

IPR2023-01414
Patent Owner
EX 2001

UNITED STATES PATENT AND TRADEMARK OFFICE

BEFORE THE PATENT TRIAL AND APPEAL BOARD

MEDIATEK INC. and NXP USA, INC.,

Petitioner,

v.

BELL NORTHERN RESEARCH, LLC,
Patent Owner

Case: IPR2023-01414
U.S. Patent No. 8,416,862

EXHIBIT 2001

**DECLARATION OF TODOR V. COOKLEV, PH.D. IN SUPPORT OF
PATENT OWNER'S RESPONSE**

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I. INTRODUCTION

1. My name is Todor V. Cooklev. I am an expert in mobile telecommunications and wireless technology. I have been retained as an expert witness to provide my independent opinion regarding certain matters at issue in *inter partes* review of U.S. Patent No. 8,416,862 (“the ’862 patent”) in IPR2023-01414. I have been retained by Bell Northern Research, LLC (“BNR”), the Patent Owner in the above proceedings. Petitioner is NXP USA, Inc. (collectively “Petitioner”).

2. For my work on this case, I am being compensated for my time at my typical consulting rate of \$650 per hour. I am also being reimbursed for expenses that I incur during the course of this work. My compensation does not depend on the substance of my opinions or the outcome of any issues in this case.

3. My analysis of the materials produced in this matter is ongoing and I will continue to review any new material as it is provided. This declaration represents only those opinions I have formed to date. I reserve the right to amend or supplement my opinions based on additional documents or evidence I am presented, including without limitation any arguments or expert declarations advanced by Petitioner in this case.

4. I am not a legal expert and offer no opinions on the law. However, I have been informed by counsel of the various legal standards that apply, and I have applied those standards in arriving at my conclusions.

II. QUALIFICATIONS

5. I am currently the Professor in the Department of Electrical and Computer Engineering at Purdue University in Fort Wayne, Indiana, where I have had several faculty and administrative positions.

6. My teaching responsibilities have included courses in communication systems and networks, signals and systems, software-defined radio, and digital signal processing. My research interests include most aspects of modern wireless systems, including hardware and software architectures. A significant part of my research is specifically focused on standards-related issues. I have received a number of research grants in these areas.

7. I am a named inventor on more than thirty U.S. patents, most of which relate to the hardware or software aspects of communication systems. In 1999, I was inducted into the Purdue Inventors Hall of Fame. I have also authored and co-authored more than one hundred peer-reviewed articles. I am the author of the textbook "Modern Communications Systems: A First Course", published by the University of Michigan in 2024 that is quickly being adopted by a number of

electrical engineering programs. A list of my publications and patents appears in my *curriculum vitae* attached as Appendix 1 to this Declaration.

8. I graduated from the Technical University of Sofia, Bulgaria in 1988 with a Diploma of Engineering in the field of Electrical Engineering. I graduated from Tokyo Institute of Technology in Tokyo, Japan in 1995 with a Doctor of Philosophy (Ph.D.) degree in Electrical Engineering.

9. My experience is not only academic. I have worked in the computer and data communications industries. I worked in research and development, but also contributed to product firmware and software development, including digital signal processing algorithms for communication systems.

10. I have contributed to the development of several major standards for communication systems and numerous amendments, including Bluetooth, DSL, Wi-Fi, cellular, and military radio systems. I have participated in many meetings of standards committees and I have chaired some committee meetings and served in other leadership roles.

11. From 2000 to 2002, and from 2005 to 2008 I was a Voting Member of the IEEE 802.11 Working Group and attended almost all meetings during those years. Generally, meetings were held every other month. During that time, I prepared, submitted, and presented documents to IEEE 802.11. On a couple of

occasions, I was involved in the drafting of liaison letters between 802.11 and other standards committees.

12. From 2005-2006 to around 2007-2008 I was Chair of a Study Group within 802.11 until I convinced the entire Working Group to approve the creation of another Task Group. For my work I received an IEEE Standards Association award in 2012.

13. Even after 2008 I continued my involvement with 802.11. For example, until about 2020 I was reviewing and voting on most amendments to IEEE 802.11.

14. In 2020 I was elected to serve on the Board of Governors of the IEEE Standards Association as Member-at-Large. The Board of Governors provides overall leadership of the IEEE Standards Association.

15. Since 2017 I have been the Series Editor for Wireless and Radio Communications for the IEEE Communications Standards Magazine (which is the premier journal in the field of communication standards). As member of the Editorial Board I coordinate the review of scholarly manuscripts that relate to the most recent communications standards.

16. A detailed record of my professional qualifications is set forth in Appendix 1 to this Declaration, which is my *curriculum vitae*, including a list of publications, awards, courses I teach in electrical and computer engineering

subjects, research grants, and professional activities. My *curriculum vitae* also lists the depositions, hearings, and trial at which I have testified.

17. Consequently, I have extensive experience in singular-value decomposition, beamforming, and multiple-input multiple-output (MIMO) wireless systems that are described in the prior-art references used by Petitioner.

18. I have considered the following materials in preparing the opinions set forth in this Declaration:

- a. the IPR Petition in this proceeding and all exhibits accompanying the Petition;
- b. the '862 patent, including the abstract, specification, claims, and figures;
- c. the prior art references relied on in each Ground of the Petition;
- d. the Declaration of Petitioner's expert Dr. Wells;
- e. the Board's Institution Decision;
- f. the June 20, 2024 deposition transcript of Dr. Wells; and
- g. all other materials cited or discussed in this Declaration.

19. I have also relied on my knowledge, education, and professional expertise of over 25 years in the areas of singular-value decomposition, beamforming, and multiple-input multiple-output (MIMO) wireless systems.

III. LEGAL STANDARDS

20. I am not a lawyer, and I do not intend to offer any opinions as to the interpretation of the law. When considering the '862 patent and stating my opinions, I rely on the following legal standards as described to me by the attorneys for Patent Owner.

21. Moreover, I only consider such legal standards in framing my opinions and conclusions as well as placing assertions made by Petitioner in the Petition into the proper context. Additionally, from a subject matter perspective, I understand that the petitioner always has the burden of persuasion regarding a challenge of patentability of an invention under an inter partes review.

22. Specifically, I understand that to prevail in its challenge to the patentability of the challenged claims, Petitioner must establish facts supporting its challenge by a preponderance of the evidence.

23. I further understand that to the extent that the petition relies on an expert declaration, it must be more than conclusory and disclose the facts underlying the opinion.

A. Priority Date of a Patent

24. I understand that the analysis of alleged obviousness of the Patent should be performed from the perspective of a POSITA as of the priority date of the Patent. The Patent claims priority to June 28, 2005. My opinions in this matter

are from the perspective of a POSITA as of that date; however, my opinions do not change if the priority date is slightly changed.

B. Level Of Ordinary Skill In The Art

25. My opinions in this declaration are based on the understandings of a person of ordinary skill in the art, as of the time of the invention. I understand that the person of ordinary skill in the art is a hypothetical person who is presumed to have known the relevant art at the time of the invention. By “relevant,” I mean relevant to the challenged claim of the '862 patent.

26. I understand that various factors should be considered when determining the person of ordinary skill in the art in connection with a particular patent. I understand that these factors include, without limitation, the type of problems encountered in the art, the prior solutions to those problems found in the prior art references, the rapidity with which innovations are made, the sophistication of the technology, the level of education of active workers in the field, and my own experience working with those of skill in the art at the time of the invention.

27. I am readily familiar with the level of ordinary skill in the art as of the priority date of the '862 patent. Based on my experience, education, and training, I met the definition of a POSITA as of the priority date of the '862 patent.

Moreover, my qualifications at that time far exceeded that of a POSITA, and I had

worked with, as well as supervised, many POSITAs throughout my work in the field. My opinions concerning the '862 patent claims and the prior art are from the perspective of a POSITA, as set forth above.

28. As further discussed below, my opinions as stated in this declaration are valid even if the Board adopts a slightly different level of ordinary skill in the art.

29. I understand the Board preliminarily adopted a level of skill in the art based on the level of skill proposed by Petitioner. (D.I. 11 at 7-8.) Specifically, the Board determined that a person of ordinary skill in the art ("POSITA") at the time of invention would have had a Bachelor's degree in Electrical Engineering, Computer Engineering, Computer Science, or a related field, and at least 2 years of experience in the field of wireless communication, or had equivalent education, work, or experience in this field.

30. For purposes of this Declaration, I adopt the Board's definition of a person of ordinary skill to the extent it does not purport to substitute experience for education. For example, I understand that Petitioner's expert, Dr. Wells, testified that his opinion as to the level of ordinary skill contemplates that "substantial experience could substitute for some of the educational background," including the requirement that a POSITA possess a Bachelor's degree. (EX2002 at 26:6-17.) In my opinion, this definition is unworkable. The wireless communications and

matrix algebra concepts described and claimed by the '862 patent would require at least a bachelor's degree to appreciate. However, under either definition of the level of ordinary skill, Petitioner has failed to meet its burden.

C. Obviousness Legal Standard

31. I understand that a patent claim is unpatentable if the claimed invention would have been obvious to a person of ordinary skill in the art at the time of the invention.

32. I understand that an obviousness analysis involves comparing a claim to the prior art to determine whether the claimed invention would have been obvious to a person of ordinary skill in the art at the time of the invention in view of the prior art and in light of the general knowledge in the art as a whole. I also understand that obviousness is ultimately a legal conclusion based on underlying facts of four general types, all of which must be considered: (1) the scope and content of the prior art; (2) the level of ordinary skill in the art; (3) the differences between the claimed invention and the prior art; and (4) any objective indicia of non-obviousness, including any praise of the invention. Objective indicia of non-obviousness may include, for example, commercial success of an embodiment, a long-felt need, skepticism, failure by others to find the solution provided by the claimed invention, copying by others of the subject matter of the claim

invention, unexpected results of the claimed invention, acceptance of others and industry praise, and licensing of the patents.

33. I also understand that obviousness may be established under certain circumstances by combining or modifying the teachings of the prior art. However, I have been informed that a claim is not proved obvious merely by demonstrating that each of the elements was independently known in the prior art. I have been informed that many, if not all, inventions rely on building blocks already previously known, and claimed discoveries almost of necessity will likely be combinations of what is already known. I have been informed that it is important to identify whether a reason existed at the time of the invention that would have motivated a person of ordinary skill in the art in the relevant field to combine the known elements in the way the claimed invention does. Specific teachings, suggestions, or motivations to combine any first prior art reference with a second prior art reference can be explicit or implicit, but must have existed before the date of purported invention. I understand that prior art references themselves may be one source of a specific teaching or suggestion to combine features of the prior art, but that such suggestions or motivations to combine art may come from the knowledge that a person of ordinary skill in the art would have had.

34. I understand that a reference may be relied upon for all that it teaches, including uses beyond its primary purpose, but also including teachings that lead

away from the invention. I understand that a reference may be said to teach away when a person of ordinary skill, upon reading the reference, would be discouraged from following the path set out in the reference, although the mere disclosure of alternative designs does not teach away.

35. I further understand that whether there is a reasonable expectation of success in combining references in a particular way is also relevant to the analysis.

36. I understand that it is improper to use hindsight to combine references or elements of references to reconstruct the invention using the claims as a guide. My analysis of the prior art is made from the perspective of a person of ordinary skill in the art at the time of the invention.

37. I am not offering any legal opinions in this declaration nor am I qualified to do so. I only consider such legal standards in framing my opinions and conclusions as well as placing assertions made by Petitioner in the Petition into the proper context. Additionally, from a subject matter perspective, I understand that the petitioner always has the burden of persuasion regarding a challenge of patentability of an invention under an inter partes review.

IV. TECHNOLOGY OVERVIEW

A. Beamforming

38. A beam is the main lobe of the radiation pattern of an antenna array. Beamforming is a method used to focus the radio signal in a given direction similar

to a flashlight. The transmitting device is called a beamformer. The receiving device is called a beamformee. Without beamforming, power is transmitted in many directions according to the properties of the antenna, so a signal intended for one user reaches other users. With beamforming, the power is transmitted mainly in the direction of the intended receiver. Beamforming involves multiple antennas and the ability to adjust the amplitudes and phases of the signals transmitted or received by the multiple antennas.

39. Because the radio signal is focused in a certain direction, beamforming leads to a higher Signal-to-Interference Noise Ratio (SINR). In turn, a higher SINR allows higher-order modulation and/or higher-rate coding to be used, which, in turn, leads to higher throughput.

40. Beamforming requires at least the beamformer to have multiple antennas and is generally implemented in multi-antenna systems like Multiple-Input Multiple-Output (MIMO) systems. Because beamforming is used in a multi-user (MU) environment, it is also described as MU-MIMO. Further, DL-MU-MIMO generally refers to beamforming in the downstream direction (from the access point to a client device) and UL-MU-MIMO refers to beamforming in the upstream direction (from a client device to the access point). Client devices may be referred to as stations (STA).

B. Beamforming According to the 802.11 Standards

41. IEEE 802.11ac specifies an interoperable approach to beamforming by requiring a single method for sounding and feedback. This enables interoperable beamforming among the products of different vendors. IEEE 802.11ac is also referred to as Very-High Throughput (VHT).

42. The IEEE 802.11ac standard defines only explicit feedback, where beamformees transmit the results of channel estimation. In MIMO systems the channel is a matrix. The full matrix includes amplitude and phase for each pair of transmit and receive antennas, and each orthogonal frequency division multiplexing (OFDM) subcarrier. The standard defines compression as a way to reduce the amount of feedback.

43. Transmit beamforming and DL-MU-MIMO require knowledge of the channel state to compute a steering matrix that is applied to the transmitted signal to optimize reception at one or more receivers. The STA transmitting using the steering matrix is called the VHT beamformer, and a STA for which reception is optimized is called a VHT beamformee.

C. The '862 Patent

44. The '862 patent resulted from the pioneering efforts of Messrs. Aldana and Kim (hereinafter "the Inventors") in the area of wireless communications systems using beamforming. These efforts resulted in the development of a method

and system for the efficient estimation of a channel response and for feedback of channel information in a closed loop beamforming wireless communication system.

45. Channel estimation refers to the process of determining the characteristics or parameters of the wireless channel through which data is transmitted. The wireless channel is subject to various impairments such as multipath fading, noise, and interference, which can distort the transmitted signal.

46. Channel estimation in a wireless communication system may involve using known training symbols to analyze how the wireless channel affects the transmitted signals. Training symbols are known sequences of symbols that are inserted into the transmitted signal specifically for the purpose of channel estimation. These symbols are designed to have known properties at the transmitter. At the receiver, these symbols are received after passing through the wireless channel, which introduces various effects. The receiver uses the received training symbols to estimate the characteristics of the channel. This typically involves comparing the known transmitted symbols with the received symbols. By analyzing the differences and distortions (such as phase shifts, amplitude changes, and delay spreads), the receiver can estimate parameters such as its amplitude response, phase response, delay spread, and signal to noise ratio.

