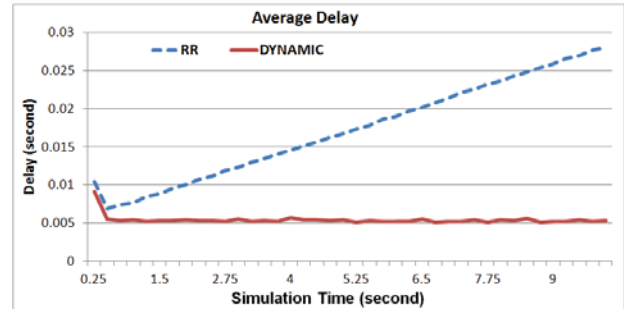


Fig. 6. Average Delay of 10 UEs

When we take a closer look, the problem is from UE6 whose queue is unstable and incurs a large delay. We further compare the throughput and delay of UE6 in Figures 7 and 8 respectively. Clearly both throughput and delay performance of the dynamic scheme is much better than the static approach:

the delay is low and stable; the throughput is much higher. The round-robin allocation assigns CCs 2.6GHz, 2.025GHz and 1.8GHz to UE6 which equivalently makes it a cell-edge user: bands with larger frequencies have smaller coverage. Different CCs may have different frequencies, hence different path loss characteristics and coverage, so proper CC assignment is very important to achieve high network utilization and user fairness. The advantage of our scheme is to dynamically reallocate CCs according to network and user conditions which gives much better network performance and user fairness.

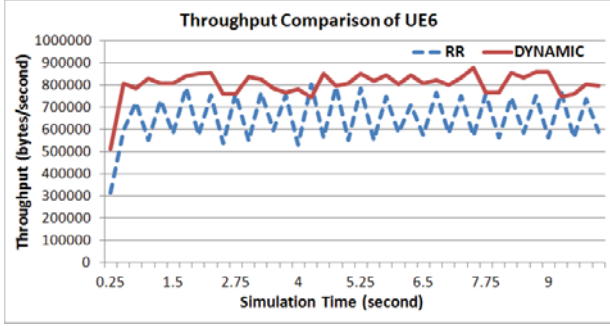


Fig. 7. Throughput of UE6

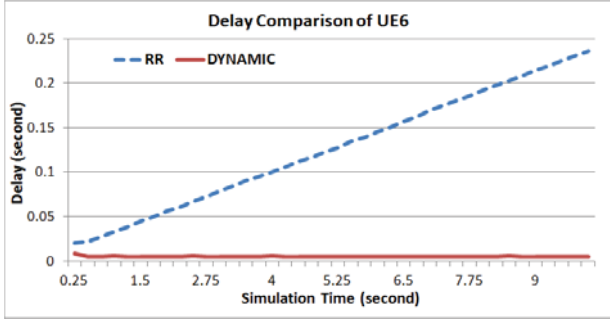


Fig. 8. Delay of UE6

B. Comparison with Proportional Fairness Scheduling Rule

In this section, we compare the backlog based scheduler (QSG) with the well-known Proportional Fairness scheduling rule [13] which is the default scheduler in many eNodeB implementations.

The Proportional Fairness scheduling rule, as the name suggests, attempts a “proportionally fair” allocation of radio resources to different users. Let $\mu_i(t)$ be the state of the channel of user i at time t , i.e. the actual rate supported by the channel. This rate is constant over one slot. Let $\bar{\mu}_i(t)$ denote the moving average rate of user i at time t . Then the rule can be defined as:

$$j = \arg \max_i \frac{\mu_i(t)}{\bar{\mu}_i(t)}$$

Compared to the Max-Rate rule [14] where a user with the highest instantaneous rate or equivalently the best channel condition is scheduled, the proportional fairness rule balances the user requests by considering their historical rates. The scheduler provides fairness in the sense that at any time users with lower moving average rates (“starved” in the past) will

have higher priorities to be allocated radio resources. However, it is noted that the proportional fairness rule does not account for packet delay and can result in poor delay performance.

We use the same topology as shown in Figure 4. The horizontal and vertical distance between UEs is 400m. A UDP video session with a rate 300KB/s runs on the downlink between eNodeB and each UE. The simulation time is 10 seconds. The aggregated throughput and average delay across 10 UEs are presented in Figures 9 and 10 respectively. Backlog scheduler offers slightly higher throughput but much better delay performance. In Figures 11 and 12 the average throughput and delay of each UE are compared. Backlog scheduler has lower delay for each UE and better fairness among UEs is achieved. 7 out of 10 UEs have higher or equal average throughput with the backlog scheduler, and other 3 UEs have comparable throughput performance. The throughput of the cell-edge UE 10 is about 14% higher than the PF scheduler, and its delay is substantially lower than the PF scheduler.

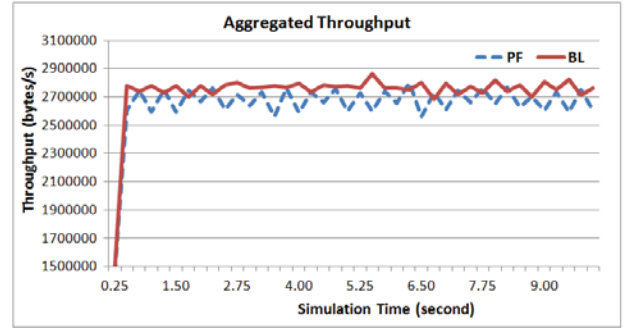


Fig. 9. Aggregated Throughput of 10 UEs

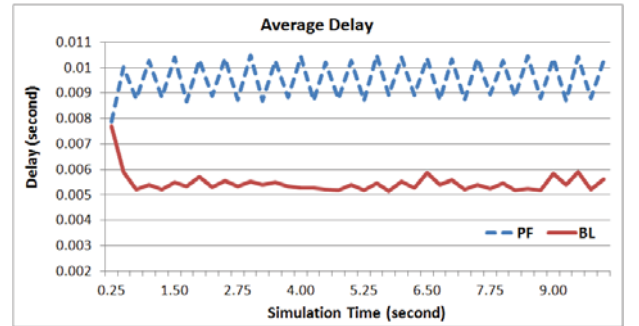


Fig. 10. Average Delay of 10 UEs

C. Comparison with Min-CQI Based Link Adaptation

In this section, we compare our weighted-average-CQI based link adaptation scheme with the minimum CQI based approach. In Figure 4, the space between UEs is 1000m. The bandwidth is 10MHz (50 PRBs). A 200KBps video session runs on the downlink from eNodeB to each UE. To better understand the impact of CQI selection, we also study the Max CQI where the MCS mode is determined by the maximum CQI of the allocated resource blocks for a UE. Min CQI and Max CQI are two extreme cases: most conservative and most

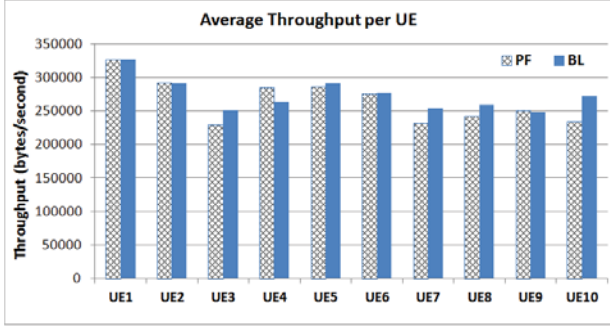


Fig. 11. Individual Average Throughput of 10 UEs

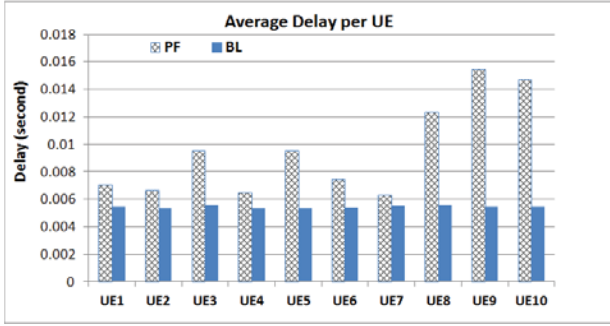


Fig. 12. Individual Average Delay of 10 UEs

optimistic. Higher CQI will indicate higher MCS mode which in turn generates higher bits per symbol. However, higher MCS mode will incur larger BER (Bit Error Rate). This shows that the tradeoff between the transmission rate and the error rate needs to be carefully considered. Min CQI favors low BER but the delay is large while Max CQI has good delay performance but the throughput is very low.

TABLE III
COMPARISON OF DIFFERENT LINK ADAPTATION SCHEMES

	Min CQI	Max CQI	Weighted CQI
Aggregated Throughput (KBps)	1664	1088	1654
Average Delay (ms)	16.7	12.8	14.5

TABLE IV
COMPARISON BETWEEN MIN-CQI AND WEIGHTED-CQI

	Min CQI	Weighted CQI
Aggregated Throughput (KBps)	2245	2190
Average Delay (ms)	31.6	9.6

In our approach, we average the CQIs across all allocated resource blocks in a weighted manner. Hence the high CQIs are weighted more but the tradeoff is also taken into account. Table III presents the results of three link adaptation schemes. Although the aggregated throughput degrades slightly (0.6% less), the delay performance is much better (13% less). It is expected that wider bandwidth may have more CQI variations, so the performance gain would be higher. In another scenario where the downlink bandwidth is 20MHz (100 PRBs) and the rate is 250KBps, Table IV shows the comparison: the throughput degradation is 2.4% but the delay is substantially

lower. In Figure 13 we further compare the per UE average delay: UE10 has a constantly increasing delay (the average over the simulation duration is 230ms and off the chart).