47. The '862 patent inventors recognized that using training symbols throughout the wireless transmission, such as interspersed with data symbols,

increased the overhead associated with performing channel estimation. As the channel characteristics are constantly changing, the channel was being estimated every time training symbols were received. This had the effect of reducing channel throughput.

48. To address this shortcoming in the prior art, the inventors proposed to incorporate a sequence of training symbols into the preamble of a wireless transmission, prior to the transmission of data carriers containing payload data. The inventors recognized that transmitting training symbols as a preamble sequence, rather than scattered throughout the data transmission, offered several advantages. First, by placing training symbols at the beginning of the transmission (in the preamble), the receiver can quickly synchronize its timing and frequency parameters with the transmitter. This ensures that subsequent data symbols can be correctly interpreted and decoded without ambiguity. Second, since the preamble is transmitted before the actual data, the receiver can use these known symbols to accurately estimate channel parameters such as amplitude and phase per subcarrier. This allows the receiver to adapt its reception techniques accordingly, mitigating the effects of channel impairments like multipath fading and noise. Third, placing training symbols in a dedicated preamble *sequence* makes the channel estimates less impacted by noise. This leads to more accurate channel estimation and subsequently better reception performance for the data symbols that follow. Finally, by

concentrating training symbols in a preamble, the overall complexity is reduced, and the efficiency of the transmission process is improved by reducing the complexity of both transmission and reception processes and reducing overhead due from additional signaling and synchronization mechanisms.

49. The inventors further recognized that the amount of beamforming feedback information was a significant problem. For instance, in a 2x2 MIMO OFDM wireless communication, the feedback per tone needs four elements that are all complex Cartesian coordinate values V_{11} , V_{12} , V_{21} , and V_{22} . In general, $V_{ik}=a_{ik}+j*b_{ik}$, where a_{ik} and b_{ik} are values between -1, 1. Thus, with 1 bit for each of the real and imaginary components, a_{ik} and b_{ik} can be either -1/2 or +1/2, which requires $4 \times 2 \times 1 = 8$ bits per tone. With 4 bits for the real and imaginary components the total number of bits required is 1728 (e.g., $4 \times 2 \times 54 \times 4 = 1728$, 4 elements per tone, each with real and imaginary components, 54 data tones per symbols, and 4 bits per element), which requires overhead for a packet exchange that is too large for practical applications.

50. The Inventors conceived of the invention claimed in the '862 patent as a way to reduce beamforming feedback information for wireless communications.

51. For example, the Inventors developed a method for feeding back transmitter beamforming information from a receiving wireless communication device to a transmitting wireless communication device, the method comprising: the

receiving wireless communication device receiving a preamble sequence from the transmitting wireless device; the receiving wireless device estimating a channel response based upon the preamble sequence; the receiving wireless device determining an estimated transmitter beamforming unitary matrix (V) based upon the channel response and a receiver beamforming unitary matrix (U); the receiving wireless device decomposing the estimated transmitter beamforming unitary matrix (V) to produce the transmitter beamforming information; and the receiving wireless device wirelessly sending the transmitter beamforming information to the transmitting wireless device.

52. For example, a beamformer conforming to the 802.11ac standard initiates channel sounding (i.e., transmitting known signals to characterize the wireless channel) by transmitting a Null Data Packet Announcement (“NDPA”) frame with a Null Data Packet (“NDP”) frame. A VHT beamformee conforming to 802.11ac calculates the channel response based on the NDP. The VHT beamformee sends back a transformed estimate of the channel state to the VHT beamformer. The VHT beamformer then uses this estimate, perhaps combining estimates from multiple VHT beamformees, to derive a steering matrix and adapt its beamforming strategies.

53. The Inventors further developed a method for producing the transmitter beamforming feedback matrix (V) in Cartesian coordinates, then converting the

feedback matrix (V) to polar coordinates before sending it to the transmitter. This approach takes advantage of the unitary property of the matrix V and offers the advantage of reducing the amount of feedback information that is sent to the beamformer, thus fulfilling an important objective of the '862 patent.

V. CLAIM CONSTRUCTION

54. I understand that claims in a post-grant review are construed using the same claim construction standard as in a civil action. Under this standard, claims terms are generally given their ordinary and customary meaning as understood by a person of ordinary skill in the art (“POSITA”) at the time of the invention.

55. I further understand that claim terms are interpreted as they would have been interpreted by a person of ordinary skill in the art at the time of the invention, in light of the specification and the patent’s prosecution history in the patent office.

56. With respect to the term “a baseband processing module operable to . . .,” Petitioner correctly noted that both a district court and the Board found the term should not be interpreted under §112, ¶6. I agree that §112, ¶6 does not apply. However, if the Board decides this term is means-plus-function, EX1001 at Figs. 2-5 (e.g., baseband processing modules 64 and 76 in Fig. 2, 100 in Fig. 3, 100-RX in Fig. 4, and 100-TX in Fig. 5), and 5:4-12:45, are examples of specific portions of the specification that describe the structure corresponding to the recited baseband processing.

57. With respect to the term “a plurality of Radio Frequency (RF) components,” I agree that the Board need not construe this term.

58. With respect to the term “decompose the estimated transmitter beamforming unitary matrix (V) to produce the transmitter beamforming information,” Petitioner noted that both a district court and the Board found that no construction was necessary. Pet. at 14. I agree that no construction is necessary.

59. I understand Petitioner does not proffer a construction for any other terms of the challenged claims or, to the extent it relies on a plain and ordinary meaning, identify what that meaning would be.

60. For example, the Petition fails to specify what constitutes the plain and ordinary meaning of “preamble” or “preamble sequence” in independent claims 1 and 9, or of “produc[ing] the estimated transmitter beamforming unitary matrix (V) in Cartesian coordinates” and “converting the estimated transmitter beamforming unitary matrix (V) to polar coordinates” in dependent claims 2 and 10, which are relevant to the deficiencies in Petitioner’s obviousness arguments.

61. I understand that at deposition, Petitioner’s expert Dr. Wells offered, for the first time, a plain and ordinary meaning of the term “preamble sequence” to mean “a distribution of information that is sent before something else.” (EX2002 at 52:24-53:4.) However, the phrase “distribution of information” is not only vague, but not a proper technical term. Specifically, the phrase “distribution of information” is not

a term of art. It is overly vague to a POSITA. I am not aware of any textbook that has used this term in this context.

62. A POSITA would have learned the term “distribution” from probability theory. Two major examples are “Gaussian distribution” and “uniform distribution.” These terms are also described in all textbooks on communications systems. Neither Gaussian nor uniform distribution fit the definition of a preamble sequence in this context.

63. I note that if by “distribution” Dr. Wells means how the information is spread, a preamble used for channel estimation (the only preamble in the context of the '862 patent) does not carry any payload information. Furthermore, it is nonsensical for a preamble to be a “distribution” or “the way information is spread” and at the same time “sent before something else.”

64. If “distribution” means Gaussian distribution, “a distribution of information that is sent before something else” is nonsensical.

65. Dr. Wells's definition also does not specify how long “before something else” the preamble must be sent. I note that as a general matter, every packet is “information sent before something else,” but every packet and every symbol are not a preamble sequence. For example, a transmission that is sent a day or an hour before OFDM symbols carrying payload data cannot be a preamble. Otherwise the

channel estimates would become stale because the channel would have changed by the time the data symbols are transmitted.

66. Consequently, Petitioner's expert is applying a technically incorrect "plain and ordinary meaning." Further, Dr. Wells did not elaborate as to what a "preamble sequence" must "be sent before." Nor did he opine in his declaration or at deposition how the term "preamble" differs from a "preamble sequence."

67. Moreover, Dr. Wells himself later contradicted the definition that he proffered. For example, he testified that "Preamble, if it was related to the data, it would come before. If the preamble has nothing to do with the data, it can come anywhere." (EX2002 at 76:8-11.) But this latter statement directly contradicts his initial interpretation that a preamble must be "sent before something else."

68. To be used for channel estimation, a preamble sequence must be known to the receiver. In other words, a preamble sequence is not itself actual (i.e., payload) data, but is sent before the payload data. Dr. Wells does not provide any basis why, in the context of the claimed inventions, a preamble would have "nothing to do with data" or "come anywhere."

69. The plain and ordinary meaning of the term "preamble," as understood by a POSITA in the context of the '862 patent, is "a segment, at the beginning of a transmission, containing information that is expected (i.e., known *a priori*) by the

receiver.” The preamble is therefore distinct from payload data, which is not known in advance by the receiver.

70. The plain and ordinary meaning of the term “preamble sequence,” as understood by a POSITA, is “two or more training symbols in the preamble.” (EX1001 at Figs. 7, 8 and their descriptions.)

71. The plain and ordinary meanings of the term “preamble” and “preamble sequence” are consistent with the disclosure of the '862 patent, in which it is explained how estimating channel response “from the preamble sequence” involves “comparing received training symbols of the preamble to corresponding expected [i.e., known *a priori*] training symbols” (EX1001 at 13:40-44 (emphasis and parenthetical added); FIG. 7 (step 702); and FIG. 8 (step 802).)

72. There is antecedent basis for the term “the transmitter beamforming information” in claim element [9f]. When viewed in light of the claims as a whole and the specification, a POSITA would understand what is meant by the term “the transmitter beamforming information” with reasonable certainty. First, viewing claim 9 as a whole, a POSITA would understand that the term refers to the product of the mathematical decompositions of the estimated transmitter beamforming unitary matrix (V) recited in the claim.

73. Second, comparing claims 1 and 9, a POSITA would understand that the term “the transmitter beamforming information” in claim 9 mirrors the term “the

transmitter beamforming information” in claim 1, for which there is undeniably antecedent basis in the preamble. The plain language of both claims is functionally identical,¹ with the difference being that claim 1 is a method claim for feeding back transmitter beamforming information from a wireless communication device, while claim 9 recites a “wireless communication device” operable to do the same thing. A POSITA would therefore understand that the term “the transmitter beamforming information” in claim 9 means the same thing as the term “the transmitter beamforming information” in claim 1.

74. Third, a POSITA, reading the '862 patent specification, would immediately understand that “the transmitter beamforming information” in claim 9 refers to the feedback information that is sent by a receiving device to a transmitting device and used by the transmitting device to generate a new beamforming matrix (V) that is used for subsequent transmissions. (*See, e.g.*, EX1001 at Figs. 7 and 8, 10:2-7, 12:56-60, 13:25-14:46.) I understand from counsel that even if there is a lack of an antecedent basis, that does not render a claim indefinite as long as the claim apprises one of ordinary skill in the art of its scope and, therefore, serves the notice function required by § 112 ¶ 2. That is precisely the situation here.

¹ The corresponding language in claim 1 recites: “the receiving wireless device decomposing the estimated transmitter beamforming unitary matrix (V) to produce the transmitter beamforming information.” (EX1001 at cl. 1.)

VI. PETITIONER HAS FAILED TO SHOW THAT ANY CHALLENGED CLAIM WAS OBVIOUS

75. For the following reasons, Petitioner has not demonstrated that the challenged claims of the '862 patent are invalid by a preponderance of the evidence.

A. Petitioner Fails to Show That The Cited Art Discloses Estimating a Channel Response Based Upon a Preamble Sequence (Grounds 1-5; Claims 1-4, 9-12)

76. All of the challenged claims in the '862 patent require a channel response to be estimated based upon "a preamble sequence." Independent claim 1 of the '862 patent recites:

1. A method for feeding back transmitter beamforming information from a receiving wireless communication device to a transmitting wireless communication device, the method comprising:

the receiving wireless communication device receiving a preamble sequence from the transmitting wireless device;

the receiving wireless device estimating a channel response based upon the preamble sequence;

the receiving wireless device determining an estimated transmitter beamforming unitary matrix (V) based upon the channel response and a receiver beamforming unitary matrix (U);

the receiving wireless device decomposing the estimated transmitter beamforming unitary matrix (V) to produce the transmitter beamforming information; and

the receiving wireless device wirelessly sending the transmitter beamforming information to the transmitting wireless device.

(EX1001 at cl. 1.)

77. Independent claim 9, the corresponding device claim, similarly recites:

9. A wireless communication device comprising:

a plurality of Radio Frequency (RF) components operable to receive an RF signal and to convert the RF signal to a baseband signal; and

a baseband processing module operable to:

receive a preamble sequence carried by the baseband signal;

estimate a channel response based upon the preamble sequence;

determine an estimated transmitter beamforming unitary matrix (V) based upon the channel response and a receiver beamforming unitary matrix (U);

decompose the estimated transmitter beamforming unitary matrix (V) to produce the transmitter beamforming information; and

form a baseband signal employed by the plurality of RF components to wirelessly send the transmitter beamforming information to the transmitting wireless device.

(EX1001, cl. 9.)

78. The rest of the challenged claims (claims 2-4 and claims 10-12) depend from independent claims 1 and 9, respectively.

79. In Grounds 1, 2, 3-4,² and 5, Petitioner relies on the disclosures of Li '748, Tong, Li '054, and Poon, respectively, for the "preamble sequence" limitations

² In Ground 4, Petitioner challenges claims 2 and 10, which depend from independent claims 1 and 9, respectively, and relies on the analysis of Ground 3 (Li '054 and Mao) for the limitations of the independent claims (including the "preamble sequence" limitations).

of independent claims 1 and 9 (emphasized above). (Pet. at 32 (Li '748), 49 (Tong), 63-64 (Li '054), 75-76 (Poon).) However, for each of these Grounds, Petitioner and its expert admit that their references do not explicitly teach receiving a “preamble sequence,” much less estimating a channel response “based upon the preamble sequence.” (EX2002 at 44:24-45:4, 51:19-21 (Li '748); 67:20-68:3 (Li '054); 85:2-10 (Poon); EX1003 at ¶ 114 (Tong).) Because this deficiency impacts all independent claims, none of the challenged claims are unpatentable.

1. Neither Petitioner Nor Its Expert Offered a Construction of “Preamble” or “Preamble Sequence” Other Than Plain and Ordinary Meaning

80. Petitioner does not assert that the terms “preamble” or “preamble sequence” must be construed to have any meaning other than their plain and ordinary meaning. However, Petitioner does not identify in the Petition what it contends is the plain and ordinary meaning of “preamble” or “preamble sequence.” Instead, in each Ground of the Petition, it simply resorts to citing the use of the term in the '862 patent specification, without construction. (See, e.g., Pet. at 32, 64, 76.)