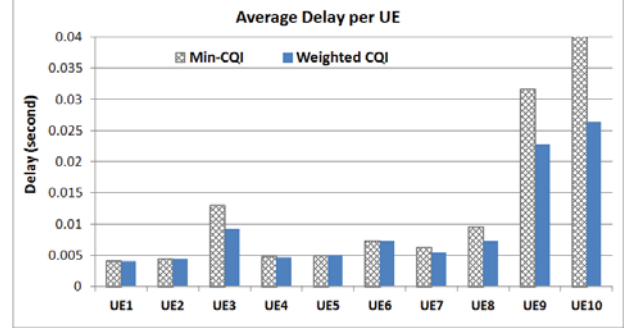


Fig. 13. Individual Average Delay of 10 UEs

D. Overall Performance

In this section, we incorporate the proposed schemes (PROPOSED in the legend) and evaluate their performance collectively in a general scenario. The baseline is the proportional fairness scheduler with the static round-robin component carrier assignment (DEFAULT in the legend). The scenario is one eNodeB with ten UEs. The UEs are uniformly distributed within a 1000m circle centered at the eNodeB, and move under the random waypoint mobility model with a speed uniformly distributed in the range of [0, 15m/s] (from pedestrian to low-speed urban vehicle). Three 3MHz bands are allocated for each UE. The downlink rate for each UE is 600KBps. We compare the aggregated throughput and average delay of UEs in Figures 14 and 15 respectively. The aggregated throughput offered by the proposed schemes is higher, so the network utilization is better. For the delay performance, the default approach produces a constantly increasing delay (the queues are unstable). The standard deviation of the average delay of 10 UEs by our schemes is 0.006ms while it is 3.478ms by the default approach, so the delay fairness is also better.

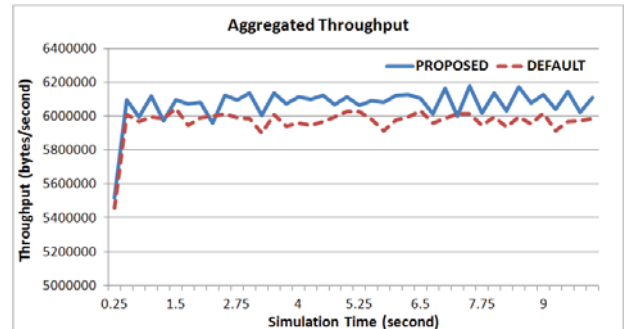


Fig. 14. Aggregated Throughput of 10 Random UEs

VI. RELATED WORK

Resource allocation in OFDMA based LTE networks has been one of the important problems of RRM in wireless networks and attracting increasing research interests recently.

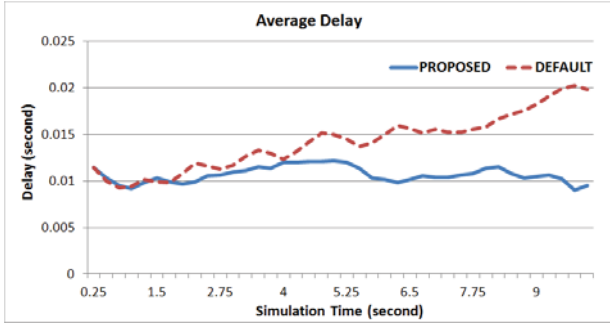


Fig. 15. Average Delay of 10 Random UEs

From the theoretical perspective, scheduling algorithms in multi-channel networks were proposed in [11][12][15]. However, in realistic scenarios, those algorithms may need significant extensions. In [10][16], the authors presented the hardness results for LTE frequency-domain scheduling. Under certain circumstances, it has been proven to be NP-hard.

Joint component carrier allocation and packets scheduling were reported in [17]. The carrier assignment algorithm was simplistic and static. At the subcarrier level, it used the PF scheduler. In [18], the authors focused on the uplink carrier allocation in favor of cell-edge users, and no delay performance was considered. Various schemes have been proposed to address the packet scheduling problem in wireless channel. In addition to the Max-Rate rule and the PF rule discussed in the simulations, two queue driven rules were presented in [19] (the EXP rule) and [20] (the LOG rule) with different focus. As the queues grow linearly, the EXP rule schedules in a manner that emphasizes queue-balancing at the cost of total weighted service rate while the LOG rule schedules in a manner that de-emphasizes queue-balancing in favor of increasing the total weighted service rate (being opportunistic). Both rules are single-user schedulers. Their scheduling metrics bundle two components – channel rate and queue-length, so the scheduling decision may not be optimal individually for both components in multi-subcarrier wideband systems for multi-user scheduling.

Most of the existing CQI schemes [21][22][23] focused on the accurate and timely feedback mechanisms which are important but did not consider the CQI adaptation when scheduling PRBs and constructing transport blocks (TBs). The tradeoff between CQI selection and corresponding MCS mode (TB size) has a significant impact on network performance.

VII. CONCLUSION

In this paper, we studied the downlink radio resource allocation problem for LTE-Advanced systems which includes both component carrier assignment and resource block scheduling. We proposed a dynamic carrier assignment algorithm and backlog based resource block scheduling policies to achieve load balancing across component carriers and better throughput and delay performance for users compared with the existing schemes. In addition, we presented an intelligent link

adaptation scheme based on weighted average CQI which can be plugged into the scheduling algorithms to further enhance the delay performance. The effectiveness of the proposed schemes is evidenced with extensive simulations under realistic models and settings. The proposed schemes consist of a two-tier (carrier and subcarrier) scheduling framework which can be extended and enhanced with more sophisticated metrics and algorithms in future research.

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APPENDIX CHEN07



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RESEACH ARTICLE

Full-Band CQI Feedback By Huffman Compression In 3GPP LTE Systems

by Onkar Dandekar



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Abstract

3GPP LTE system exhibits a vital feature of Frequency Selective Scheduling(FSS). Frequency scheduling relies on Channel Quality Indicator(CQI) report by the user equipment (UE). The main challenge in CQI reporting consists of reduction in number of reporting bits maintaining the performance of the system. This paper recommends a new CQI reporting approach which uses Huffman compression for reduction of overhead bits for full-band CQI report. Full-band feedback technique transmits entire CQI report instead of reporting limited bands as done in Best-M reporting techniques. The constraint of Huffman coding that the coding table must be known to both transmitter and receiver prior to transmission, is efficiently explored in this technique. Results indicate appreciable reduction in feedback bits as compared to uncompressed full-band reports. Also, full-band Huffman feedback technique shows profound rise in throughput of the system over sub-band feedback techniques.

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Index Terms

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Full-Band CQI Feedback by Huffman Compression in 3GPP LTE Systems

Onkar Dandekar

M. Tech (E&C)

ABSTRACT

3GPP LTE system exhibits a vital feature of Frequency Selective Scheduling(FSS). Frequency scheduling relies on Channel Quality Indicator(CQI) report by the user equipment (UE). The main challenge in CQI reporting consists of reduction in number of reporting bits maintaining the performance of the system. This paper recommends a new CQI reporting approach which uses Huffman compression for reduction of overhead bits for full-band CQI report. Full-band feedback technique transmits entire CQI report instead of reporting limited bands as done in Best-M reporting techniques. The constraint of Huffman coding that the coding table must be known to both transmitter and receiver prior to transmission, is efficiently explored in this technique. Results indicate appreciable reduction in feedback bits as compared to uncompressed full-band reports. Also, full-band Huffman feedback technique shows profound rise in throughput of the system over sub-band feedback techniques.

General Terms

Wireless communication.

Keywords

Huffman compression, 3GPP LTE CQI, LTE uplink feedback.

1. INTRODUCTION

3GPP Long Term Evolution (LTE) system exploits OFDMA as air interface for improved spectrum management [1]. OFDMA grants downlink transmission for different users on different frequency channels at the same time. Accordingly, need of frequency scheduling at eNodeB(base station) arises. In order to accomplish this type of scheduling, eNodeB demands channel quality information from every user.

Channel information inherently depends on user's received signal quality. Channel Quality Indicator(CQI), an integer value, maps effective SINR [2] for each group of subcarriers known as sub-band. Apart from SINR, this mapping could also deal with multipath delay spread [3]. Link adaptation algorithms have also been investigated for appropriate CQI value selection [4]. E-NodeB transmits pilot (reference) signals at proper intervals for CQI measurement. UE then sends back CQI to its corresponding eNodeB, beneficial for frequency scheduling [5].

CQI feedback leads to vast utilization of uplink resources. CQI feedback information being the control information, must use minimum possible bits. Use of lower number of bits which could be achieved by feedback of partial information, leads to declination of average throughput of the system. A balance has to be struck between overhead bits and throughput of the system.

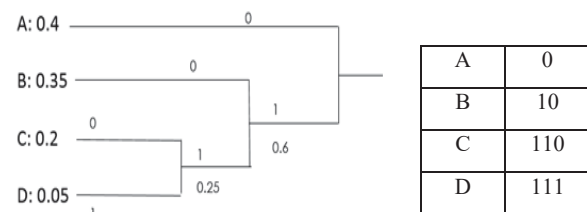
Considerable research has been done to come up with a viable CQI reporting technique. CQI reporting techniques could be roughly classified as full-band and sub-band feedback techniques [6]. Full-band feedback uses compression methods with quality report for entire bandwidth. DCT and Haar

compression based methods have been designed for the same [7]-[9]. Sub-band feedback reports limited number of bands corresponding to best channel quality[10]-[13]. Such technique improves overhead, weakening the throughput of the system [14].

This paper concentrates on application of variable length coding for overhead reduction of full-band feedback technique. Huffman compression is an efficient variable length coding technique which works on probability of occurrence of symbols to be encoded. Since Huffman compression is applied on full band reports, it provides throughput similar to that of uncompressed full-band reports. Paper structure is as follows: Sec 2 throws light upon basic Huffman compression. Full band Huffman compression scheme is explained thoroughly in Sec.3. Overhead and performance analysis for the scheme is presented in Sec 4. The work is concluded in Sec 5.