81. In his accompanying declaration, Petitioner's expert Dr. Wells similarly did not elaborate on the meaning of either term. Dr. Wells sidestepped this issue by focusing instead on the alleged “similarity” of the '862 patent and cited art in the use of training symbols, etc., for estimating a channel response. For example, in Ground 1, Dr. Wells states:

the “preamble” disclosed in the ’862 patent includes essentially the same type of traditional “training symbols” (as disclosed in Li ’748) to estimate the channel response and determine the beamforming matrix, and a POSITA would have recognized this similarity because it was a customary practice at the time in such wireless devices. Thus, Li ’748 discloses receiving a preamble sequence carried by the baseband signal.

(EX1003 at ¶ 83.)

82. In Ground 2 Dr. Wells states:

the “preamble” disclosed in the ’862 patent include essentially the same type of traditional “pilot symbols” (as disclosed in Tong) to estimate the channel response and determine the beamforming matrix, and a POSITA would have recognized this similarity because it was a customary practice at the time in such wireless devices. Thus, Tong discloses receiving a preamble sequence carried by the baseband signal.

(*Id.* at ¶ 114.)

83. In Grounds 3 and 4, Dr. Wells states:

the “preamble” disclosed in the ’862 patent includes essentially the same type of traditional “training symbols” (as disclosed in Li ’054) to estimate the channel response and determine the beamforming matrix, and a POSITA would have recognized this similarity because it was a customary practice at the time in such wireless devices. Thus, Li ’054 discloses receiving a preamble sequence carried by the baseband signal

(*Id.* at ¶ 151.)

84. In Ground 5, Dr. Wells states:

the “preamble” disclosed in the ’862 patent includes traditional “training symbols,” or a training pattern (as disclosed in Poon), to estimate the channel response (e.g., estimate the spatial channel) and determine the transmit beamforming matrix V , and a POSITA would have recognized this similarity because it was a customary practice at the time in such wireless

devices. Thus, Poon discloses receiving a preamble sequence carried by the baseband signal.

(*Id.* at ¶ 191.)

85. Nowhere in Dr. Wells's declaration does he provide a plain and ordinary meaning of the terms "preamble" or "preamble sequence" nor does he explain how these terms are met by the cited art. Instead, Dr. Wells seems to be arguing that merely because the '862 patent and the cited art teach training symbols, etc., the cited art discloses a preamble sequence. I understand that at deposition, Dr. Wells stated, for the first time, that the plain and ordinary meaning of a "preamble sequence" was "a distribution of information that is sent before something else." (EX2002 at 52:24-53:4.) But as previously set forth, Dr. Wells's definition is technically incorrect and overly vague. As also noted previously, the proper definition of "a preamble sequence" is "two or more training symbols in a preamble," where the term "preamble" means "a segment, at the beginning of a transmission, containing information that is expected (i.e., known *a priori*) by the receiver." Dr. Wells therefore lacks a proper framework by which to assess whether a prior art reference taught estimating a channel response based upon a "preamble sequence."

86. Dr. Wells nevertheless testified that Li '748 (Ground 1) "***certainly*** discloses" a "preamble sequence." (EX2002 at 44:16-45:9.) Dr. Wells similarly

testified that Li '054 (Grounds 3-4) “*certainly*” discloses a preamble. (*Id.* at 67:20-68:3.) In his declaration, Dr. Wells similarly opined that Tong (Ground 2) “*discloses* receiving a preamble sequence,” (EX1003 at ¶ 113), and that Poon (Ground 5) “*discloses* or at least renders obvious receiving a preamble sequence.” (*Id.* at ¶ 190.) The cited disclosures from Li '748, Tong, Li '054, and Poon are deficient, as will be explained below. Moreover, Dr. Wells's testimony shows that Petitioner's arguments for limitations 1.a, 1.b, 9.c, and 9.d are actually an inherency argument (i.e., implicit disclosure), not an argument that these references explicitly disclose the limitations. And as set forth below, even an inherency argument would fail.

2. Petitioner Has Failed to Show That Any of Its References Explicitly Disclose a Preamble Sequence or Render it Obvious

87. None of the references in the Petition Grounds explicitly teach a “preamble,” much less a “preamble sequence,” as those terms would have been understood by a POSITA. In each of their Grounds, Petitioner and its expert appear to rely on the teachings of “training symbols,” “pilot symbols,” “received signals,” or a “training pattern,” as teaching the claimed preamble sequence. (Pet. at 32 (Li '748), 49 (Tong), 63-64 (Li '054), 75-76 (Poon); EX1003 at ¶¶ 82-83, 113-14, 150-51, 190-91.) However, they do not identify any evidence that such “training symbols,” “pilot symbols,” “received signals,” or a “training pattern” are a “preamble sequence” as required by the claim. Instead, in each Ground, they seek

to compare “training symbols,” “pilot symbols,” or a “training pattern” to the **'862 patent specification's own teaching** of “training symbols” in a preamble, and argue that it would *therefore* have been obvious to receive a preamble sequence and estimate a channel response based on it. (Pet. at 32 (Li '748), 49 (Tong), 63-64 (Li '054), 75-76 (Poon); EX1003 at ¶¶ 82-83, 113-14, 150-51, 190-91.)

88. In these paragraphs, I did not find any basis for Dr. Wells's obviousness opinions other than the teachings of the challenged patent itself. But Dr. Wells does not explain why relying on the challenged patent itself for obviousness is appropriate. I disagree that a POSITA would have found the claims obvious based on the specification of the '862 patent itself. (EX1003 at ¶¶ 18-20.)

89. More generally, neither the Petition nor Dr. Wells's opinions contain any actual obviousness analysis—which is a fatal flaw for each Ground. In the Petition, I have not found any articulated reasoning with any rational underpinning supporting the legal conclusion of obviousness with respect to limitations 1.a, 1.b, 9.c, or 9.d—just a bare assertion that because the cited art teaches “training symbols,” “pilot symbols,” “received signals,” or a “training pattern,” it discloses a “preamble sequence” as claimed.

90. I understand that at deposition, Dr. Wells stated only that it was “customary practice” for training symbols to be included in a preamble. (EX2002 at 44:24-45:9.) But when pressed to identify any evidence of such a “customary

practice,” he simply cited his “years” of experience. (*Id.* at 51:24-52:10; 66:4-9; 71:24-72:3.) This testimony is plainly insufficient to demonstrate that any of Li ’748, Tong, Li ’054, or Poon teach or suggest a “preamble sequence” as recited by the challenged claims. And because Dr. Wells repeats this analysis for **Grounds 1-5**, each of the Grounds fails. (Pet. at 32, 49-50, 63-64, 75-76.)

91. Nor does Dr. Wells identify any evidence that the “training symbols,” “pilot symbols,” or “training pattern” in the corresponding references are “sent before” any other sequence or information under his own stated definition of a “preamble.” For example, Tong—which Petitioner relies on in **Ground 2** for the preamble sequence limitations—teaches that “pilot symbols . . . are *scattered among* the data symbols throughout the OFDM sub-carriers” and therefore cannot “come before” any other sequence or symbols. (EX1003 at ¶ 115, citing EX1005 at [0090].) I understand that at deposition, Dr. Wells did not have an explanation for how pilot symbols could be “scattered among the data symbols” and yet be transmitted within a preamble. (EX2002 at 61:23-63:2.) A POSITA would understand that the “data symbols” referenced in Tong are not a preamble sequence and instead constitute payload data. Therefore, Tong’s pilot symbols are not transmitted within a preamble as they are transmitted amidst data symbols, and not as a segment *before* the data symbols.

92. **Ground 2** therefore fails for this additional reason.

3. Because Petitioner Has Failed to Show That Any of Its References Explicitly Disclose a Preamble Sequence, Petitioner Has Also Failed to Show That Any of Its References Explicitly Disclose Estimating a Channel Response Based Upon a Preamble Sequence

93. Each of the challenged claims requires that the receiving terminal estimate a channel response based upon the preamble sequence (elements 1[b] and 9[d]). Because the references underlying each Ground do not teach a “preamble sequence,” they also do not teach using the preamble sequence to estimate a channel response.

94. Li '748 (**Ground 1**) and Li '054 (**Grounds 3-4**) only teach, at best, that the receiver estimates a channel response based on “received signals.” (EX1004 at Fig. 2; EX1007 at Fig. 3.) There is no disclosure in either of the Li references that the “received signals” are “training symbols,” much less “a preamble sequence.” Nor does Dr. Wells offer any evidence that Li '748 and Li '054 teach estimating a channel response based on training symbols. (EX1003 at ¶¶ 82-84, 152.) I understand that at deposition, Dr. Wells merely stated that the “received signals” must be training symbols, but did not provide any evidence in support of that opinion. (EX2002 at 57:8-21, 58:8-18 (Li '748); 68:10-22, 70:20-72:20 (Li '054).) Because this is another conclusory opinion, it must be disregarded. Grounds 1 and 3 fail for this additional reason.

95. The other Grounds are similarly deficient. With respect to **Ground 2**, at best, Dr. Wells opines that Tong teaches “compar[ing] the received pilot symbols with the pilot symbols that are expected in certain sub-carriers at certain times to determine a channel response.” (EX1003 at ¶ 115, citing EX1005 at [0090].) But as I explain above, Tong’s pilot symbols are scattered throughout the data subcarriers and are not transmitted within a preamble sequence. Therefore, any channel estimation Tong purportedly teaches is not based upon a preamble sequence. Ground 2 fails for this additional reason.

96. With respect to **Ground 5**, Dr. Wells also opines that Poon teaches that the “receiving station receives a training pattern” and separately that “the receiving station estimates N spatial channels.” (EX1003 at ¶ 192, citing EX1009 at 3:20-60; Fig. 2.) But Dr. Wells does not provide any evidence that Poon teaches “estimating N spatial channels” based on a “*preamble sequence*.” (EX1003 at ¶ 192.) Therefore, Ground 5 fails for this additional reason.

97. As such, Petitioner has not established that it would have been obvious to include “training symbols,” “pilot symbols,” or a “training pattern” in a “preamble sequence,” as recited by the challenged claims. Furthermore, Petitioner has not established that it would have been obvious to estimate a channel response based on a preamble sequence. Each of Petitioner’s Grounds fails for these reasons.

98. Petitioner's obviousness assertions as to limitations 1.a, 1.b, 9.c, and 9.d are based entirely on the unsupported testimony of their expert and disclosures from the challenged patent, which is tantamount to using the '862 patent as a roadmap. These assertions, which are nothing more than hindsight analysis, must therefore be rejected.

4. Petitioner Has Not Established That Any of Its References Inherently Discloses Estimating a Channel Response Based Upon a Preamble Sequence

99. Apparently recognizing that its references do not explicitly disclose receiving a preamble sequence or estimating a channel response based upon the preamble sequence, Petitioner and its expert advance an argument that is vaguely worded as part inherency and part obviousness. (EX2002 at 52:4-9 ("And in my 35 years of working with wireless systems, I can't think of any other system that I've ever seen that doesn't send -- when training symbols are sent when they're not sent in a preamble."); id. at 66:4-9, 72:1-3.)

100. But any such argument would fail under an inherency theory. As an initial matter, Dr. Wells acknowledged that he was not relying on inherency (or anticipation generally) for any of his opinions. (EX2002 at 40:6-15.) Consequently, the Board should not accept any arguments by Dr. Wells that are based on inherency. And even if the Board were inclined to credit Dr. Wells's testimony above as directed to an inherency theory, I understand that inherency is only applicable when

prior art *necessarily* functions in accordance with, or includes, the claimed limitations. Inherency should not be established by probabilities or possibilities. The mere fact that a certain thing may result from a given set of circumstances is not sufficient. In essence, to show that a particular function is inherently the result of an operation disclosed in an alleged prior art reference, it should be shown that the natural result flowing from the operation as taught would result in the performance of the questioned function. Petitioner has not attempted to make such a showing, other than relying on the say-so of Dr. Wells, at best.

101. Moreover, the testimony of Dr. Wells is also self-contradictory to the extent it suggests that training symbols must necessarily be transmitted within a preamble sequence. For example, Dr. Wells did not disagree that in Tong (**Ground 2**), pilot symbols are scattered throughout a data transmission. (EX2002 at 61:23-63:2.) This alone eliminates the necessity required for inherency. Dr. Wells also did not rule out that “training symbols” (in Petitioner’s **Ground 1, Ground 3, and Ground 4** references) could be “scattered among data symbols throughout OFDM sub-carriers like the pilot symbols in Tong.” (EX2002 at 84:1-19.) Similarly, Dr. Wells did not rule out that the “training pattern” in Poon (**Ground 5**) could likewise be “scattered among the data symbols.” (*Id.* at 83:2-7.)

102. Indeed, Dr. Wells sought to sidestep these deficiencies in his analysis by “arguing obviousness.” (*Id.* at 85:6-7.) But as detailed above, Dr. Wells’s (and

Petitioner's) primary basis for asserting that it would have been obvious to include training symbols, pilot symbols, and/or a training pattern within a preamble sequence was that he "[could not] think of any other system" where they were not. (EX2002 at 52:4-9; 66:4-9; 72:1-3.)³ But because this basis falls flat, Dr. Wells's "obviousness" theory also fails.

103. Each of the Grounds fails for this additional reason.

5. Petitioner Fails To Show That The Dependent Claims Are Unpatentable

104. Claims 2-4 depend from independent claim 1, and claims 10-12 depend from independent claim 9. Petitioner asserts under **Ground 1** that dependent claims 2-4 and 10-12 are obvious in view of Li '748, Tong, and Mao. However, as I explain above, neither Li '748 nor Tong discloses estimating a channel response based upon a preamble sequence. Mao is relied on for allegedly teaching the "radio frequency (RF) components" and "form a baseband signal" limitations of the claims, (Pet. at 23-24, 25, 40), and therefore fails to remedy the deficiencies of Li '748 and Tong. Accordingly, Ground 1 of the Petition fails to show by a preponderance of evidence that claims 2-4 and 10-12 are unpatentable.

³ The only other basis relies on the '862 patent's own specification, which is improper.

105. Petitioner asserts under **Ground 2** that claims 2-4 and 10-12 are obvious in view of Tong and Mao. However, as I explain above, Tong does not disclose estimating a channel response based upon a preamble sequence and Mao is relied on for allegedly teaching the “radio frequency (RF) components” and “form a baseband signal” limitations of the claims, (Pet. at 23-24, 53), and therefore fails to remedy the deficiencies of Tong. Accordingly, Ground 2 of the Petition fails to show by a preponderance of evidence that claims 2-4 and 10-12 are unpatentable.