2. HUFFMAN COMPRESSION

Huffman coding allows accurate retrieval of original data from compressed data. Variable number of bits are assigned in such a way that symbols with higher probability of occurrence are assigned lower number of bits and vice-versa. A fascinating property of Huffman compression is that generated symbol code forms a prefix code. No code word is prefix of any other code word in a prefix code. This facilitates accurate decoding of data from compressed data, by making use of coding table that was used for encoding. Huffman code formation for 4 symbols with probabilities {0.4,0.35,0.2,0.05} is shown.



Symbols are arranged in descending order of their probabilities. Lower two probabilities are added up and resulting sum along with remaining probabilities are again arranged in descending order. This process is continued until only two probabilities are left out. At every stage 0 and 1 are assigned to the probabilities which are added. Symbols are then traced from last to first stage to get Huffman code. Huffman code for above case is shown in table. As observed, no code word is prefix of other code word.

3. FULL BAND HUFFMAN CQI FEEDBACK SCHEME

The basic idea is to assign minimum no. of bits to CQI values occurring the most & maximum no. of bits to CQI values occurring the least, thereby reducing the overall CQI feedback overhead. Number of occurrence for each CQI value could be counted & number of bits to be assigned to each value could be decided. However, Huffman coding has a constraint that receiver must know the coding table used at the transmitter for decoding purpose. Hence coding table used needs to be transmitted to receiver. But this would lead to unacceptable overhead. Thus assignment of bits dynamically is not possible & a static scheme has to be developed.

This static scheme assumes that CQI values from a particular range occur more number of times in the current CQI report, compared to other values. Values in this range are then assigned least number of bits. Keeping this in mind, Huffman code for all CQI values could be generated. CQI range (1 to 15) is divided into groups where occurrence of each group in CQI report is assumed to be different. Group A values are assumed to occur the most & hence assigned least no. of bits. Descending order of occurrence of groups is:

Group A > Group B > Group C > Group D & so on.

Scheme uses one of the possible group formation. Possible group formations are shown.

Table 1.Huffman Code for 2 groups

Group	Huffman Code
A	[0,0,0]
	[1,1,0]
	[0,1,1]
	[0,1,0]
	[1,0,1]
	[1,0,0]
	[0,0,1]
B	[1,1,1,1,0,1]
	[1,1,1,1,0,0]
	[1,1,1,1,1,1]
	[1,1,1,1,1,0]
	[1,1,1,0,0,1]
	[1,1,1,0,0,0]
	[1,1,1,0,1,1]
	[1,1,1,0,1,0]

Table 2.Huffman Code for 3 groups

Group	Huffman Code
A	[1,0,1]
	[1,0,0]
	[1,1,1]
	[1,1,0]
	[0,0,1]
B	[0,1,0,1]
	[0,1,0,0]
	[0,1,1,1]
	[0,1,1,0]
	[0,0,0,1]
C	[0,0,0,0,1,1]
	[0,0,0,0,1,0]
	[0,0,0,0,0,0,1]
	[0,0,0,0,0,0,0]
	[0,0,0,0,0,1]

Table 3.Huffman Code for 4 groups

Group	Huffman Code
A	[1,1]
	[1,0]
	[0,1]
B	[0,0,1,1]
	[0,0,0,0,0]
	[0,0,0,1,0]
	[0,0,0,0,1]
C	[0,0,1,0,0,1]
	[0,0,1,0,0,0]
	[0,0,1,0,1,1]
	[0,0,1,0,1,0]
D	[0,0,0,1,1,0,1]
	[0,0,0,1,1,0,0]
	[0,0,0,1,1,1,1]
	[0,0,0,1,1,1,0]

Table 4. CQI Grouping for each code table

No. of groups	No. of code tables	CQI grouping for each code table	Comments
2	2	Code 1: A (1 - 7),	Group with minimum bits

		B (8 – 15) Code 2: A (8 – 15), B (1 – 7)	per CQI value is group A. Group with maximum bits per CQI value is group B.
3	6	Code 1: A (1 – 5), B (6 – 10), C (11 – 15) Code 2: A (1 – 5), B (11 – 15), C (6 – 10) Code 3: A (6 – 10), B (1 – 5), C (11 – 15) Code 4: A (6 – 10), B (11 – 15), C (1 – 5) Code 5: A (11 – 15), B (1 – 5), C (6 – 10) Code 6: A (11 – 15), B (6 – 10), C (1 – 5)	Group with minimum bits per CQI value is group A. Group with maximum bits per CQI value is group C.
4,5..... 15	4!,5!.. 15!	“4!,5!.....15!” combinations of “4,5.....15” groups respectively	Group with minimum bits per CQI value is group A. Group with maximum bits per CQI value is last group.

Formation of code tables is done prior to transmission of CQI values. One of the above combination is used.

The steps to be carried out for this scheme could be summarized as follows:

1. Divide CQI value range (1 to 15) into groups. Min. 2 groups & max. 15.
2. Form Huffman code tables for the decided group formation.
3. Get the CQI values for all active sub-bands (full-band CQI report).
4. Count the number of occurrence for individual CQI values within each group.
5. Add & obtain the total occurrence number for each group.
6. Arrange groups in descending order of total occurrence number.
7. Select relevant code table from available code tables. Group with maximum occurrence is group A & subsequent groups in descending order of occurrence number.

For example, consider following CQI vector and scheme with 2 groups:

CQI	12	12	4	10	5	8	8	7	4	5
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Count for group 1 to 8 : 7, Count for group 9 to 15 : 3. Higher count group is the first group and hence group A is from 1 to 8 and group B from 9 to 15. Hence, Code 1 is selected. Thus, range of values with more count are assigned less number of bits.

Key Points:

1. CQI values within a particular group are considered to be with equal probability of occurrence. Hence, roughly same number of bits are assigned to individual values within a group.
2. More number of groups allows to assign lesser number of bits per value.
3. The decision of number of groups and formation of code tables should be done prior to CQI computation.
4. A particular group is not distributed over CQI value range. A set of consecutive CQI values is considered to be a group (such as 1 to 8 and 9 to 15).
5. Better compression is possible if reported CQI values are concentrated in a single group (particularly Group A). For this case, more number of groups is feasible. However if CQI values are distributed in entire CQI range then it is better to have lesser number of groups.

4. OVERHEAD & PERFORMANCE ANALYSIS

4.1 Overhead Analysis

Compression depends on occurrence of CQI values. The analysis is shown for system with 25 sub-bands. Hence maximum occurrence of values in group A could be 25 which corresponds to maximum compression. Similarly, min. occurrence of values in group A will result in minimum compression. For example, consider scheme with 2 groups :

Occurrence number for group A $\geq$ Occurrence number for group B

1. Distribution of 25 values: 13 in group A and 12 in group B

$$\text{Total bits required (min. compression)} \\ = (13 \times 3) + (12 \times 6) = 111 \text{ bits}$$

2. Distribution of 25 values: 25 in group A and 0 in group B

$$\text{Total bits required (max. compression)} = (25 \times 3) \\ = 75 \text{ bits}$$

Same analysis could be extended to schemes with higher groups.

(For a single group with variable length of bits for individual values, max. number of bits for single value is considered)

Table 5.Compression for different number of groups

Full band with Huffman compression			Full band feedback without compression
Number of Groups	Total bits in minimum compression	Total bits in maximum compression	
2	111 bits (A/B : 13/12)	75 bits (A/B : 25/0)	125 bits
3	115 bits (A/B/C : 9/8/7)	75 bits (A/B/C : 25/0/0)	
4	122 bits (A/B/C/D : 7/6/6/6)	50 bits (A/B/C/D : 25/0/0/0)	

Table 6.Overhead comparison with sub-band methods

Feedback Scheme	Bit Computation Formula	Total bits required $N_{sb} = 25,$ $M = 7$
Full feedback without compression	$5 \times N_{sb}$	125 bits
Full feedback Huffman with 4 groups	Max. compression: $N_{sb} \times 2$	50 bits
Best-M individual	$5 \times M + \left\lceil \log_2 \left(\frac{N_{sb}}{M} \right) \right\rceil + 5$	59 bits
DCT significant-M	$5 \times M + \left\lceil \log_2 \left(\frac{N_{sb} - 1}{M - 1} \right) \right\rceil$	53 bits
DCT partitioning	$5 \times (N_1 + N_2) + \left\lceil \log_2 \left(\frac{N_{sb}}{M} \right) + \log_2 \left(\frac{M - 1}{N_1 - 1} \right) + \log_2 \left(\frac{N_{sb} - M - 1}{N_2 - 1} \right) \right\rceil$	$N_1 = 6,$ $N_2 = 1$ 57 bits

As seen from table 5, maximum compression of up-to 50 bits is possible for scheme with 4 groups. Huffman scheme results in bit saving of 11.2% to 40% for 2 groups, 8% to 40% for 3 groups, 2.4% to 60% for 4 groups.

More maximum compression is possible for schemes with higher number of groups.

As seen from table 6, scheme with 4 groups outperforms Best M individual and DCT based schemes for M=7.

4.2 Performance Analysis

Simulation results for comparison of throughput for different feedback techniques, considering various parameters are presented in this section.

Table 7.Simulation parameters

Parameters	Values
System bandwidth	10 MHz
RB bandwidth	180 kHz
Carrier frequency	2 GHz
Scheduler	Proportional Fair
Number of TX antennas	1
Number of Rx antennas	2
Channel model	Pedestrian B
UE speed	3 km/h, 15km/h
CQI feedback delay	2 TTIs
FFT size	1024
Number of sub-carriers	600
Target BLER	10%

It was evident from the simulation results that full-band Huffman scheme produced better throughput over sub-band schemes such as Best-M individual and DCT based schemes. Higher throughput for full-band scheme was obvious as it reported entire CQI thereby providing more precise information to base station as compared to sub-band schemes.

Simulation was carried out for UE speed's of 3km/h & 15km/h.

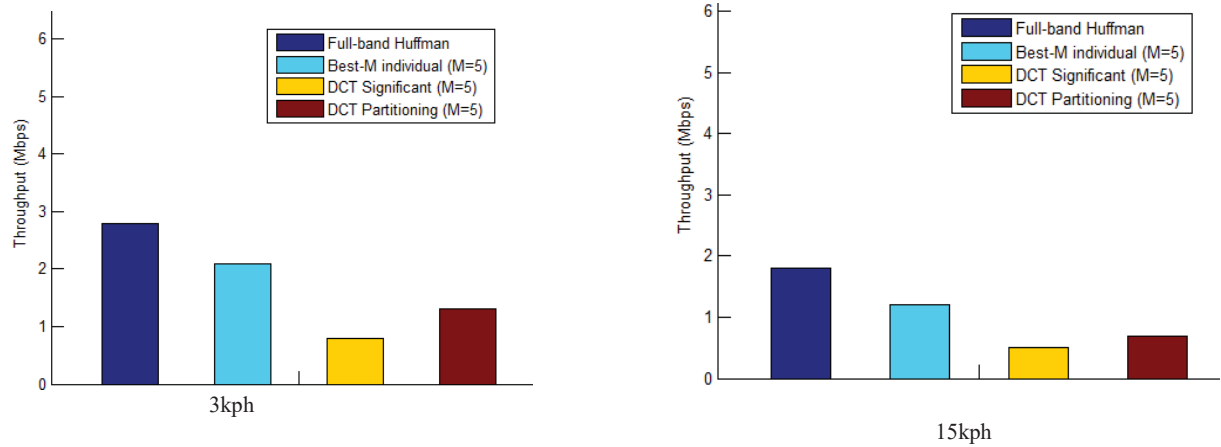


Figure 1. Throughput comparison for 3kph & 15kph UE speed's

5. CONCLUSIONS

This paper proposes Huffman compression for full-band CQI feedback in LTE systems. The proposed scheme results in considerable bit saving for full-band reports. Proper grouping of CQI values followed by occurrence of full-band values over these groups forms the basis for this scheme. Scheme allows compression to such an extent that it even outperforms some of the sub-band feedback schemes. This scheme reports full-band values thereby providing better throughput over all other feedback schemes. Huffman compression thus achieves perfect balance between overhead reduction and throughput requirements.

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APPENDIX CHEN08

Link adaptation algorithms for channel estimation error mitigation in LTE systems

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Abstract

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Abstract:

In Long Term Evolution (LTE) systems, the evolved Node B (eNodeB) performs link adaptation to improve the system performance on the basis of channel quality information estimated and feedback by the user equipments (UEs). However, the channel estimation error (CEE) can not be avoided due to hardware constraint. To make up the performance loss caused by CEE, two types of link adaptation algorithms are proposed: weighted average (WA) algorithm based on three different parameters and an enhanced adaptive time window (ATW) algorithm. Unlike pervious work, this paper not only presents the specific process of all the algorithms but also takes the theoretical derivation of performance comparison into consideration. Moreover, simulation results are demonstrated using an LTE system-level simulator, which show that the WA algorithm based on channel estimation value can effectively mitigate CEE and achieve a significant gain. Subsequently, a better system performance can be obtained using ATW algorithm by adjusting the window size dynamically.

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I. Introduction

With the development of broadband wireless communication, one of the goals of future communication network is the almost-ubiquitous provision of high data rate, coverage and throughput. Long Term Evolution (LTE) system is spurred by the technical trend in wireless communication, which adopts Multiple Input Multiple Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) technology to provide high data rate, coverage and capacity effectively. Moreover, Hybrid Automatic Repeat Request (HARQ) applied in real systems can compensate performance loss caused by multipath fade through Acknowledgement/Negative Acknowledgement (ACK/NACK) feedback. Besides this, Adaptive Modulation and Coding (AMC) as one of the

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Link Adaptation Algorithms for Channel Estimation Error Mitigation in LTE systems

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Abstract—In Long Term Evolution (LTE) systems, the evolved Node B (eNodeB) performs link adaptation to improve the system performance on the basis of channel quality information estimated and feedback by the user equipments (UEs). However, the channel estimation error (CEE) can not be avoided due to hardware constraint. To make up the performance loss caused by CEE, two types of link adaptation algorithms are proposed: weighted average (WA) algorithm based on three different parameters and an enhanced adaptive time window (ATW) algorithm. Unlike pervious work, this paper not only presents the specific process of all the algorithms but also takes the theoretical derivation of performance comparison into consideration. Moreover, simulation results are demonstrated using an LTE system-level simulator, which show that the WA algorithm based on channel estimation value can effectively mitigate CEE and achieve a significant gain. Subsequently, a better system performance can be obtained using ATW algorithm by adjusting the window size dynamically.

Index Terms—channel estimation error, weighted average algorithm, adaptive time window algorithm, LTE systems

I. INTRODUCTION

With the development of broadband wireless communication, one of the goals of future communication network is the almost-ubiquitous provision of high data rate, coverage and throughput. Long Term Evolution (LTE) system is spurred by the technical trend in wireless communication, which adopts Multiple Input Multiple Output (MIMO) and Orthogonal Frequency Division Multiplexing (OFDM) techniques to improve spectrum efficiency and coverage effectively. Moreover, Hybrid Automatic Repeat Request (HARQ) applied in real systems can compensate performance loss caused by multipath fade through Acknowledgement/Negative Acknowledgement (ACK/NACK) feedback. Besides this, Adaptive Modulation and Coding (AMC) as one of the techniques can also increase the throughput.

Channel Quality Indicator (CQI) derived by user equipment (UE) is the key indicator for the quality of LTE downlink channel and the data rate supported by the UE. UE feeds back CQI to evolved Node B (eNodeB) for resource utilization and conducting AMC operation. In LTE systems, 5 bits are generally used to denote CQI, which size is related with transport-block size, modulation scheme and other performance parameters [1] [2]. However, due to the user's hardware limitations, eNodeB is unable to obtain accurate CQI. Subsequently, imprecise CQI will stir up the wrong decisions made by eNodeB and decline the Quality of Service (QoS) of UEs. Thus, people focus on

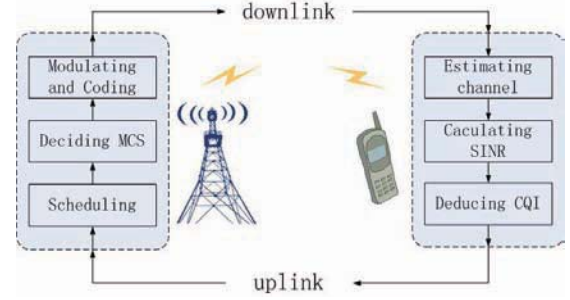


Fig. 1. Data transmission in LTE systems

how to guarantee the accuracy of CQI, so as to maintain high QoS.

[3] [4] indicated three factors leading to CQI errors, namely channel estimation error (CEE), CQI quantification error and CQI time delay. The impact of CEE and delay was investigated in [5] [6]. Many papers focused on CQI adjustment schemes in HSDPA systems. [7] gave out a Signal to Interference rate (SIR) average algorithm to improve performance of link adaptation. In [8], the authors utilized the power control information of Dedicated Physical Channel (DPCH) to improve the veracity of the feedback information. [9] [10] presented future CQI estimation calculated by filters. However, the aforementioned approaches do not take LTE systems and the theoretical derivation of performance comparison into consideration. In this paper, we aim at the analysis of weighted average (WA) algorithm in LTE systems considering CEE. The LTE system-level simulation is adopted and three types of WA algorithms on the basis of different parameters are compared by both the simulation and the theoretical derivation. Moreover, in order to get a better performance of WA algorithm, we propose an enhanced adaptive time window (ATW) algorithm.

The rest of the paper is organized as follows. Section II provides a brief system model. In section III, we discuss the data transmission of LTE systems and the effect of CEE on performance. Three WA algorithms based on different parameters and an ATW algorithm are presented in details in Section IV. Section V and VI describe theoretical derivation and simulation results, respectively. Finally, we conclude the paper in Section VII.

Notations: Superscripts $(\cdot)^*$ stands for complex conjugated transpose operation. $(\cdot)^{-1}$ and $tr(\cdot)$ represent inversion of

matrices and trace operation, respectively.

II. SYSTEM MODEL

We consider a LTE downlink MIMO system consisting of N_t transmit antennas and N_r receive antennas. We assume that all eNodeBs use the same MIMO scheme. The signal model is described as

$$\mathbf{y}^{(0)} = p^{(0)}\mathbf{H}^{(0)}\mathbf{x}^{(0)} + \sum_{i=1}^{N_t} p^{(i)}\mathbf{H}^{(i)}\mathbf{x}^{(i)} + \mathbf{u}^{(0)}, \quad (1)$$

where $\forall i \in [1, N_t]$ denotes the index of interfering eNodeB, $i = 0$ denotes the target eNodeB, $\mathbf{y}^{(0)}$ is the $N_r \times 1$ received signal for target UE and $p^{(i)}$ means the product of transmit power for the signal $\mathbf{x}^{(i)}$ and path loss between the target UE and the eNodeB i , $\mathbf{H}^{(i)}$ is a $N_r \times N_t$ channel matrix between the target UE and the eNodeB i , $\mathbf{u}^{(0)}$ represents $N_r \times 1$ zero-mean additive white Gaussian noise (AWGN) matrix which covariance is $\sigma^2\mathbf{I}$ and $\mathbf{I}$ is a $N_r \times N_r$ unit matrix.