106. Petitioner asserts under **Ground 3** that claims 3, 4, 11, and 12 are obvious in view of Li '054 in view of Mao. However, as I explain above, Li '054 fails to disclose estimating a channel response based upon a preamble sequence and Mao is relied on for allegedly teaching the “radio frequency (RF) components” and “form a baseband signal” limitations of the claims, (Pet. at 23-24, 61-62, 66), and therefore fails to remedy the deficiencies of Li '054. Accordingly, Ground 3 of the Petition fails to show by a preponderance of evidence that claims 3, 4, 11, and 12 are unpatentable.

107. Petitioner asserts under **Ground 4** that claims 2 and 10 are obvious over Li '054, Mao, and Yang. However, as I explain above, Li '054 fails to disclose estimating a channel response based upon a preamble sequence. Mao is relied on for allegedly teaching the “radio frequency (RF) components” and “form a baseband signal” limitations of the claims, (Pet. at 23-24, 71), and Yang is relied on for

allegedly teaching the “converting the estimated transmitter beamforming unitary matrix (V) to polar coordinates” limitation. (Pet. at 67-70.) Therefore, Mao and Yang fail to remedy the deficiencies of Li ‘054 with respect to claims 1 and 9, from which claims 2 and 10 depend. Accordingly, Ground 4 of the Petition fails to show by a preponderance of evidence that claims 2 and 10 are unpatentable.

108. Petitioner asserts under **Ground 5** that claims 3, 4, 11, and 12 are obvious in view of Poon and Mao. However, as I explain above, Poon fails to disclose estimating a channel response based upon a preamble sequence. Mao is relied on for allegedly teaching the “radio frequency (RF) components” and “form a baseband signal” limitations of the claims, (Pet. at 23-24, 78), and therefore Mao fails to remedy this deficiency. Accordingly, Ground 5 of the Petition fails to show by a preponderance of evidence that claims 3, 4, 11, and 12 are unpatentable.

109. For at least the reasons set forth above, Petitioner has not shown by a preponderance of evidence that claims 1-4 and 9-12 are unpatentable.

B. Petitioner Fails to Show That Producing the Estimated Transmitter Beamforming Unitary Matrix (V) in Cartesian Coordinates and Converting the Matrix (V) to Polar Coordinates Would Have Been Obvious (Grounds 1, 2, 4; Claims 2, 10)

110. Claims 2 and 10 are also patentable over the cited references because of the additional limitations they recite. Claim 2 of the ’862 patent recites:

2. The method of claim 1 wherein the receiving wireless device determining an estimated transmitter beamforming unitary matrix (V) based upon the channel response and a receiver beamforming unitary matrix (U) comprises:

the receiving wireless device *producing the estimated transmitter beamforming unitary matrix (V) in Cartesian coordinates*; and

the receiving wireless device *converting the estimated transmitter beamforming unitary matrix (V) to polar coordinates*.

(EX1001, cl. 2 (emphasis added).)

111. Claim 10 of the '862 patent—the corresponding device claim—similarly recites:

10. The wireless communication device of claim 9, wherein in determining an estimated transmitter beamforming unitary matrix (V) based upon the channel response and a receiver beamforming unitary matrix (U), the baseband processing module is operable to:

produce the estimated transmitter beamforming unitary matrix (V) in Cartesian coordinates; and

convert the estimated transmitter beamforming unitary matrix (V) to polar coordinates.

(EX1001, cl. 10 (emphasis added).)

112. Petitioner asserts that only three of its Grounds (namely, Grounds 1, 2, and 4) render claims 2 and 10 obvious. (Pet. at i-iii.) In Grounds 2 and 4, Petitioner relies exclusively on Yang (EX1008) for the additional limitations of claims 2 and 10. (Pet. at 54-56, 67-70.) In Ground 1, Petitioner appears to rely on Yang only as a backup reference for the additional limitations of these claims. As explained below, to the extent Yang can be considered by the Board, Yang does not teach

producing a beamforming matrix V in Cartesian coordinates and converting it to polar coordinates. Moreover, Li '748 in view of Tong, relied on by Petitioner as separately rendering claims 2 and 10 obvious in Ground 1, does not teach producing a beamforming matrix V in Cartesian coordinates and converting the matrix V to polar coordinates.

1. Petitioner Fails to Show That Li '748, Alone or in View of Tong, Renders Claims 2 and 10 Obvious (Ground 1)

113. In Ground 1, Petitioner and Dr. Wells rely on Li '748 for the element “produc[ing] . . . (V) in Cartesian coordinates.” Here, Dr. Wells first cites the following excerpt of Li '748:

In some embodiments of the present invention, the beamforming matrix V is represented by n^2-1 real numbers instead of $2n^2$ real numbers. By sending n^2-1 real numbers instead of $2n^2$ real numbers to represent the beamforming matrix, the feedback bandwidth may be reduced.

(EX1003 at ¶ 98, citing EX1004 at 2:63-67.)

114. I understand that at deposition, Dr. Wells explained that the “ n^2-1 real numbers” of Li '748 were the “Cartesian coordinates” recited by the claims. (EX2002 at 98:1-10; 98:22-99:7.) However, Dr. Wells is mistaken that the “ n^2-1 real numbers” are elements of the matrix V in Cartesian coordinates. The entire excerpt from Li '748 describes:

The current channel state information may be represented by an n by n unitary beamforming matrix V determined using a singular value

decomposition (SVD) algorithm, and the transmitter may process an outgoing signal using the beamforming matrix V to transmit into multiple spatial channels. In a straightforward implementation, the receiver sends each element of the unitary matrix V back to the transmitter. This scheme involves sending information related to the $2n^2$ real numbers for any n by n complex unitary matrix, where n is the number of spatial channels in the MIMO system.

In some embodiments of the present invention, the beamforming matrix V is represented by n^2-1 real numbers instead of $2n^2$ real numbers. By sending n^2-1 real numbers instead of $2n^2$ real numbers to represent the beamforming matrix, the feedback bandwidth may be reduced.

(EX1004 at 2:52-67.)

115. In other words, Li '748 teaches that V is an $n \times n$ complex matrix and includes n^2 elements. Each of these n^2 elements may have a real and an imaginary component, and therefore the total number of real numbers values comprising the matrix V are $2n^2$.

116. Li '748 purports to reduce feedback bandwidth by using “ n^2-1 real numbers *instead of* $2n^2$ real numbers,” for example, via compression or decomposition techniques. But the resulting “ n^2-1 real numbers” are no longer elements of the matrix V and are instead, coefficients in front of Hermitian generator matrices. Therefore, Dr. Wells and Petitioner have not established that Li '748 actually teaches a matrix V produced with n^2-1 Cartesian coordinates.

117. Dr. Wells also states that Li '748's teachings of "hermitian generator matrices" shows that the matrix V is converted to polar coordinates. (EX1003 at ¶ 98.) That excerpt from Li '748 is reproduced below in its entirety:

Various embodiments of the present invention exploit the structure of unitary matrixes and represent the unitary matrices by a combination of n^2-1 orthogonal generator matrices, where the feedback numbers are the projections on the generator bases. For example, multiple hermitian generator matrices known to both the transmitter and receiver may be utilized to represent the beamforming matrix. Further, ***the numbers are also angles from $-\pi$ to π of an (n^2-1) -dimension polar coordinate***, which facilitate a fine control of quantization error.

(EX1004 at 2:67-3:11.)

118. Again, Li '748 does not teach ***converting the matrix V*** to polar coordinates as the claims require. Dr. Wells does not identify any disclosure of "converting" in Li '748. Nor does Dr. Wells identify the specific disclosure in Li '748 he considers "polar coordinates." To the extent he considers the "angles from $-\pi$ to π " as meeting this element, those numbers are "angles . . . ***of an (n^2-1) -dimension polar coordinate***," (EX1004 at 3:7-10), not polar coordinate elements of the matrix V as the claims require. Moreover, Li '748 teaches using a plurality of (i.e., n^2-1) "orthogonal generator matrices," such as "hermitian generator matrices," to represent V . (EX1004 at 2:67-3:11.) Specifically, rather than convert V to polar coordinates, Li '748 teaches that V is represented in terms of a hermitian generator matrix G_k and the angle a_k of the k -th rotation, as follows:

$$V = \exp\left(i \sum_{k=1}^{n^2} a_k G_k\right)$$

where G_k is the k -th hermitian generator matrix; a_k is the angle of the k -th rotation and it is between $-\pi$ and π ; and i is the square root of -1 . Example generator matrices for $n=2, 3$, and 4 are provided at the end of this description.

(EX1004 at 3:45-54.)

119. The above excerpts (which Dr. Wells did not consider or address) confirm that the matrix V is never converted to polar coordinates. Indeed, even the exemplary generator matrices G_k are in Cartesian coordinates and do not contain *any* polar coordinates:

Generator Matrices

For U(2) group, the generator matrices are:

$$G_1 = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix}, G_2 = \begin{pmatrix} 0 & -i \\ i & 0 \end{pmatrix}, G_3 = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}, G_4 = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix}$$

For U(3) group, the generator matrices are:

$$G_1 = \begin{pmatrix} 0 & 1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, G_2 = \begin{pmatrix} 0 & -i & 0 \\ i & 0 & 0 \\ 0 & 0 & 0 \end{pmatrix}, G_3 = \begin{pmatrix} 1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & 0 \end{pmatrix},$$

$$G_4 = \begin{pmatrix} 0 & 0 & 1 \\ 0 & 0 & 0 \\ 1 & 0 & 0 \end{pmatrix}, G_5 = \begin{pmatrix} 0 & 0 & -i \\ 0 & 0 & 0 \\ i & 0 & 0 \end{pmatrix}, G_6 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 1 & 0 \end{pmatrix},$$

$$G_7 = \begin{pmatrix} 0 & 0 & 0 \\ 0 & 0 & -i \\ 0 & i & 0 \end{pmatrix}, G_8 = \frac{1}{\sqrt{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & -2 \end{pmatrix}, G_9 = \sqrt{\frac{2}{3}} \begin{pmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{pmatrix}$$

(EX1004 at 11:1-12:5.)

120. Therefore, Dr. Wells is plainly mistaken that “angles from $-\pi$ to π ” in Li ’748 teach “conversion” of V to polar coordinates. Dr. Wells does not identify any specific disclosures from Li ’748 showing a polar coordinate representation of V, or even the claimed conversion.

121. Therefore, Li ’748 does not render obvious claims 2 and 10.

2. Petitioner Fails to Show That Tong Renders Claims 2 and 10 Obvious (Grounds 1, 2)

122. Petitioner and Dr. Wells similarly miss the mark with Tong (Grounds 1 and 2). Tong teaches merely that “the V matrix is decomposed by the Givens transform 330 to produce a series of matrices,” each of which can be “uniquely represented by two parameters Θ and C.” (EX1005 at [0223].) Even if the resultant matrices following the Givens transforms are in polar coordinates, nothing in the cited disclosures describes that the V matrix itself is first *produced in Cartesian coordinates* and subsequently converted to polar coordinates. Nor does Dr. Wells identify what such a Cartesian-coordinate representation of V would look like at all, other than offer a conclusory opinion that it was “common at the time” to “convert from Cartesian coordinate[s].” (EX2002 at 106:18-107:12.) Further, in connection with **Ground 1**, Dr. Wells does not provide any evidence that a POSITA reading Li ’748 and Tong would have been motivated to convert a matrix of n^2-1 real numbers (as in Li ’748) to polar coordinates. Tong does not even contemplate such a situation.

123. Therefore, Tong alone, or in combination with Li ’748 (**Ground 1**) or Mao (**Ground 2**) does not render obvious claims 2 and 10.

3. To the Extent it Can be Considered, Yang Does Not Render Claims 2 and 10 Obvious (Grounds 1, 2, 4)

124. Ground 4 is the only Ground where Petitioner explicitly purports to rely on Yang for the additional limitations of claims 2 and 10. (Pet. at i-iii.) In Grounds 1 and 2, Petitioner and Dr. Wells characterize the teachings of Yang as “demonstrat[ing] the well-known technique of converting Cartesian coordinates to polar coordinates,” and thereby seek to incorporate the teachings of Yang in their obviousness combinations. (EX1003 at ¶¶ 100, 128; Pet. at 43-44, 55-56.) But Petitioner does not provide any authority for trying to backdoor the *explicit* disclosures from a reference outside its stated Grounds. Yang should be disregarded in Grounds 1 and 2 on this basis alone.

125. In its Institution Decision, the Board did not indicate whether it considered the teachings of Yang in any Ground. (Paper 11 at 18.) To the extent the Board is inclined to consider the teachings of Yang, the reference nevertheless is not relevant because its teachings are inapposite to the specific limitations of claims 2 and 10.

126. Dr. Wells's reliance on Yang is limited to the following teachings:

Yang describes a “method for computing two-sided rotations involved in singular value decomposition (SVD)” that “leads to significantly reduced computations.” EX1008, Abstract.

Yang explains that there was “massive interest in parallel architectures for computing SVD” and discloses the use of “coordinate rotation digital computer (CORDIC) processors” to avoid the “computational overhead” of previous computational methods. EX1008, 1, Abstract.

Yang discloses a “***CORDIC algorithm***” for computing “Cartesian-to-polar coordinates conversions.” Id., 4. Yang explains that SVD, which arises in beam-forming, has a “high computational complexity,” but that the CORDIC algorithm reduces the complexity in part because of its Cartesian-to-polar coordinates conversions Id., 1, 5, Abstract.

Using ***this algorithm***, Yang explains “the Cartesian coordinate (x_0 , y_0) of a plane vector is converted to its polar representation.” Id., 6.

(EX1003 at ¶ 128.)

127. In other words, Dr. Wells relies solely on Yang’s teachings of a “CORDIC algorithm” (i.e., “this algorithm”) for “Cartesian to polar coordinates conversions.” However, these opinions disregard the context of the “CORDIC algorithm.” Specifically, Dr. Wells disregards the fact that Yang does not teach or suggest “Cartesian to polar coordinates conversions” on a beamforming unitary matrix V and, instead, teaches at best operations performed on a real-valued matrix M (Yang’s counterpart to the matrix H).

128. First, Yang describes that its “CORDIC algorithm” follows from its teachings of a “TPR-method” (two plane rotation method) involving the matrix M :

4. The CORDIC algorithm. In the previous section, we have seen that the main operations of the TPR-method are plane rotations and Cartesian-to-polar coordinates conversions.

(EX1008 at 5.)

129. Specifically, Yang teaches that M is a real-valued matrix of dimension N , and represents the left hand side of a Jacobi SVD method:

2. Jacobi SVD method. In this paper, we consider real, square, and nonsymmetric matrices. Let $M \in \mathbb{R}^{N \times N}$ be a matrix of dimension N . The SVD is given by

$$(1) \quad M = U \Sigma V^T,$$

(*Id.* at 2.)

130. Dr. Wells confirmed that the notation $M \in \mathbb{R}^{N \times N}$ means that M is a real valued matrix of dimension N . (EX2002 at 30:11-24.) He also testified that M in equation (1) of Yang corresponds to H , the channel state matrix described in the '862 patent and claimed as " $H=UDV^*$ " in, for example, claim 11. (EX2002 at 39:17-21.) But Dr. Wells did not opine that M is a channel state matrix. While equation (1) of Yang represents an exemplary SVD operation, M is not itself a channel state matrix.

131. Yang then goes on to describe the two-plane rotation method. First, "the matrix M is partitioned into 2×2 submatrices," A and B :

(Fig. 1). To do this, the matrix M is partitioned into 2×2 submatrices. Each PE contains one submatrix and performs a two-sided rotation

$$(4) \quad B = R(\theta_1)^T A R(\theta_2),$$

where

$$(5) \quad A = \begin{pmatrix} a_{11} & a_{12} \\ a_{21} & a_{22} \end{pmatrix} \quad \text{and} \quad B = \begin{pmatrix} b_{11} & b_{12} \\ b_{21} & b_{22} \end{pmatrix}$$

denote the submatrix before and after the two-sided rotation, respectively, and

$$(6) \quad R(\theta) = \begin{pmatrix} \cos \theta & \sin \theta \\ -\sin \theta & \cos \theta \end{pmatrix}$$

describes a plane rotation through the angle θ . At first, the diagonal PEs (symbolized by

(EX1008 at 3.)

132. Here, $R(\theta_1)$ and $R(\theta_2)$ are elements of M^{rot} , while A_2 belongs to M^{ref} . (*Id.* at 4.) Yang further teaches that the two-sided rotation in equation (4) is computed through a series of “two plane rotations, ten additions, and four scalings by $\frac{1}{2}$.” (*Id.* at 3-4.) Yang specifically explains that “If the 2 X 2 matrix A is given, we can diagonalize A and calculate the corresponding rotation angles θ_1 and θ_2 by two Cartesian-to-polar coordinates conversions, eight additions, and four scalings by $\frac{1}{2}$.” (*Id.* at 4.) I understand that at deposition, Dr. Wells either agreed with the aforementioned description of these mathematical operations or did not have an opinion on them. (EX2002 at 32:15-35:1; 35:2-20; 37:6-39:9.)

133. Yang is therefore inapposite to claims 2 and 10. First, it is undisputed that Yang teaches, at best, mathematical operations performed on matrix M. While matrix M may “correspond to” H, it is a real-valued matrix (unlike H, which is complex-valued) and therefore is not a channel state matrix. Consequently, because M is real-valued, all matrices in its SVD will necessarily be real, including V.

134. The elements of a MIMO channel matrix H are complex numbers. As I explain in my textbook, baseband channels have complex-valued impulse responses: “Similar to SISO channels, at the baseband level the channel is a linear time-invariant system with a complex-valued baseband impulse response.” T. Cooklev and A. Yagle, “*Modern Communication Systems*,” at p. 387 (excerpts attached as Appendix 2 to this Declaration). As another example, every component of the

channel matrix impulse response is “a zero-mean, complex Gaussian random variable.” *See id.* at 387.

135. In contrast, Yang does not describe or even contemplate operations performed on complex-valued elements of a matrix, unlike the specification of the '862 patent. The '862 patent explicitly describes that the matrix V is complex-valued:

For instance, in a 2×2 MIMO wireless communication, the feedback needs four elements that are all complex Cartesian coordinate values $[V_{11} \ V_{12}; V_{21} \ V_{22}]$. In general, $V_{ik} = a_{ik} + j * b_{ik}$, where a_{ik} and b_{ik} are values between $[-1, 1]$.

(EX1001 at 3:35-39; see also EX1001 at 12:64-67.)

136. In fact, a POSITA would have known that in beamforming applications of the type addressed in the '862 patent, the estimated transmitter beamforming unitary matrix V would be complex-valued.

137. While Yang references a matrix V (*see* EX1008 at 2, equation (1)), none of the teachings of Yang describe any mathematical operations performed on V or suggest that V is complex-valued or converted from Cartesian to polar coordinates. Instead, Yang is concerned with solving a different problem altogether: “A ***new, efficient, two-plane rotation (TPR) method*** for computing two-sided rotations,” (EX1008 at Abstract), thereby reducing computational complexity of the SVD operation. (*Id.* at 1-2.) Yang's subsequent explanation of the “CORDIC algorithm”

is therefore also limited to the M matrix and rotations performed to the M matrix, not the V matrix. Indeed, other than the reference to V in equation (1), nothing in Dr. Wells's cited sections of Yang mentions the matrix V at all.

138. Therefore, Grounds 2 and 4, and 1 (to the extent it relies on Yang) fail as to claims 2 and 10.

139. Petitioner's assertions that a POSITA could not only produce the unitary beamforming matrix V in Cartesian coordinates and convert the matrix V to polar coordinates is therefore based on the unsupported testimony of their expert and various disparate teachings from the prior art that are not relevant to the challenged claims. These assertions, which are again nothing more than hindsight analysis, must be rejected.

4. Petitioner Has Not Demonstrated that a POSITA Would Have Had a Reasonable Expectation of Success With Its Proposed Combinations

140. The Petition lacks sufficient discussion or facts to support a reasonable expectation of success with any of its proposed combinations to meet the limitations of claims 2 and 10 of the '862 patent. The only mention of a "reasonable expectation of success" (or similar language) is for a different claim element altogether (9a) and in connection with Ground 2. (*See* Pet. at 30.) Therefore, Petitioner ignores the requirement in its entirety.

141. At best, Petitioner asserts that a POSITA “would have understood” disclosures from Yang, that it would have been a “predictable combination,” (Pet. at 44; *see also* Pet. at 56), that a POSITA “would have implemented” the combination as proposed, (Pet. at 68), that “the combination would have advantageously resulted in a station using less processor bandwidth to determine matrix V .” (Pet. at 69.) However, even in these instances—which, in any event, do not encompass all Grounds—Petitioner fails to address *how* one would reconfigure the circuitry or algorithms in any of the primary references to incorporate the teachings of Yang. As set forth above, Yang is inapplicable to the teachings of the primary references and the '862 patent itself. Specifically, while Yang is limited to operations on a real-valued matrix M (analogous to H)—the claims and the primary references all involve operations on a complex-valued matrix V . For example, as previously set forth, Li '748 explicitly teaches that the matrix V is complex-valued. (EX1004 at 2:52-62.) Instead of addressing these issues or describing how Yang would actually be combined with Li '748 or other references, Petitioner again makes a conclusory assertion that it would be “predictable” to arrive at its proposed combinations. (Pet. at 44, 56, 68-69.) For example, Petitioner fails to address how the reconfigured circuitry or algorithms would work if they were to incorporate the teachings of Yang. Accordingly, Petitioner has failed to show by a preponderance of evidence that a

POSITA would have been motivated to combine the prior art references as proposed with a reasonable expectation of success.

VII. OBJECTIVE INDICIA OF NON-OBVIOUSNESS WARRANT
AGAINST A FINDING OF OBVIOUSNESS

142. I understand that objective indicia of non-obviousness can weigh against a finding of unpatentability. Here, as I explain, the inventions of claims 1 and 9 of the '862 patent are widely adopted within the industry and enjoys significant commercial success due to their merits.

1. Applicability of Industry Standards

143. An industry standard refers to a set of criteria or specifications that have been widely accepted and adopted by a particular industry for ensuring compatibility, interoperability, and consistency among products and systems. For example, the 802.11ac standard is a wireless networking standard that operates in the 5 GHz frequency band. It is a part of the IEEE 802.11 family of standards, which define the specifications for implementing wireless local area networking (WLAN) communication. 802.11ac is designed to provide higher data rates, increased capacity, and improved performance compared to its predecessors, such as 802.11n.

144. The 802.11ac standard is developed and maintained by the Institute of Electrical and Electronics Engineers (IEEE). The IEEE is an international organization that sets standards for a variety of technologies, including networking.

Compliance with 802.11 standards benefits device manufacturers by ensuring interoperability with other devices, meeting user expectations, facilitating global adoption, adhering to regulatory requirements, streamlining development, and enhancing the overall quality and marketability of their products.

145. Moreover, a patent is deemed a Standards Essential Patent (SEP) if the technology the patent covers is considered essential for compliance with a particular industry standard. SEPs are often associated with standard-setting organizations (SSOs) such as the IEEE, and participants may agree to incorporate certain technologies into industry standards, and patent holders may commit to licensing their SEPs on fair, reasonable, and non-discriminatory (FRAND) terms.

146. If a patented invention becomes widely adopted within the industry and gains recognition from industry experts or peers, it serves as evidence of non-obviousness. Industry standards—such as the 802.11 standards—often reflect the accepted practices and solutions to common problems within a particular field and therefore a patent's status as an SEP reflects the fact that the patented invention has become widely adopted and gained recognition from industry experts and peers, such as those who participate in the standard setting process within the IEEE.

147. The inventions of claims 1 and 9 of the '862 patent are highly relevant to the 802.11ac and later 802.11 standards because, among other things, the aforementioned standards adopted estimating a channel response based upon a

received preamble sequence. (EX2003 (802.11-2016) at 2542, 2548, 2580.) The adoption of this aspect of the claimed invention into industry standards is an objective indicia of non-obviousness. And while the aforementioned standards may not require practicing all of the limitations of claims 1 and 9 of the '862 patent, a majority of the 802.11-compliant products on the market today do practice all of the limitations of claims 1 and 9 of the '862 patent.

148. As just one example, most 802.11ac-compliant devices, including “smart” televisions and phones, sold in the United States incorporate the channel estimation technology claimed in the '862 patent.

VIII. CONCLUSION

149. For the foregoing reasons, based on my expertise and experience and the record of this case that I have reviewed, it is my opinion that the challenged claims are not shown to be disclosed or obvious.

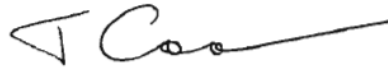
150. I understand that my opinions discussed above support a legal conclusion that the challenged claims are nonobvious.

In signing this declaration, I recognize 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 also recognize 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, I will appear for cross-examination within the United States during the time allotted.

I hereby declare that all statements made herein of my own knowledge are true and all statements made herein on information and belief were and are believed by me to be true, and that all statements herein were and are 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 and that any such willful false statements may jeopardize the validity of the application or any patents issued thereon.

Respectfully Submitted,

A handwritten signature in black ink, appearing to read 'T Cooklev', with a long horizontal stroke extending to the right.

July 3, 2024

Todor V. Cooklev, Ph.D.

Appendix 1

Todor Cooklev, PhD.

Curriculum Vitae

Personal

1336 Sycamore Hills Parkway, Fort Wayne, IN 46814

Contact e-mail: tcooklev@gmail.com

Cell: 925-984-5283

Citizenship: United States (by naturalization)

Professional experience

2016 –

Professor of Electrical and Computer Engineering

2101 E Coliseum Blvd., ETCS 349

Purdue University Fort Wayne, Indiana 46805

- Research on most aspects of wireless systems, including hardware, signal processing, and software techniques, in particular for software-defined radios.
- Courses:
 - ECE 428 Communication Systems
 - ECE 549 Software-Defined Radio
 - ECE 543 Wireless Communications and Networks

2013 – 2017

Co-founder and CEO, Adaptive RF, Fort Wayne, IN

- Developed innovative RF technology and served as co-founder of a company that received funding from the Department of Defense

2018 – 2019

Chief Technology Officer, Stryke Industries LLC

- CTO of a company receiving a grant from the Air Force Research Laboratory, Rome, NY

2010 – 2016

ITT Associate Professor of Wireless Communication and Applied Research, Purdue University Fort Wayne

2008 – 2022

Director, Wireless Technology Center *Purdue University Fort Wayne*

2005 – 2008

Consultant, Hitachi America Ltd., San Jose, California

- Voting Member, IEEE 802.11 WG; participated in the work on several 802.11 amendments
- Chair, IEEE 802.11 VTS Study Group; responsible for the proposal and approval to create a Task Group that lead to the IEEE 802.11aa standard

- 2011 – 2012 Consultant, Hitachi America Ltd., San Jose, California**
- Attended meetings of the 3GPP RAN1 standardization committee in Dresden, Germany, Jeju Island, Korea, Prague, Czech Republic, and Qindao, China, 2012.
 - Contributed to several documents submitted to 3GPP
- 2006 – 2008 Consultant, Datamars, Lugano, Switzerland**
- Evaluated and produced reports on certain wireless technologies and standards
 - Participated in the IEEE 802.15.4f committee
- 2004 – 2006 Consultant, Leica Geosystems, Switzerland**
- IEEE 802.16 (WiMAX) and related technologies
- 2005 – 2007 Technical Advisory Board Member, Doceotech, San Ramon, CA**
- 2002 – 2008 Assistant Professor with tenure (2008), San Francisco State University.**
- 2000 – 2002 Member of the Technical Staff, Aware, Inc., Bedford, MA and Lafayette, CA**
- Worked on DSL standards. Participated in the International Telecommunications Union, Study Group 15, Question 4. Chaired the session on coding for DSL at the session in Antwerp, Belgium, June 2000. Participated in the Telecommunications Industry Association T1E1 Committee on DSL
 - Developed advanced coding and decoding methods for DSL
 - Worked on the design of an IEEE 802.11a chipset.
 - Voting member, IEEE 802.15; Co-Founder and First Vice-Chair of IEEE 802.15.3 (High-data rate wireless personal area networking)
- 1998-1999 Consultant, Quantronix, Framingham, Utah**
- Image processing; developed software for edge detection and wrote a report
- 1996-1997 Consultant, Communications Research Center, Government of Canada.**
- Designed digital filter banks for communication systems and wrote two technical reports
- 1997-1999 Senior Engineer, 3Com Corporation**
- Worked on V.90 voice-band modems
 - Implemented data compression and other signal processing algorithms V.42 and V.42bis
 - Worked on the Bluetooth Standard, one of the first contributors to the Host Controller Interface of Bluetooth.
 - Participated in the Bluetooth/IEEE group, which drafted the license agreement between Bluetooth and the IEEE 802, which in turn led to the establishment of the IEEE 802.15 Working Group.