In this paper, we assume that only CEE occurs and the channel matrix with CEE can be modeled as follows [11].

$$\mathbf{H}^e = \mathbf{H} + e\mathbf{E}, \quad (2)$$

where $\mathbf{E} = \{a_{ij}\}_{N_r \times N_t}$, $a_{ij} = 1, \forall i, j$ and e is the estimation error coefficient which can control size of $\mathbf{E}$. The channel matrix with CEE can not reflect the real channel state information, thereby affecting subsequent operations of the system and degrading the throughput.

III. LTE SYSTEM AND EFFECT OF CEE

A typical LTE system works as depicted in Fig. 1:

- **Step 1:** UE receives downlink data;
- **Step 2:** UE estimates channel condition;
- **Step 3:** UE calculates signal-to-interference and noise ratio (SINR) based on channel estimation value in **Step 2**;
- **Step 4:** based on SINR calculated above, UE gets the proper CQI through reading curve of SINR versus bit error rate (BER) given by the link-level simulation;
- **Step 5:** UE transfers uplink data, CQI and ARQ information to eNodeB through uplink channel;
- **Step 6:** eNodeB receives uplink data;
- **Step 7:** eNodeB schedules UEs;
- **Step 8:** eNodeB decides MCS of each UE on the basis of CQI in **Step 4**;
- **Step 9:** eNodeB transfers downlink data using MCS decided in **Step 8** through downlink channel.

Obviously, due to hardware limitations, UE cannot guarantee that channel estimation value accurately portrays the instantaneous channel condition. Then, channel estimation value with CEE will affect the accuracy of SINR calculation, which further makes CQI unreliable. Finally, eNodeB makes unwise scheduling and MCS decision based on the unreliable CQI, which will reduce the system throughput and the users' QoS. Therefore, CEE is an important factor affecting system performance.

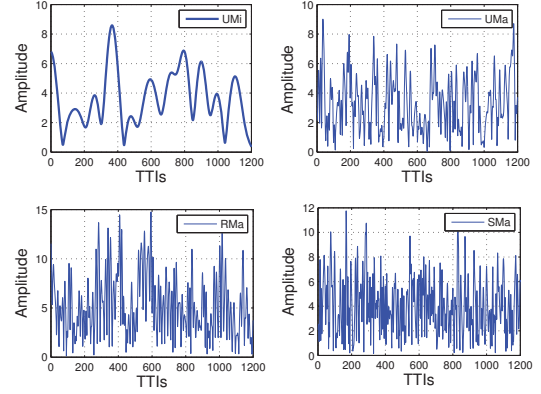


Fig. 2. Characteristics of four channel scenarios

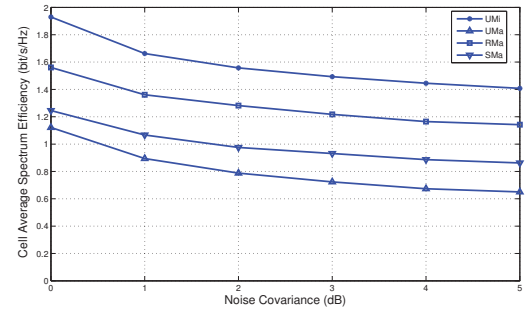


Fig. 3. Effect of channel estimation error on four channel scenarios

In this paper, we adopt system-level simulation based on LTE release 8 version, so as to analyze the impact of CEE on system performance. All details of configurations including network layout, simulation parameters, antenna patterns and channel models are provided in [12]. Our methods are in strict accordance with the provisions of [13]. Four scenarios are considered, namely 1) Urban micro-cell scenario (UMi), 2) Urban macro-cell scenario (UMa), 3) Rural macro-cell scenario (RMa) and 4) Suburban macro-cell scenario (SMa).

Fig. 2 depicts the varying situation of channels. It can be concluded that $\text{SMa} > \text{RMa} > \text{UMa} > \text{UMi}$ in accordance with the order of channel change from fast to slow. The conclusion will be used in the subsequent sections. The simulation results of cell average spectrum efficiency (CASE) versus e for the four scenarios are depicted in Fig. 3, where $e \in [0, 5]$ dB. It shows that with the increase of CEE's covariance, the CASE of all scenarios decreases. When CEE's covariance is 1 dB, CASE of UMi, UMa, RMa and SMa degrade 13.86%, 20.25%, 12.80% and 14.35% compared with that of $e = 0$ dB, respectively. Moreover, almost 27.05%, 42.01%, 26.82% and 30.76% performance lost with $e = 5$ dB. Thus, proposing algorithms to eliminate the effect of CEE and improve system performance is crucial.

IV. PROPOSED ALGORITHMS

In this section, we propose three WA algorithms on the basis of different parameters respectively and one enhanced algorithm based on WA algorithm named as ATW algorithm.

A. WA Algorithms

Considering CEE, we assume $\mathbf{H}_t^e$ and S_t^e denote channel estimation value and SINR calculated by UE at time t . MCS decided by eNodeB at time t is presented as M_t^e .

1) H-WA algorithm (HWA)

In this algorithm, we achieve a more reasonable channel estimation value, by taking the average of channel estimation values in a period of time to reduce the randomness of the CEE. At time t , the channel information used to calculate SINR in **step 3** is denoted as $\mathbf{H}_t'$.

$$\mathbf{H}_t' = \sum_{i=1}^T w_i \mathbf{H}_{t-i+1}^e. \quad (3)$$

Assume T denotes the window size for WA algorithm. w_i is weight coefficient used to control weight size of $\mathbf{H}_{t-i+1}^e$. For the sake of simplicity, we make $w_i = \frac{1}{T}$, $\forall i \in [1, T]$. Equation (3) is simplified as

$$\mathbf{H}_t' = \frac{1}{T} \sum_{i=1}^T \mathbf{H}_{t-i+1}^e. \quad (4)$$

2) SINR-WA algorithm (SWA)

The core of SWA algorithm is to eliminate CEE by keeping the channel estimation value calculated in **step 2** unchange and taking the arithmetic average of SINR. At time t , the SINR for getting CQI in **step 4** is given as

$$S_t' = \sum_{i=1}^T w_i S_{t-i+1}^e. \quad (5)$$

Substituting $w_i = \frac{1}{T}$, $\forall i \in [1, T]$ into Equation (5), it is reproduced as

$$S_t' = \frac{1}{T} \sum_{i=1}^T S_{t-i+1}^e. \quad (6)$$

3) MCS-WA algorithm (MWA)

HWA and SWA algorithms are both applied at UE side. Taking the computational complexity of UE into consideration, we propose MWA algorithm applied at eNodeB side. In the MWA algorithm the channel estimation value and SINR are maintained the same. MCS used in **step 9** will be modified at eNodeB side as

$$M_t' = \sum_{i=1}^T w_i M_{t-i+1}^e \quad (7)$$

where $w_i = \frac{1}{T}$, $\forall i \in [1, T]$. Equation (7) is simplified as

$$M_t' = \frac{1}{T} \sum_{i=1}^T M_{t-i+1}^e. \quad (8)$$

Algorithm 1 Adaptive Time Window Algorithm

```

1: Initialization
2:  $T_1 = 50$  ms and data transmission in  $T_1$  is  $P_1$ ;
3:  $T_2 = 49$  ms and data transmission in  $T_2$  is  $P_2$ ;
4: Defining variables  $stepnum = 10000$  and  $i = 2$ ;
5: while ( $\sum_{n=1}^i T_n < stepnum$ ) do
6:   if ( $((P_i \geq P_{i-1}) \&\&(T_i > T_{i-1})) \parallel ((P_i < P_{i-1}) \&\&(T_i \leq T_{i-1}))$ ) then
7:      $T_{i+1} = T_i + 1$ 
8:   else
9:      $T_{i+1} = T_i - 1$ 
10:  end if
11:   $i = i + 1$ 
12: end while

```

B. ATW Algorithm

As described in HWA algorithm, its performance depends on window size T . Substituting equation (2) into equation (4), we can obtain equation as

$$\mathbf{H}_t' = \frac{1}{T} \sum_{i=1}^T \mathbf{H}_{t-i+1} + \frac{e}{T} \sum_{i=1}^T \mathbf{E}_{t-i+1}. \quad (9)$$

In order to trace the instantaneous condition of channel, T in $\frac{1}{T} \sum_{i=1}^T \mathbf{H}_{t-i+1}$ should be close to 1. However, to eliminate the estimation error, T should be close to infinity such that

$$\lim_{T \rightarrow \infty} \frac{e}{T} \sum_{i=1}^T \mathbf{E}_{t-i+1} = 0. \quad (10)$$

Thus, the time window size T is a key factor to impact the WA algorithms. In a practical system, it is very challenging to select a suitable T . Meanwhile, a fixed T does not necessarily meet the real-time channel information changes in the system. For a better performance, an ATW algorithm is proposed to maximize the throughput by adjusting T dynamically.

Assume that P_i is the data rate calculated in the i th time period which is denoted as T_i . The idea of the ATW algorithm is presented as follows. First, two time periods T_1 and T_2 are initialized and the corresponding data rate P_1 and P_2 are calculated, respectively. Second, T is dynamically adjusted by iteratively comparing the data rate and time periods. The process continues. Finally, the time period converges to a steady value which is adjusted for the maximum throughput until the simulation time is over. The details are described in Algorithm 1.