Grants Awarded

1. Office of Naval Research Summer Fellow 2020, Naval Surface Warfare Center Crane
2. National Science Foundation S²ERC I/UCRC, “FPGA implementation of shared-memory middleware”, 2017-2019, PI
3. National Science Foundation S²ERC I/UCRC, “Shared-memory middleware”, 2016-2017, PI
4. City of Fort Wayne, Economic Development Fund, 2013-15, co-PI.
5. Allen County Capital Improvement Board (CIB), 2013-15, co-PI
6. U.S. Defense Advanced Research Projects Agency (DARPA) Small Business Technology Transfer (STTR) Phase I “A flexible and extensible solution to incorporating new RF devices and capabilities into EW/ISR networks, co-PI, August 2013 – February 2014.
7. National Science Foundation S²ERC I/UCRC, “The performance of middleware solutions for SDR”, 2013-2014, PI
8. National Science Foundation S²ERC I/UCRC, “Cognitive decision applications for embedded use,” 2011-2012, PI
9. Visiting Fellowship, National Institute of Communication Technology (Japan), 2011
10. National Science Foundation S²ERC I/UCRC, “Signal processing techniques for multicarrier modulation,” 2009-2011, PI
11. NMDG, Belgium, laboratory grant 2010, PI
12. National Science Foundation, Professional Science Master’s Program, MS in engineering, with concentration in wireless and systems engineering, 2010-2013, Co-PI.
13. Emona Instruments, Sydney, Australia, Laboratory exercises in communications, Principal Investigator, 2008.
14. Lilly Endowment, wireless laboratory grant, 2010, PI.
15. ITT (now Harris) Communications Systems, 2007-2011, PI.
16. State of Indiana, workforce development, 2008-2010, PI
17. National Science Foundation DUE-0442313, “Standards in Education for Product, Process, and Service Design and Development: A Proof-of-Concept Project,” 2005-2008, PI.

18. France Telecom, Paris, France, “New methods for multicarrier modulation for high data-rate wireless systems,” Principal Investigator, 2006.
19. Agilent Technologies/Sun Microsystems, Palo Alto, CA, “Distributed wireless sensor network for environmental monitoring,” Co-principal Investigator, 2005.
20. CSU summer research grant, 2004.
21. U.S. Air-Force Research Laboratory, Wright-Patterson AFB, “Data over voice communications,” Principal Investigator, 2004.

Honors and Awards

- | | |
|-----------|--|
| 2012 | IEEE Standards Association, “for outstanding contributions to the development of IEEE 802.11aa” |
| 2006 | Wireless Educator of the Year Award with the citation “In recognition of the pivotal role of educators in preparing tomorrow’s wireless technology leaders”. |
| 2005 | Duke’s Choice Award, Sun Microsystems, (group award) |
| 2003 | IEEE Communications Society Oakland/East Bay Chapter Achievement Award, (group award) |
| 1999 | 3Com Inventor Award |
| 1995-1997 | NATO Science Fellowship |
| 1994 | IEEE Asia - Pacific Conference on Circuits and Systems Best Paper Award for the paper “Theory of filter banks over finite fields” |

Education

- | | |
|---------------|---|
| 1995 | <i>Tokyo Institute of Technology, Tokyo, Japan,</i>
Doctor of Philosophy in Electrical Engineering |
| Dissertation: | Regular Perfect-Reconstruction Filter Banks and Wavelet Bases |
| 1988 | <i>Technical University of Sofia, Bulgaria,</i> Dipl. Eng. in Electrical Engineering |

Professional Activities

Board Membership:

Board of Governors, IEEE Standards Association, 2021-2022

Committee/Editorial Board Membership:

IEEE Communications Standards Magazine, Series Editor, Wireless and Radio Communications, 2017-

Committee Membership:

- IEEE 802.11 Working Group Voting Member, 2001-2003, 2006-present

- IEEE 802.15 Working Group Voting Member 1999-2001
- Chairman, IEEE Standards in Education Committee, 2006 – present
- Member of the Editorial Board, Journal of Networks.
- 2004-2005 Chairman and 2003-2004 Secretary of the Oakland/East Bay Chapter of the IEEE Communication Society.

Program Committee Membership:

- General Chair, Tactical Communications and Interoperability Conference, 2011
- General Chair, Fort Wayne Wireless Summer School 2009 and 2010
- Program Committee Member, Int. Conf. on Wireless Applications and Computing, 2007.
- Program Committee Member, Int. Conference on WLAN, WPAN, and WMAN, Hawaii, Aug. 2007.
- Program Committee Member, Int. Joint Conf. e-Business and Telecommunications, Barcelona, Spain, 2007.
- Program Committee Member, Int. Conf. Wireless Information Networks and Systems, Lisbon, Portugal, 2006.
- Technical Program Committee Member, Int. Conf. Networking and Services, ICNS 2006, Santa Clara, CA.
- Technical Program Committee Member, Advanced Int. Conference on Telecommunications, AICT, Guadeloupe, French Caribbean 2006.
- Program Committee Member, Int. Joint Conf. e-Business and Telecommunications, Reading, UK, 2005.
- Technical Program Committee Member, Int. Conf. Convergent Services and Next-Generation Networks, June 2005, Chicago, IL.
- Technical Program Committee Member, Int. Conference on Service Assurance with Partial and Intermittent Resources, Lisbon, Portugal, July 2005.
- Technical Program Committee Member, Int. Conf. Telecommunications, 2004, Brazil.
- 3rd Int. Workshop on Signal and Image Processing, Manchester, UK, Special session on wavelets in communication systems, signal and image processing, special session co-organizer, Nov. 1996.

Tutorials at International Conferences

- 1) T. Cooklev, “The analog RF-digital interface: the VITA 49 standard and evolution roadmap,” First IEEE Next G Summit, Johns Hopkins University, June 14, 2022.
- 2) T. Cooklev, “Open RF-digital interfaces and wireless ontologies,” IEEE BlackSeaCom, 4th International Black Sea Conference on Communications and Networking, Varna, Bulgaria, June 2016.
- 3) M. Cummings, T. Cooklev, “Software Defined Radio Technology”, Tutorial at the 2008 Symposium System on Chip, Tampere, Finland, Nov. 2008.
- 4) M. Cummings, T. Cooklev, “Software Defined Radio Technology”, Tutorial at the IASTED Int. Conference Computer Communications, Palma de Mallorca, Spain, Sept. 2008.
- 5) M. Cummings, T. Cooklev, “Software Defined Radio Technology”, Tutorial at the 2007 International Conference on Computer Design, Squaw Creek, CA 2007.
- 6) T. Cooklev, “Wireless communication standards: 802.11, 802.15, and 802.16,” Int. Conference Telecommunications, Fortaleza, Brazil, Aug. 2004, tutorial.
- 7) T. Cooklev, “Wireless data communication standards, IEEE Globecom 2003, Dec. 2003, San Francisco, CA, tutorial.

Short Courses and Invited Talks excluding conferences:

- 1) T. Cooklev, "Open RAN", Technical University of Sofia, Bulgaria, November 2019.
- 2) T. Cooklev, "Software-defined radio technology," Oulu University, Finland, Oct. 2017.
- 3) T. Cooklev, "Software-defined radio technology," Aarhus University, Denmark, Oct. 2017.
- 4) T. Cooklev, "Modern wireless systems," Technical University of Sofia, Bulgaria, 2014.
- 5) T. Cooklev, "Modern Wireless Systems," Featured faculty presentation, Feb. 2012, IPFW.
- 6) T. Cooklev, "Software-defined radio technology," Tokyo Institute of Technology, Dec. 2011.
- 7) T. Cooklev, "Software-defined radio technology," University of Akron, OH, 2010.
- 8) T. Cooklev, "Modern wireless systems," Catholic University of Leuven, Leuven, Belgium, 2010
- 9) T. Cooklev, "Modern wireless systems," University of Qatar, Doha, Qatar, 2009.
- 10) T. Cooklev, "Modern wireless systems," Technical University of Sofia, Bulgaria, 2009.
- 11) T. Cooklev, "Modern wireless systems: from Marconi's radio to cognitive radio," Sigma Xi presentation, February 2009, IPFW.
- 12) T. Cooklev "Software-Defined Radio Technology," Talk at IPFW, Oct. 2008.
- 13) M. Cummings, T. Cooklev, "Software Defined Radio Technology", IEEE Communication Society, Oakland/East Bay Chapter, presentation, Oct. 2007, San Ramon, CA.
- 14) T. Cooklev, "Engineering Standards in Engineering Education," presentation and a panel participant, Standards Engineering Society Annual Conference, San Francisco, CA, August. 2007. (panelist and presenter)
- 15) T. Cooklev, "Vector transform for multicarrier modulation", France Telecom, June 2007, Rennes, France.
- 16) T. Cooklev, "Wireless Communication Standards," Distinguished Lecture, IEEE Communication Society, Oct. 2006, University of Maine.
- 17) T. Cooklev, "The IEEE 802.11, 802.15, and 802.16 Families of Standards," Short Course, April 2006, Lietuvos Telekomas, Vilnius, Lithuania,
- 18) T. Cooklev, "The IEEE 802.11, 802.15, and 802.16 Families of Standards," Short Course, Feb. 2006, Austin, TX.
- 19) T. Cooklev, "The IEEE 802.11, 802.15, and 802.16 Families of Standards," Invited Talk, Dec. 2005, Cisco Systems, San Jose, CA.
- 20) Wireless local area networks, Hitachi Ltd., Brisbane, CA, June 2005.
- 21) T. Cooklev, "The IEEE 802.11, 802.15, and 802.16 Families of Standards," Invited Talk, May 2005, Texas Instruments, Dallas, TX.
- 22) T. Cooklev, "Standards for the Wireless Internet", IEEE Communication Society, Oakland/East Bay Chapter, presentation, January 2005. Freemont, CA.
- 23) T. Cooklev, "Wireless data communication standards, IEEE Wescon, Aug. 2003, San Francisco, CA, tutorial.
- 24) Short Course on 802.11, 802.15, 802.16, West Long Branch, NJ, August 2003
- 25) Wireless data communication standards, Lockheed Palo Alto Research Center, June 5, 2003.
- 26) Short Course on IEEE 802.11, 802.15, and 802.16, San Francisco, CA, Dec. 2002.
- 27) Standards for wireless data communications, University of Utah, Salt Lake City, UT, 1999
- 28) OFDM for wireless communications, 3Com Technology Forum, Boston, MA, Nov. 1998.
- 29) Filter banks and wavelets: a modern applied mathematics tool, Invited Lecture at the Analysis Day, Department of Mathematics and Statistics, Carleton University, Ottawa, Canada, 1997
- 30) Filter banks and wavelets for video signal processing, Genesis Microchip Inc, Markham, Ontario, Canada, July 1996.

- 31) Advanced topics in filter banks, wavelets, and their applications in modern communications systems, CRC, Ottawa, March and August 1996.
- 32) Digital filter banks and wavelets, Dept. Elect. Eng., University of Ottawa, March 1996.
- 33) Digital filter banks and wavelets, Dept. Elect. Eng., Queen's University, Kingston, March 1996.
- 34) Perfect-reconstruction filter banks and wavelet bases and their applications in digital communications, Fujitsu Laboratories, Kawasaki, Japan, July 1994.
- 35) Fast algorithms for signal processing, Istanbul University, Istanbul, Turkey, Jan. 1994.

Publications

Books and Monographs

- 1) T. Cooklev and A. Yagle, *Modern Communication Systems: A first course*, Michigan Publishing, 2023. (Available at <https://services.publishing.umich.edu/Books/M/Modern-Communications-Systems>)
- 2) T. Cooklev, *Wireless communications standards: A Study of IEEE 802.11, 802.15, 802.16*, IEEE Press, New York, NY. 2004.

Chapters in Books

- 1) A. Vlahov, D. Elkova, V. Poulkov, T. Cooklev, Virtualized, open, and intelligent: the evolution of the Radio Access Network,” River Publishers, 2021.
- 2) Subbu Ponnuswamy, Todor Cooklev, Yang Xiao, and Krishna Sumanth Velidi, “Security in fixed and mobile IEEE 802.16 networks,” Chapter 4, *WiMAX/MobileFi: Advanced Research and Technology*, edited by Yang Xiao, Taylor and Francis, January 2008.
- 3) T. Cooklev and A. Hristozov, “The Software Communications Architecture,” in *Resource Management in Future Internet*, edited by Ramjee Prasad, River Publishers, Denmark, 2015.

Journal Papers

- 1) V. Kolev, T. Cooklev, F. Keinert, “Bauer’s spectral factorization method for low order multiwavelet filter design”, *Journal of Computational and Applied Mathematics*, vol. 441, May 2024.
- 2) Kolev, T. Cooklev, F. Keinert, “Design of a Simple Orthogonal Multiwavelet Filter by Matrix Spectral Factorization,” *Circuits, Systems, and Signal Processing*, 2019.
- 3) Y. Acar and T. Cooklev, “High performance OFDM with index modulation”, *Physical Communication*, vol. 32, pp. 192-199, 2019.
- 4) M. Sherman and T. Cooklev, “Abstract descriptions of spectrum: VITA 49 and IEEE 1900.5.2”, *IEEE Communications Standards Magazine*, vol. 2, no. 4, pp. 43-48, December 2018.
- 5) T. Cooklev, V. Poulkov, D. Bennett, K. Tonchev, “Enabling RF data analytics services and applications via cloudification,” *IEEE Aerospace Electronic Systems Magazine*, vol. 33, no. 5-6, pp. 44-55, May-June 2018.

- 6) V. Kolev, T. Cooklev, F. Keinert, "Matrix spectral factorization for the SA4 multiwavelet," *Journal of Multidimensional Systems and Signal Processing*, vol.29, Issue 4, pp 1613–1641, 2018.
- 7) H. Dogan, T. Cooklev, and J. Darabi, "Improved low-complexity zero-padded OFDM receivers", *Digital Signal Processing*, vol. 51, pp. 92–100, April 2016.
- 8) P. Baltiiski, I. Iliev, B. Kehaiov, V. Poulkov, and T. Cooklev, "Long-Term Spectrum Monitoring with Big Data Analysis and Machine Learning for Cloud-Based Radio Access Networks," *Wireless Personal Communications*, vol. 87, issue 3, pp. 815-835, April 2016.
- 9) T. Cooklev, J. Darabi, C. McIntosh, and M. Mosaheb, "Cloud-based approach for spectrum monitoring," *IEEE Instrumentation and Measurement Magazine*, vol. 18, no. 2, pp. 33-37, April 2015.
- 10) Sven Bilen, A. Wyglinski, C. Anderson, T. Cooklev, C. Dietrich, B. Farhang-Boroujeny, "On Software-Defined Radio as an integrative educational resource," *IEEE Communications Magazine*, vol. 52, no. 5, pp. 184-193, May 2014.
- 11) Hakan Yıldız, Yusuf Acar, Todor Cooklev, Hakan Dogan, "Generalized Prefix for Space-Time Block Coded OFDM Wireless Systems over Correlated MIMO Channels," *IET Communications*, vol. 8, no. 9, pp. 1589-1598, June 2014.
- 12) T. Cooklev, A. Nishihara, "An Open RF-Digital interface for software-defined radios," *IEEE Micro*, vol. 33, no. 6, pp. 47-55, Dec. 2013.
- 13) T. Cooklev, R. Normoyle, and D. Clendenen, "The VITA 49 RF-digital interface," *IEEE Circuits Systems Magazine*, vol. 12, no. 4, pp. 21-32, Dec. 2012.
- 14) T. Cooklev, "An improved prefix for OFDM-based cognitive radios", *Electron. Lett.*, vol. 48, No. 4, Feb. 2012.
- 15) Y. Alqudah and T. Cooklev, "Hands-on open access broadband wireless technology lab", *Int. J. Interactive Mobile Tech.*, Vol. 6, No 4, 2012, pp. 13-18.
- 16) T. Cooklev, H. Dogan, R. Cintra, H. Yildiz, "Generalized prefix for OFDM wireless systems over quasi-static channels," *IEEE Transactions on Vehicular Technology*, vol. 60, No. 8, pp. 3684 – 3693, Nov. 2011.
- 17) F. Ramirez-Mireles, T. Cooklev, and G. A. Paredes-Orozco, "UWB-FSK: Performance tradeoffs for high-complexity receivers," *IEEE Transactions on Consumer Electronics*, vol. 56, no. 4, pp. 2123-2131, 2010.
- 18) S. Hossain, D. Batovski, and T. Cooklev, "Eight-channel transmultiplexer with binary matrix sequences," *Assumption Univ. Journal of Technology (Thailand)*, vol. 13, No. 4, pp. 193-202, 2010.

- 19) T. Cooklev, "Engineering standards and engineering education," *Journal of IT Standardization Research*, vol. 8, 2010, pp. 1-10.
- 20) R. Cintra and T. Cooklev, "Robust image watermarking using non-regular wavelets," *Journal of Signal, Image, and Video Processing*, 2008.
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Appendix 2

MODERN COMMUNICATIONS SYSTEMS:

A FIRST COURSE

Todor Cooklev
Andrew E. Yagle





MODERN COMMUNICATIONS SYSTEMS: A First Course

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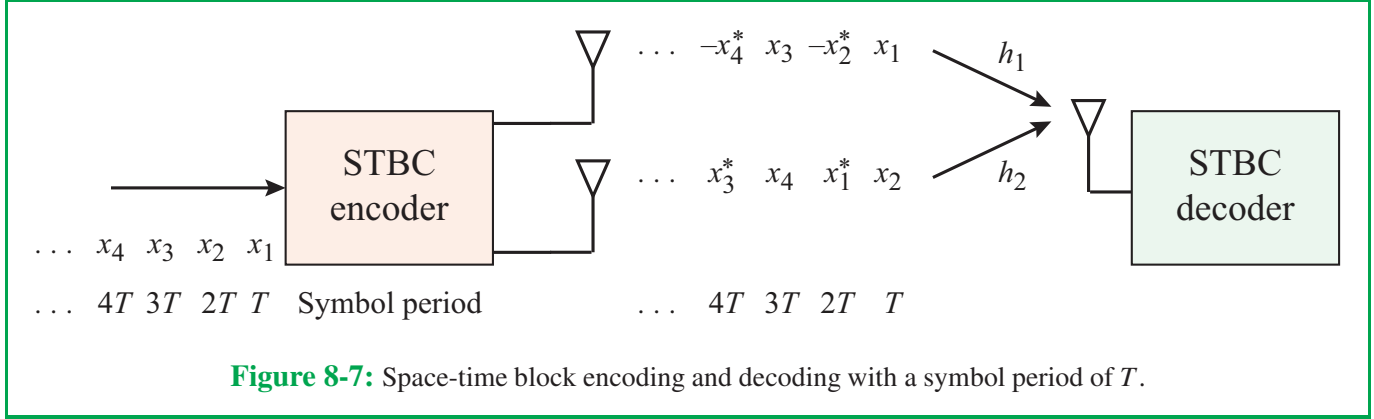
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STBC eliminates ISI since the matrix

$$\begin{bmatrix} h_1^* & h_2 \\ h_2^* & -h_1 \end{bmatrix}$$

is orthogonal. After multiplication with an orthogonal matrix, the noise vector will remain white. Since two symbols are transmitted for the duration of two symbol periods, the data rate is the same as a SISO connection. However, the reliability has increased because the channel gains are $|h_1|^2 + |h_2|^2$. If there is fading, it is likely that fading will impact either h_1 or h_2 , but not both.

At the output of the decoder the SNR becomes

$$\gamma = \frac{(|h_1|^2 + |h_2|^2)^2}{2(|h_1|^2 + |h_2|^2)\sigma_n^2} = \frac{|h_1|^2 + |h_2|^2}{2\sigma_n^2}. \quad (8.53)$$

The factor of 2 in the denominator comes from the fact that every symbol is transmitted using half of the total power. Both STBC and MRC have diversity order equal to two as the slope of the bit error rate curves is the same. However, the array gain of STBC is equal to 1 and MRC outperforms the STBC by 3 dB because its array gain is equal to 2.

Transmit and receive diversity methods have become very popular. *For example, a base station might use diversity transmission when communicating to a mobile device, and diversity reception when receiving from a mobile.* In this way, both uplink and downlink benefit from the process even though only the base station has multiple antennas.

8-3 Introduction to MIMO Channels

Like SISO, MIMO transmission is also characterized by large-scale, medium-scale, and small-scale fading. Path loss models for multiantenna systems are identical to the path loss model for single-antenna systems.

However, small-scale fading effects in MIMO systems, observed at small changes in distance, are more complex mathematically, compared with SISO.

If we assume that there are M inputs and N outputs, it is convenient to write the input and output signals as column vectors:

$$\mathbf{x}(t) = [x_1(t) \ x_2(t) \ \cdots \ x_M(t)]^T \quad (8.54a)$$

(input MIMO bandpass signal)

and

$$\mathbf{y}(t) = [y_1(t) \ y_2(t) \ \cdots \ y_N(t)]^T. \quad (8.54b)$$

We also assume that all antennas have the same polarization and radiation pattern.

If $\mathbf{x}(t)$ is the vector bandpass signal emitted from the antennas, then the received bandpass signal is the combination of multiple paths, the k th path arriving with delay τ_k :

$$\mathbf{y}(t) = \sum_k \mathbf{a}_k(t) \mathbf{x}[t - \tau_k(t)] + \mathbf{n}(t), \quad (8.55)$$

where $\mathbf{n}(t)$ is a noise vector and $\mathbf{a}_k$ is an $(N \times M)$ matrix for which the number of rows is equal to

the number of channel outputs and the number of columns is equal to the number of channel inputs. Some elements of each $\mathbf{a}_k$ could be zeros. Each path is described by a matrix coefficient and the number of matrix coefficients in this sum depends on the receiver sensitivity.

In general, the matrix coefficients and the delays are functions of time, due to motions of the transmitter, receiver, or objects in the environment.

We will assume that any motion is slow enough so that the channel remains constant over the duration of at least one symbol. Then, the time index t can be removed so that $\mathbf{a}_k(t) = \mathbf{a}_k$, $\tau_k(t) = \tau_k = d_k/c$, and $\mathbf{y}(t)$ becomes

$$\mathbf{y}(t) = \sum_k \mathbf{a}_k \mathbf{x}(t - \tau_k). \quad (8.56)$$

The propagation MIMO channel is a linear system, and with the slow-motion assumption, it also becomes time-invariant. Hence, the received signal can be described by the MIMO convolution:

$$\mathbf{y}(t) = \mathbf{h}(t) * \mathbf{x}(t) = \int_{-\infty}^{\infty} \mathbf{h}(\tau) \mathbf{x}(t - \tau) d\tau. \quad (8.57)$$

(definition of MIMO convolution)

Since $\mathbf{h}(t)$ is of dimension $(N \times M)$, and $\mathbf{x}(t)$ is a vector of dimension $(M \times 1)$, $\mathbf{h}(t)$ and $\mathbf{x}(t)$ are not mathematically interchangeable; i.e., *MIMO convolution is not commutative*.

A MIMO channel is described by an $(N \times M)$ **matrix impulse response**:

$$\mathbf{h}(\tau) = \sum_k \mathbf{a}_k \delta(\tau - \tau_k). \quad (8.58)$$

(MIMO channel impulse response)

Each (j, i) th element of each matrix $\mathbf{a}_k^{ji}$ is measured at the j th output when an impulse is present only at the i th input.

Following the rules of matrix multiplication, the j th output of the LTI MIMO channel is the sum

$$y_j(t) = \sum_{i=1}^M \int_{-\infty}^{\infty} h_{ji}(\tau) x_i(t - \tau) d\tau. \quad (8.59)$$

As illustrated in **Fig. 8-8**, the signal received by every receive antenna includes reflection paths that are due to every transmit antenna.

It can be proven in a way that is entirely analogous to the SISO case in Eq. (2.59) that the MIMO convolution operation corresponds to multiplication in the frequency domain (with the distinction that it is not commutative):

$$\mathbf{Y}(f) = \mathbf{H}(f) \mathbf{X}(f), \quad (8.60)$$

where $\mathbf{Y}(f)$ is an N -vector, $\mathbf{X}(f)$ is an M -vector, and $\mathbf{H}(f)$ is an $(N \times M)$ matrix. The j th element of the vector $\mathbf{y}(f)$ is

$$Y_j(f) = \sum_{i=1}^M H_{ji}(f) X_i(f).$$

The frequency response of the passband MIMO channel is

$$\mathbf{H}(f) = \int_{-\infty}^{\infty} \mathbf{h}(\tau) e^{-j2\pi f\tau} d\tau \quad (8.61a)$$

$$= \sum_k \mathbf{a}_k e^{-j2\pi f\tau_k}. \quad (8.61b)$$

The amplitude gain of each path is $|\mathbf{a}_k|$ and the power gain is $|\mathbf{a}_k|^2$, where the $|\mathbf{a}_k|$ is an element-wise absolute value.

One fundamental property of electromagnetic fields is reciprocity. The electromagnetic field at a destination by a source remains the same if the source and destination points swap their positions and the carrier frequency remains the same. This property is known as **channel reciprocity**.

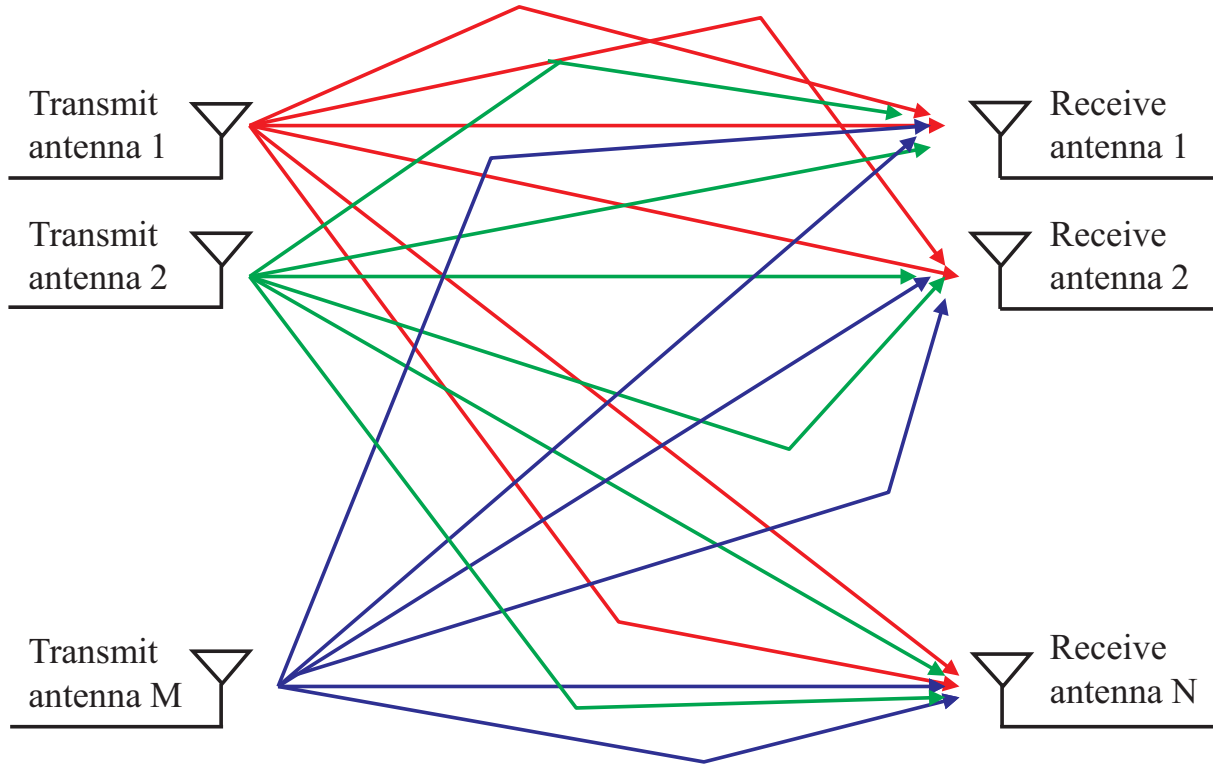


Figure 8-8: Illustration of the MIMO propagation channel.

The passband MIMO channel has a baseband equivalent. If $\mathbf{x}(t)$ is the transmitted passband signal with a complex envelope $\mathbf{x}_{\text{bb}}(t) = \mathbf{x}_I(t) + j\mathbf{x}_Q(t)$, then

$$\mathbf{x}(t) = \Re[\mathbf{x}_{\text{bb}}(t) e^{j2\pi f_c t}]. \quad (8.62)$$

The received passband signal $y(t)$ also has a complex envelope

$$\mathbf{y}(t) = \Re[\mathbf{y}_{\text{bb}}(t) e^{j2\pi f_c t}]. \quad (8.63)$$

Using Eq. (8.56) in Eqs. (8.62) and (8.63) leads to

$$\begin{aligned} \mathbf{y}(t) &= \Re[\mathbf{y}_{\text{bb}}(t) e^{j2\pi f_c t}] \\ &= \sum_k \mathbf{a}_k \Re[\mathbf{x}_{\text{bb}}(t - \tau_k) e^{j2\pi f_c (t - \tau_k)}] \\ &= \Re \left[\sum_k \mathbf{a}_k e^{-j2\pi f_c \tau_k} \mathbf{x}_{\text{bb}}(t - \tau_k) e^{j2\pi f_c t} \right]. \end{aligned} \quad (8.64)$$

Therefore, the received baseband signal is equal to

$$\begin{aligned} \mathbf{y}_{\text{bb}}(t) &= \sum_k \mathbf{a}_k e^{-j2\pi f_c \tau_k} \mathbf{x}_{\text{bb}}(t - \tau_k) \\ &= \sum_k \mathbf{a}_k e^{j\theta_k} \mathbf{x}_{\text{bb}}(t - \tau_k) \\ &= \sum_k \mathbf{a}_k^{\text{bb}} \mathbf{x}_{\text{bb}}(t - \tau_k). \end{aligned} \quad (8.65)$$

(received baseband signal)

Each baseband multipath component is characterized by an amplitude and a phase; i.e., it is complex-valued:

$$\mathbf{a}_k^{\text{bb}} = \mathbf{a}_k e^{-j2\pi f_c \tau_k} = \mathbf{a}_k e^{j\theta_k}. \quad (8.66)$$

The coefficient θ_k is the carrier phase offset between the transmitting and receiving stations due to path

delay τ_k . According to the channel reciprocity principle, the passband channel is reciprocal. Channel reciprocity extends to baseband channels only in theory. In practice, the upconversion and downconversion circuits are not ideal. Therefore, while the transmission between a pair of antennas is reciprocal, the baseband channels between the pair of devices cannot be considered exactly reciprocal.