V. THEORETICAL DERIVATION

According to the details of WA algorithms depicted in subsection IV-A, three algorithms can eliminate randomness of CEE more or less. However, because of limited AMC technology, MCS are integers extending from 1 to 29. So the tiny error of channel estimation value and SINR will lead to slight effect on MCS, so as to insignificant effect on the system performance. Thus, in this section we focus on the

theoretical derivation of HWA and SWA algorithms without MWA algorithm.

Assume the MIMO system above employs a linear minimum mean square error (MMSE) receiver. Because of good channel condition and low interference between UEs, we can ignore interference to simplify the analysis. $N_r = 1$ and the stream k for UE is 1. Thus equation (1) is adjusted as

$$\mathbf{y} = p\mathbf{H}\mathbf{m}\mathbf{x} + \mathbf{u}, \quad (11)$$

where $\mathbf{m}$ is a $N_t \times 1$ dimensional precoding matrix. We assume $\mathbf{s} = \mathbf{H}\mathbf{m}$ is a $N_r \times 1$ dimensional vector and $\mathbf{s}^e = \mathbf{H}^e\mathbf{m}$ denotes the channel matrix with CEE.

We solve the simplified problem following the details in [11] which provides the complex computational process using MMSE receiver and the SINR of the target UE for the k th stream. The MMSE weight is defined as

$$\mathbf{w}^e = (\sigma_0^2 p^2 \mathbf{s}^e (\mathbf{s}^e)^* + \sigma^2)^{-1} \sigma_0^2 p^2 \mathbf{s}^e. \quad (12)$$

Because Gaussian white noise covariance is relatively small and there is a signal gain of p^2 , we can get $\sigma^2 \ll \sigma_0^2 p^2 \mathbf{s}^e (\mathbf{s}^e)^*$. Assume $\mathbf{F}^e = (\mathbf{s}^e (\mathbf{s}^e)^*)^{-1}$. Thus equation (12) is simplified as

$$\mathbf{w}^e \approx (\sigma_0^2 p^2 \mathbf{s}^e (\mathbf{s}^e)^*)^{-1} \sigma_0^2 p^2 \mathbf{s}^e = \frac{\mathbf{F}^e \mathbf{s}^e}{p}. \quad (13)$$

Define that D^e and I_{self}^e stand for desired signal component and self interference between MIMO streams, respectively.

$$D^e = \text{diag}[(\mathbf{w}^e)^* p \mathbf{s}]_{1 \times 1} = (\mathbf{w}^e)^* p \mathbf{s}. \quad (14)$$

$$I_{self}^e = (\mathbf{w}^e)^* p \mathbf{s} - D^e = 0. \quad (15)$$

The received SINR is given out as follows.

$$\begin{aligned} S^e &= \frac{\sigma_0^2 D^e (D^e)^*}{\sigma^2 (\mathbf{w}^e)^* \sigma^2 (\mathbf{w}^e + \sigma_0^2 I_{self}^e (I_{self}^e)^*)} \\ &= \frac{\sigma_0^2 D^e (D^e)^*}{\sigma^2 (\mathbf{w}^e)^* \sigma^2 \mathbf{w}^e} \\ &= \frac{\sigma_0^2 p^2 (\mathbf{s}^e)^* (\mathbf{F}^e)^* \mathbf{s} \mathbf{s}^* \mathbf{F}^e \mathbf{s}^e}{\sigma^2 (\mathbf{s}^e)^* (\mathbf{F}^e)^* \mathbf{F}^e \mathbf{s}^e}. \end{aligned} \quad (16)$$

It is clear from equation (16) that CEE makes SINR smaller, further reducing the throughput. Therefore, the key of the algorithm performance is that whose SINR is greater. Substituting equation (6) into (16), the SINR in SWA algorithm is denoted as

$$S'_t = \frac{1}{T} \sum_{i=1}^T \frac{\sigma_0^2 p^2 ((\mathbf{s}^e)^* (\mathbf{F}^e)^*)_{t-i+1} (\mathbf{s})_{t-i+1} (\mathbf{s}^*)_{t-i+1} (\mathbf{F}^e \mathbf{s}^e)_{t-i+1}}{\sigma^2 ((\mathbf{s}^e)^* (\mathbf{F}^e)^*)_{t-i+1} (\mathbf{F}^e \mathbf{s}^e)_{t-i+1}}. \quad (17)$$

Taking equation (4) into (16), we can get the SINR in HWA algorithm.

$$(S_h)_t = \frac{\sigma_0^2 p^2 [\frac{1}{T} \sum_{i=1}^T ((\mathbf{s}^e)^* (\mathbf{F}^e)^*)_{t-i+1}] (\mathbf{s})_t (\mathbf{s}^*)_t [\frac{1}{T} \sum_{i=1}^T (\mathbf{F}^e \mathbf{s}^e)_{t-i+1}]}{\sigma^2 [\frac{1}{T} \sum_{i=1}^T ((\mathbf{s}^e)^* (\mathbf{F}^e)^*)_{t-i+1}] [\frac{1}{T} \sum_{i=1}^T (\mathbf{F}^e \mathbf{s}^e)_{t-i+1}]}. \quad (18)$$

$$\lim_{T \rightarrow \infty} (S_h)_t = \frac{\sigma_0^2 p^2 (\mathbf{s}^e)^* (\mathbf{F}^e)^* (\mathbf{s})_t (\mathbf{s}^*)_t \mathbf{F}^e \mathbf{s}^e}{\sigma^2 (\mathbf{s}^e)^* (\mathbf{F}^e)^* \mathbf{F}^e \mathbf{s}^e}. \quad (19)$$

TABLE I
NUMERICAL RESULTS FOR COMPARISON OF S'_t AND $(S_h)_t$

Method	$S'_t > (S_h)_t$	$S'_t \leq (S_h)_t$
One	19.55%	80.45%
Two	19.56%	80.44%

According to the parameters configuration listed in [12] and the varying change of channels depicted in Fig. 2, the channel of UMi scenario changes relatively slowly. So, it is reasonable to assume channel state condition of UMi scenario remains the same in a long time as

$$\mathbf{s}_t = \mathbf{H}_t \mathbf{m} = \mathbf{H}_i \mathbf{m} = \mathbf{H} \mathbf{m} = \mathbf{s}, \forall i \in \mathcal{R}. \quad (20)$$

$$\lim_{T \rightarrow \infty} (S_h)_t = \frac{\sigma_0^2 p^2 (\mathbf{s}^e)^* (\mathbf{F}^e)^* \mathbf{s} \mathbf{s}^* \mathbf{F}^e \mathbf{s}^e}{\sigma^2 (\mathbf{s}^e)^* (\mathbf{F}^e)^* \mathbf{F}^e \mathbf{s}^e}. \quad (21)$$

We deal with equation (17) with equation (20).

$$S'_t = \frac{1}{T} \sum_{i=1}^T \frac{\sigma_0^2 p^2 ((\mathbf{s}^e)^* (\mathbf{F}^e)^*)_{t-i+1} \mathbf{s} \mathbf{s}^* (\mathbf{F}^e \mathbf{s}^e)_{t-i+1}}{\sigma^2 ((\mathbf{s}^e)^* (\mathbf{F}^e)^*)_{t-i+1} (\mathbf{F}^e \mathbf{s}^e)_{t-i+1}}. \quad (22)$$

Theorem: For $\mathbf{a} \in \mathbb{C}^{n \times 1}$, $\mathbf{b} \in \mathbb{C}^{n \times 1}$, thus $\mathbf{a}^* \mathbf{b} \mathbf{b}^* \mathbf{a} \leq \mathbf{a}^* \mathbf{a} \mathbf{b}^* \mathbf{b}$.

Proof: see Appendix A.

According to **Theorem**, we get $(S_h)_t < \mathbf{s}^* \mathbf{s}$ and $S'_t < \mathbf{s}^* \mathbf{s}$. To compare $(S_h)_t$ and S'_t , we work on numerical simulation about randomly scattered points in computer simulation. Two methods are applied. The first one is that $\mathbf{s}$ and $\mathbf{s}^e$ are independent zero mean complex Gaussian variables with variance 1. The second method is that $\mathbf{s}$ is the same described as method one and $\mathbf{s}^e = \mathbf{s} + \mathbf{e}$, where $\mathbf{e}$ is zero mean complex Gaussian with variance 0.001.

The simulation results are listed in Table I. $S'_t \leq (S_h)_t$ accounts for almost 80.5% and $S'_t > (S_h)_t$ only occupies 19.5% in both method one and method two. Thus we can conclude that when channel state condition change slowly, $S'_t \leq (S_h)_t$. HWA algorithm is better than SWA algorithm for slowly varying channel model as UMi.

VI. SIMULATION RESULTS

In this section, simulation results are presented. Simulation parameters are described in section III.

A. Comparisons of WA Algorithms

Considering the slow change of UMi channel, we adopt three WA algorithms in UMi scenario. We assume effective simulation time is 1000 ms and time window T is 20 ms. The covariance of e is 0, 1, 3, 5 dB, respectively. Baseline represents basic configuration without any process for comparison.

Fig. 4 shows that the largest CASE are achieved by HWA algorithm in all situations. Obviously, SWA is not effective to mitigate CEE. Through observation of SINR, we can get that SINR at each step changes rapidly because of fast varying interference. Under the situation that order of magnitude of SINR has huge difference, doing average on SINR will reduce its ability to track the instantaneous character of SINR

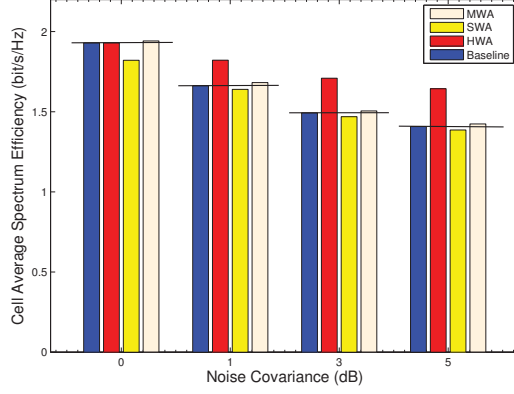


Fig. 4. Cell Average Spectrum Efficiency versus Noise Covariance (UMi scenario)

variation, which further degrades the throughput. Moreover, MWA is slightly better than baseline. Considering flexible environment of simulation, the factors, such as scheduling, HARQ and feedback time delay, will affect the performance of MWA. Meanwhile, MCS is derived after CEE undergoing a series of process of UE and eNodeB. MWA does little contribution to eliminate CEE. Thus, HWA is of great help to eliminate CEE and improve spectrum efficiency.