Similar to SISO channels, at the baseband level the channel is a linear time-invariant system with a complex-valued baseband impulse response:

$$\mathbf{h}_{\text{bb}}(t) = \sum_k \mathbf{a}_k e^{j\theta_k} \delta(t - \tau_k). \quad (8.67)$$

We can also develop a discrete-time model if we sample this impulse response according to $\mathbf{h}[l] = \mathbf{h}[lT_s]$. The matrix $\mathbf{h}[l]$ is one channel “tap” at a specific time delay lT_s , keeping in mind that a tap may not coincide with an integer multiple of the sampling period T_s and is due to the cumulative effect of all paths arriving at approximately $lT_s = l/W$. A tap can be rounded to the closest sampling instance $\lfloor \tau_k/T_s + 0.5 \rfloor T_s$, where $\lfloor x \rfloor$ denotes the greatest integer function; i.e., $\lfloor x \rfloor$ discards the fractional part of x .

The total number of resolvable paths is L and the channel is described by the discrete linear MIMO convolution:

$$\mathbf{y}[k] = \sum_{l=0}^{L-1} \mathbf{h}[l] \mathbf{x}[k-l]. \quad (8.68)$$

(definition of discrete MIMO convolution)

There are several detailed models for MIMO channels. One approach is to model each SISO component $h_{ij}[l]$ as the sum of a large number of random components, and according to the Central Limit Theorem, it becomes a zero-mean, complex Gaussian random variable:

$$h_{ij}[l] \sim N(0, 1/2) + jN(0, 1/2) \sim CN(0, 1). \quad (8.69)$$

This is the simplest nontrivial MIMO channel model. It assumes that the elements of the MIMO

channel matrix are IID zero-mean complex Gaussian variables, with zero mean and unit variance. This model is accurate if the antennas are separated by more than one-half of the carrier wavelength, or if other measures are taken. This model also requires that the propagation channel contains a large number of scattering objects, which leads to independent fading at the antenna elements.

Other models are also possible. For example, using simulation software, it is possible to perform ray tracing to calculate the ray paths between each transmitting and each receiving antenna. In an indoor scenario, this requires taking into account the building floor plan, the main pieces of furniture, and the electromagnetic characteristics of the building materials used for walls, floors, ceiling, windows, and doors.

8-4 Review of Singular-Value Decomposition of the Channel Matrix

Singular-value decomposition (SVD) is a very useful tool for the study of MIMO systems. According to SVD, any $(N \times M)$ matrix $\mathbf{H}$ can be written as the product of three matrices

$$\mathbf{H}_{N \times M} = \mathbf{U}_{N \times N} \mathbf{\Sigma} \mathbf{V}_{M \times M}^H, \quad (8.70)$$

(definition of singular value decomposition (SVD))

where $\mathbf{U}$ and $\mathbf{V}$ are $(N \times N)$ and $(M \times M)$ unitary matrices:

$$\mathbf{U}^H \mathbf{U} = \mathbf{U} \mathbf{U}^H = \mathbf{I}_N \quad (8.71a)$$

and

$$\mathbf{V}^H \mathbf{V} = \mathbf{V} \mathbf{V}^H = \mathbf{I}_M. \quad (8.71b)$$

Unitary matrices have orthonormal columns.

In the SVD, $\mathbf{\Sigma}$ is an $(N \times M)$ rectangular diagonal matrix with nonnegative elements along the main

diagonal:

$$\mathbf{\Sigma} = \begin{bmatrix} \sigma_1 & & & & & \\ & \sigma_2 & & & & \\ & & \ddots & & & \\ & & & \sigma_r & & \\ & & & & 0 & \\ & & & & & \ddots \\ & & & & & & 0 \end{bmatrix}. \quad (8.72)$$

The diagonal elements of $\mathbf{\Sigma}$ are the *singular values* of $\mathbf{H}$, which are unique and arranged in descending order: $\sigma_1 > \sigma_2 > \dots$. The number of nonzero singular values is equal to the rank r of $\mathbf{H}$ and is at most $\min(M, N)$. Since some of these singular values may be close to zero, the number of nonzero singular values larger than a specific threshold is the effective rank of $\mathbf{H}$.

The SVD serves to diagonalize a channel matrix because $\mathbf{U}^H \mathbf{H} \mathbf{V}$ is the diagonal matrix $\mathbf{\Sigma}$. In this context, it is conceptually similar to the diagonalization of a circulant matrix by the DFT matrix introduced in Chapter 6. The difference is that the DFT matrix does not depend on the channel $\mathbf{H}$ and is known in advance. The DFT matrix does not need to be computed because diagonalization is accomplished by calculating the FFT of the received signal. However, the DFT is capable of diagonalizing only circulant matrices. The SVD can diagonalize any matrix, but needs to be calculated.

The columns of $\mathbf{U}$ are the eigenvectors of $\mathbf{H} \mathbf{H}^H$ because

$$\mathbf{H} \mathbf{H}^H = \mathbf{U} \mathbf{\Sigma} \mathbf{V}^H \mathbf{V} \mathbf{\Sigma}^H \mathbf{U}^H = \mathbf{U} \mathbf{\Sigma}_M^2 \mathbf{U}^H \quad (8.73)$$

and

$$\mathbf{H} \mathbf{H}^H \mathbf{U} = \mathbf{U} \mathbf{\Sigma}_M^2. \quad (8.74)$$

The matrix $\mathbf{\Sigma}_M^2$ is $(N \times N)$ with $(N - r)$ trailing zeros and is denoted by $\mathbf{\Lambda}$:

$$\begin{aligned} \mathbf{\Lambda} &= \text{diag}(\sigma_1^2 \ \sigma_2^2 \ \dots \ \sigma_r^2 \ 0 \ \dots \ 0) \\ &= \text{diag}(\lambda_1 \ \lambda_2 \ \dots \ \lambda_r \ 0 \ \dots \ 0). \end{aligned} \quad (8.75)$$

The squared singular values are the eigenvalues of $\mathbf{H} \mathbf{H}^H$ and also of $\mathbf{H}^H \mathbf{H}$. Similar to Eqs. (8.73) and (8.74), the columns of $\mathbf{V}$ are the eigenvectors of $\mathbf{H}^H \mathbf{H}$:

$$\mathbf{H}^H \mathbf{H} = \mathbf{V} \mathbf{\Lambda} \mathbf{V}^H, \quad (8.76)$$

$$\mathbf{H}^H \mathbf{H} \mathbf{V} = \mathbf{V} \mathbf{\Lambda}, \quad (8.77)$$

where $\mathbf{\Lambda}$ is now $(M \times M)$ with $M - r$ trailing zeros.

Calculating the SVD amounts to finding the eigenvalues and eigenvectors of $\mathbf{H} \mathbf{H}^H$ and $\mathbf{H}^H \mathbf{H}$. The singular values are the square roots of the eigenvalues of $\mathbf{H} \mathbf{H}^H$ or $\mathbf{H}^H \mathbf{H}$. The eigenvectors of $\mathbf{H}^H \mathbf{H}$ make up the columns of $\mathbf{V}$, and the eigenvectors of $\mathbf{H} \mathbf{H}^H$ make up the columns of $\mathbf{U}$. The columns are ordered according to the order of the singular values.

From the SVD, it follows that:

$$\mathbf{H} \mathbf{V} = \mathbf{U} \mathbf{\Sigma} \quad (8.78a)$$

and

$$\mathbf{H}^H \mathbf{U} = \mathbf{V} \mathbf{\Sigma}. \quad (8.78b)$$

Hence, $\mathbf{U}$ and $\mathbf{V}$ can be computed from each other.²

Here are some examples:

Example 8-5: Singular-Value Decompositions

$$\begin{aligned} \begin{bmatrix} 1 & 1 & j \\ 1 & 1 & j \end{bmatrix} &= \frac{1}{\sqrt{2}} \begin{bmatrix} -1 & 1 \\ -1 & -1 \end{bmatrix} \begin{bmatrix} \sqrt{6} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \\ &\cdot \frac{1}{\sqrt{6}} \begin{bmatrix} -\sqrt{2} & 2 & 0 \\ -\sqrt{2} & -1 & \sqrt{3}j \\ -j\sqrt{2} & -j & \sqrt{3} \end{bmatrix}^H. \end{aligned} \quad (8.79)$$

$$\frac{1}{\sqrt{2}} \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} = \frac{1}{\sqrt{2}} \begin{bmatrix} -1 & j \\ -j & 1 \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} -1 & 0 \\ 0 & 1 \end{bmatrix}^H$$

²For example, MATLAB includes a function, called `svd`, for computing the SVD.

$$\begin{aligned}
& \begin{bmatrix} 0.9 + j0.1 & 0.2 - j0.3 \\ -0.3 + j0.4 & -0.8 - j0.2 \end{bmatrix} \\
&= \begin{bmatrix} -0.71 + 0.07j & -0.55 - 0.43j \\ -0.61 - 0.34j & -0.69 - 0.18j \end{bmatrix} \\
&\cdot \begin{bmatrix} 1.2 & 0 \\ 0 & 0.67 \end{bmatrix} \begin{bmatrix} -0.79 & -0.6 \\ -0.6 - 0.04j & 0.79 + 0.05j \end{bmatrix}^H
\end{aligned}$$

$$\begin{aligned}
\begin{bmatrix} 1 & -1 \\ 0 & 1 \\ 1 & 0 \end{bmatrix} &= \begin{bmatrix} -2/\sqrt{6} & 0 & -1/\sqrt{3} \\ -1/\sqrt{6} & -1/\sqrt{2} & -1/\sqrt{3} \\ -1/\sqrt{6} & -1/\sqrt{2} & 1/\sqrt{3} \end{bmatrix} \\
&\cdot \begin{bmatrix} \sqrt{3} & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} -1 & -1 \\ 1 & -1 \end{bmatrix}^H,
\end{aligned}$$

$$\begin{bmatrix} 1 & 1 \end{bmatrix} = \begin{bmatrix} \sqrt{2} & 0 \end{bmatrix} \frac{1}{\sqrt{2}} \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}^H.$$

Next we show that the SVD of column and row vectors can be computed efficiently.

Example 8-6: SVD of Column and Row Vectors

Find the SVD of the $N \times 1$ column vector $\mathbf{h}$.

Solution: First, form the column vector $\mathbf{u}$ by normalizing $\mathbf{h}$:

$$\mathbf{u} = \frac{\mathbf{h}}{\|\mathbf{h}\|_2}. \quad (8.80)$$

Therefore $\mathbf{u}^H \mathbf{u} = 1$. Let us define $\mathbf{U}_1$ to be an $N \times (N-1)$ matrix with orthonormal columns such that $\mathbf{u}^H \mathbf{U}_1 = \mathbf{0}$. This can be done with the Gram-Schmidt procedure described below. Then $\mathbf{U} = [\mathbf{u} \ \mathbf{U}_1]$ is a square $N \times N$ unitary matrix because

$$[\mathbf{u} \ \mathbf{U}_1]^H [\mathbf{u} \ \mathbf{U}_1] = \begin{bmatrix} \mathbf{u}^H \mathbf{u} & \mathbf{u}^H \mathbf{U}_1 \\ \mathbf{U}_1^H \mathbf{u} & \mathbf{U}_1^H \mathbf{U}_1 \end{bmatrix} = \mathbf{I}. \quad (8.81)$$

The SVD of the column vector is

$$\mathbf{h} = \mathbf{U} \begin{bmatrix} \|\mathbf{h}\|_2 \\ 0 \\ \vdots \\ 0 \end{bmatrix} \mathbf{1}. \quad (8.82)$$

There is only one nonzero singular value and it is equal to the norm of $\mathbf{h}$. Also, $\mathbf{V}^H = \mathbf{1}$ and $\mathbf{\Sigma}$ is a column vector since $N = 1$.

For example,

$$\begin{bmatrix} h_1 \\ h_2 \end{bmatrix} = \left(\frac{1}{\|\mathbf{h}\|_2} \begin{bmatrix} h_1 & h_2^H \\ h_2 & -h_1^H \end{bmatrix} \right) \begin{bmatrix} \|\mathbf{h}\|_2 \\ 0 \end{bmatrix} \mathbf{1}. \quad (8.83)$$

Note that the orthogonal matrix is the same one that appears in Eq. (8.50).

The SVD of a row vector can be found by transposition. For example,

$$\begin{bmatrix} h_1 & h_2 \end{bmatrix} = \mathbf{1} \begin{bmatrix} \|\mathbf{h}\|_2 & 0 \end{bmatrix} \frac{1}{\|\mathbf{h}\|_2} \begin{bmatrix} h_1^H & h_2 \\ h_2^H & -h_1 \end{bmatrix}^H \quad (8.84)$$

8-5 Capacity of a Memoryless MIMO Channel

A MIMO system is *memoryless* if, at any time instant t_0 , the output vector $\mathbf{y}(t)$ depends on the input vector $\mathbf{x}(t)$ only at the same time instant; i.e.,

$$\mathbf{y}(t_0) = \mathbf{H}\mathbf{x}(t_0). \quad (8.85)$$

Otherwise the received vector depends on previously transmitted vectors and the system is referred to as having memory. A memoryless channel has an impulse response that is just an $(N \times M)$ matrix $\mathbf{H}$, unlike Eq. (8.68).

Narrowband MIMO channels where all M transmitted signals occupy the same narrow bandwidth are examples of memoryless systems. When the bandwidth of the transmitted signal is narrow enough, the signal amplitude can be considered constant in frequency; i.e., it is *frequency-flat*. The channel is described by a single $(N \times M)$ complex matrix $\mathbf{H}$, which is both a time-domain tap and a frequency-domain coefficient,