B. Effects of ATW Algorithm

The window size T can be calculated either on UE side or on eNodeB side. Without loss of generality, the performance of the proposed algorithms is only evaluated in UMi and RMa, which are listed in Table II. Note that the evaluations for UMa and SMa are ignored because their channel situations are similar to RMa as shown in Fig. 2.

It is observed that, for UMi scenario, the steady window size is obtained, which is 18 ms for UE side and 16 ms for eNodeB side respectively. The corresponding throughput is maximized, which is better than that of WA algorithm when T is set to 20 ms. As we can see, the steady T on UE side is smaller than that on eNodeB side. This is because, for the UE, the throughput is calculated based only on its own channel while for the eNodeB, it should consider all its serving UEs and the channels are much more complicated. The T is thus chosen to be smaller to maintain maximum instantaneous condition of all channels for the eNodeB. For RMa scenario, $T = 1$ ms stands for that its channel changes rapidly and the instantaneous character of channel is more important than the impact of CEE. This result also support the discussion about RMa>UMi presented above.

VII. CONCLUSION

Three WA algorithms on the basis of channel estimation value, SINR and MCS respectively are proposed. Among them, HWA is confirmed to compensate the impact of CEE and achieve the best performance through both theoretical derivation and simulation. In order to obtain the greatest

TABLE II
SIMULATION RESULTS OF THE ADAPTIVE TIME WINDOW ALGORITHM

Scenario	UMi		RMa	
	UE	eNodeB	UE	eNodeB
CASE (bit/s/Hz)	1.9599	1.9678	1.5409	1.5409
T in steady state	18 ms	16 ms	1 ms	1 ms

benefit from HWA, an ATW algorithm is derived which can adjust the window size T dynamically according to radio channel conditions.

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APPENDIX

We quota two Lemmas for Proof of Theorem first.

Lemma 1: Assume $\mathbf{A} = (a_{ij})_{m \times n} \in \mathbb{C}^{m \times n}$, thus $|\mathbf{A}|_F = (\sum_{i=1}^m \sum_{j=1}^n (|a_{ij}|^2))^{\frac{1}{2}} = (tr(\mathbf{A}^* \mathbf{A}))^{\frac{1}{2}}$ is Frobenius norm (one of matrix norm) on $\mathbb{C}^{m \times n}$ and we have $|\mathbf{Ax}|_2 \leq |\mathbf{A}|_F |\mathbf{x}|_2$.

Lemma 2: For $\mathbf{A} \in \mathbb{C}^{m \times n}$, $\mathbf{B} \in \mathbb{C}^{m \times l}$, $\mathbf{C} \in \mathbb{C}^{m \times l}$, $|\mathbf{A}|$, $|\mathbf{B}|$ and $|\mathbf{AB}|$ are matrix norms derived through the same rules. They meet condition that $|\mathbf{AB}| \leq |\mathbf{A}| |\mathbf{B}|$.

According to Lemma 1, $|\mathbf{a}|_F^2 = tr(\mathbf{a}^* \mathbf{a})$, $|\mathbf{b}|_F^2 = tr(\mathbf{b}^* \mathbf{b})$ and $|\mathbf{b}^* \mathbf{a}|_F^2 = tr((\mathbf{b}^* \mathbf{a})^* \mathbf{b}^* \mathbf{a})$.

Because of $\mathbf{a} \in \mathbb{C}^{n \times 1}$, $\mathbf{b} \in \mathbb{C}^{m \times 1}$, $\mathbf{a}^* \mathbf{a} \in \mathbb{C}^{1 \times 1}$, $\mathbf{b}^* \mathbf{b} \in \mathbb{C}^{1 \times 1}$, and $(\mathbf{b}^* \mathbf{a})^* \mathbf{b}^* \mathbf{a} \in \mathbb{C}^{1 \times 1}$, thus we get that as follows.

$$\begin{aligned}
 |\mathbf{a}|_F^2 &= tr(\mathbf{a}^* \mathbf{a}) = \mathbf{a}^* \mathbf{a}; \\
 |\mathbf{b}|_F^2 &= |\mathbf{b}^* \mathbf{b}|_F^2 = tr(\mathbf{b}^* \mathbf{b}) = \mathbf{b}^* \mathbf{b}; \\
 |\mathbf{b}^* \mathbf{a}|_F^2 &= tr((\mathbf{b}^* \mathbf{a})^* \mathbf{b}^* \mathbf{a}) = (\mathbf{b}^* \mathbf{a})^* \mathbf{b}^* \mathbf{a}.
 \end{aligned}$$

According to lemma 2, $|\mathbf{b}^* \mathbf{a}|_F \leq |\mathbf{a}|_F |\mathbf{b}|_F = |\mathbf{a}|_F |\mathbf{b}|_F$. Thus $\mathbf{a}^* \mathbf{b} \mathbf{b}^* \mathbf{a} = (\mathbf{b}^* \mathbf{a})^* \mathbf{b}^* \mathbf{a} \leq \mathbf{a}^* \mathbf{a} \mathbf{b}^* \mathbf{b}$. The proof of Theorem is completed.

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APPENDIX CHEN09



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A Novel Hybrid CQI Feedback Method For Throughput Improvement In 3GPP LTE Systems



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Abstract

Frequency Selective Scheduling (FSS) is a prominent characteristic in 3GPP LTE systems. Frequency scheduling depends on Channel Quality Indicator(CQI) feedback report by mobile station. CQI being control information must use minimal bits maintaining the performance of system. This paper recommends a new CQI feedback method which uses existing schemes for improvement of performance of system. It throws light on enhancing throughput of Distributed Haar scheme with suitable usage of Best-M scheme. Proposed technique improves throughput while maintaining overhead reduction achieved by Haar compression schemes. Performance results indicate noticeable rise in throughput of the system as compared to Distributed Haar technique.

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Keywords

3GPP LTE CQI, LTE uplink feedback, Distributed Haar feedback, Best-M feedback.

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A Novel Hybrid CQI Feedback Method For Throughput Improvement In 3GPP LTE Systems

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Abstract— Frequency Selective Scheduling (FSS) is a prominent characteristic in 3GPP LTE systems. Frequency scheduling depends on Channel Quality Indicator(CQI) feedback report by mobile station. CQI being control information must use minimal bits maintaining the performance of system. This paper recommends a new CQI feedback method which uses existing schemes for improvement of performance of system. It throws light on enhancing throughput of Distributed Haar scheme with suitable usage of Best-M scheme. Proposed technique improves throughput while maintaining overhead reduction achieved by Haar compression schemes. Performance results indicate noticeable rise in throughput of the system as compared to Distributed Haar technique.

Keywords— 3GPP LTE CQI, LTE uplink feedback, Distributed Haar feedback, Best-M feedback.

I. INTRODUCTION

This 3GPP Long Term Evolution(LTE) adopts interesting OFDMA air interface for proper management of available spectrum [1]. OFDMA permits simultaneous downlink transmission on different frequency channels for different users. e-NodeB (base station) schedules users for allotment of frequency channels. Each frequency channel is group of subcarriers known as sub-band. This frequency scheduling requires channel quality information from every user.

Channel Quality Indicator (CQI), an integer value ranging from 1 to 15, indicates quality of each sub-band by computing its SINR value [2]. This CQI-SINR mapping could also consider multipath delay spread [3]. Reference signals are transmitted from time to time by e-NodeB to user equipment for CQI measurement. UE sends back CQI value to e-NodeB with one of the feedback method [4]. CQI feedback information being the control information, must use minimum possible bits. Use of lower number of bits which could be achieved by feedback of partial information, leads to declination of average throughput of the system [5]. A balance has to be struck between overhead bits and throughput of the system.

Many CQI feedback methods have been proposed which could be broadly categorized as full band & sub-band methods [6]. In full band methods, CQI for entire bandwidth is fed back to e-NodeB. For this, certain compression scheme was also been used [7]-[8]. Sub-band methods transmit partial CQI information to e-NodeB. Best-M individual method, one of the sub-band method, transmits best M CQI values along with average CQI value of remaining bands [9]-[10]. Another method employs haar compression in distributed fashion with

best-M individual method [11]. Both these methods have been used for hybrid method.

This paper is structured as follows : Section II explains best-M individual & distributed haar best-M individual methods. Limitation of distributed haar best-M individual method is detailed in section III. Proposed method is explained in section IV. Analysis of this method is investigated in section V. This work is concluded in section VI.

II. BEST-M INDIVIDUAL & DISTRIBUTED HAAR

A. Best-M Individual

Best-M individual is perhaps the best feedback amongst sub-band schemes as far as balance between throughput & overhead reduction is concerned. In this method, best M CQI values are fed back along with average CQI of remaining bands. Value of M doesn't exceed one-third of the total active bands. Label indicating M bands which are reported is also fed back.

B. Distributed Haar Best-M individual

This feedback method was proposed for overhead reduction. In this method, all active sub-bands were divided into odd & even groups. For each of the group, best M CQI values were separated out. Haar transform was applied on array of these best M values. Transformed Haar coefficients were quantized & allotted variable length code words. More bits were allotted for approximate (first) coefficient while lesser bits were allotted to remaining coefficients. This statistical distribution which is explored in quantization process, forms the basis for overhead reduction. Moreover, distributed fashion of reporting allows lower M which in turn allows lesser number of CQI values to be transmitted in each reporting interval. Hence this method reduces overhead as compared to best-M individual method.

III. LIMITATION OF DISTRIBUTED HAAR BEST-M INDIVIDUAL SCHEME

In [11], it was shown that throughput for distributed haar scheme was more than other feedback schemes at around 10 bits/TTI. However for a particular reporting interval (RI) best-M individual scheme provides better throughput over distributed haar scheme. Although distributed haar scheme provides overhead reduction up-to 10bits/TTI, it fails to provide better throughput, when it comes to comparison with other schemes at a particular reporting interval. This limitation of distributed haar is explored here.

Limitation of distributed haar feedback scheme lies in grouping of CQI values prior to selection of best-M values. This could be explained considering an example. Consider 10 sub-bands with CQI values as shown:

Sub-band Number	1	2	3	4	5	6	7	8	9	10
CQI value	13	12	14	10	5	8	8	7	4	5

Let us apply above explained distributed haar scheme with M=3. Thus it first divides bands into even and odd groups.

13	14	5	8	4
12	10	8	7	5

Applying Best-M individual with M=3 for each group, following set of values are to be transmitted.

14	13	8
12	10	8

Haar compression is applied on these values and are transmitted separately in two consecutive reporting intervals.

Now applying Best-M individual on same 10 bands with M=4 we have

14	13	12	10
----	----	----	----

As observed lower CQI values such as 8 are part of distributed haar scheme whereas these values are avoided in best-M individual scheme, lowest value being 10.

After scheduling at e-NodeB, user equipment (UE) might carry out its downlink data transmission on channels with one of lower CQI values, as in case of distributed haar scheme. Due to this, throughput offered for distributed haar scheme could be lower than that for best-M individual scheme.

This explanation shows that best M band values need not be the only values to be part of feedback in case of distributed haar scheme. Some lower CQI values may be part of this feedback.

IV. HYBRID FEEDBACK METHOD

In this method, best M bands are first separated out from all bands to be reported. Then these bands are distributed in two groups & transmitted after haar compression.

The step by step hybrid method can be summarized as follows:

1. Get the full CQI report (CQI for all bands) & get value of M which is decided by eNodeB.
2. Separate out top M CQI values.
3. Divide these values into two groups so as to transmit in distributed fashion.
4. Get average CQI of unreported bands for each group.

5. Apply haar transformation on both these groups. Details of haar transformation on CQI array are given in [11].
6. Transmit these groups in two consecutive reporting intervals along with their labels.

The key point in this method is to apply best-M individual method first & then apply haar compression as against distributed haar best-M individual method which uses the other way round approach.

Consider an example for method with M=4 & 10 sub-bands.

Sub-band Number	1	2	3	4	5	6	7	8	9	10
CQI value	12	2	4	13	5	11	8	9	14	6

Separating out top 4 CQI values

Sub-band Number	9	4	1	6
CQI value	14	13	12	11

Divide into odd & even groups and also compute average CQI for unreported bands.

Sub-band Number	9	1	Average CQI of unreported bands
CQI value	14	12	7

Sub-band Number	4	6	Average CQI of unreported bands
CQI value	13	11	7

Apply haar transformation on these groups & transmit in two reporting intervals along with labels indicating location of bands in each group.

V. PERFORMANCE ANALYSIS FOR HYBRID FEEDBACK METHOD

Hybrid method could be analysed depending on number of best M bands reported. Specifically, M above & below certain value leads to different behaviour of this method. Throughput for various feedback methods was compared with hybrid method as part of performance analysis. Various parameters

considered for simulation are shown below. Performance simulation was done for 3kph & 15kph UE speed's.

Table I: SIMULATION PARAMETERS

Parameters	Values
System bandwidth	10 MHz
RB bandwidth	180 kHz
Carrier frequency	2 GHz
Scheduler	Proportional Fair
Number of TX antennas	1
Number of Rx antennas	2
Channel model	Pedestrian B
UE speed	3km/h, 15km/h
CQI feedback delay	2 TTIs
FFT size	1024
Number of sub-carriers	600
Target BLER	10%

Value of M is decided by e-NodeB for each of its users considering various factors. Performance of hybrid scheme depends on value of M.

A. Lower M (less than 6)

Number of minimum bands reported in single reporting interval for distributed haar best-M individual scheme generally are 3. Hence for schemes with best bands lesser than 6 provide lesser throughput for distributed scheme than hybrid scheme. For 3 bands in each reporting interval, total 6 bands are reported by distributed haar scheme & hybrid scheme. If best M CQI bands are less than 6, then distributed haar would report even low CQI values along with best M values, as explained in section III. The limitation of distributed haar scheme explained in section III finds its place in this case. It was observed that hybrid method provided better throughput than distributed haar scheme in this case. Hence maintaining the overhead reduction by distributed haar scheme, its throughput was seen to do better.

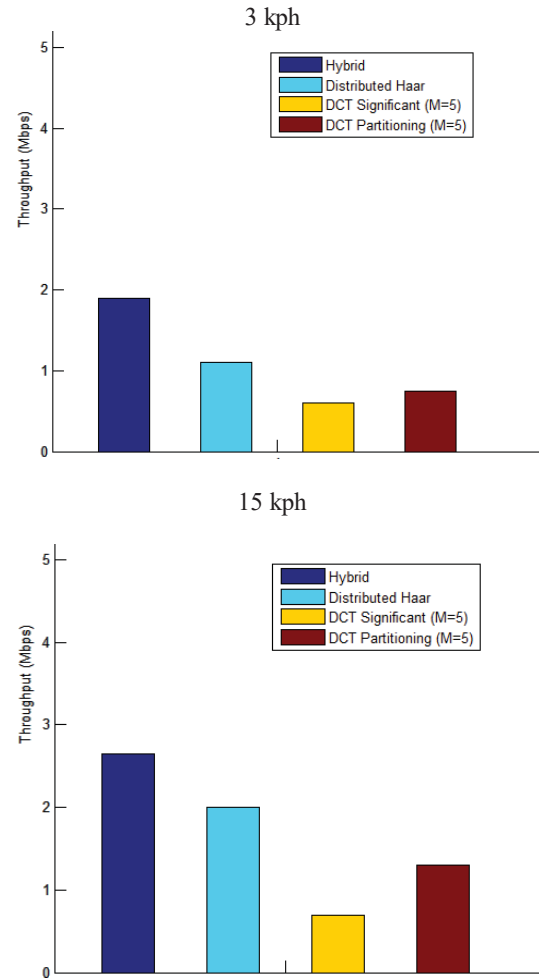


Figure 1: Throughput comparison for UE speeds of 3kph & 15kph for lower M (less than 6)

B. Higher M (higher than equal to 6)

For best M CQI bands greater than 6, there is a higher probability that distributed haar scheme would have only best M values as a part of its feedback. However, this depends on order of occurrence of these values, as even & odd grouping is done prior to haar transformation. It was hence observed that hybrid method provided smaller improvement in throughput over distributed haar method, as compared to the previous case.

VI. CONCLUSIONS

This paper proposes a new hybrid CQI feedback method for LTE systems. This method used best M individual & distributed haar best M individual method for its formation. This method primarily aimed at improving the existing distributed haar method. The limitation of distributed haar method was analyzed in this paper & hybrid method was suggested to overcome that limitation. Application of best M individual method first & then haar compression forms the basis for hybrid method. It was shown that proposed method improves throughput of distributed haar method under different values of M. It was also shown that hybrid method responded differently for two different ranges of M. As hybrid method used distributed haar scheme, it maintained the overhead reduction, at the same time it improved throughput. Thus hybrid method was seen as one of the best balance between overhead reduction & throughput.

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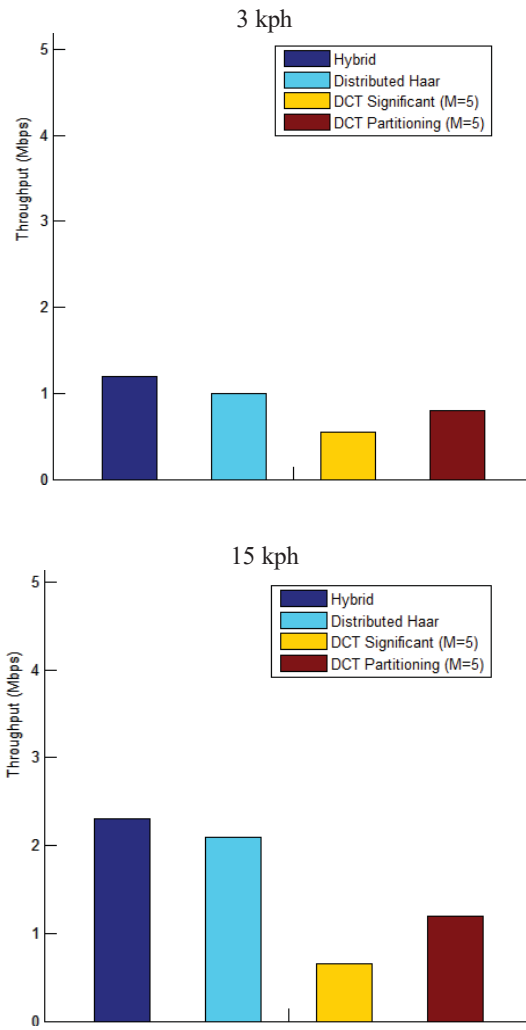


Figure 2: Throughput comparison for UE speeds of 3kph & 15kph for higher M (greater than equal to 6)