OPTIMAL ANTENNA DIVERSITY COMBINING FOR IEEE 802.11A SYSTEM

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Abstract

IEEE 802.11a/g devices promise to accommodate the increasing consumer demands for high data rate wireless communications. A novel optimal decoding method for receiver antenna diversity combining for COFDM system is discussed in this paper. The proposed method provides robust wireless connections for applications such as wireless multimedia communications. The proposed optimal diversity combining integrates the channel equalization, demodulation (bit metrics calculation) and diversity combining in the decoder, which is the maximum likelihood decoding method for the diversity combining for COFDM system. The proposed method can have about 4-6 dB gain over a single antenna receiver and 2-4 dB gain over a conventional symbol level diversity-combining receiver without increasing the implementation complexity.

***Index terms*—WLAN, COFDM, antenna diversity combining, optimal decoding**

I. INTRODUCTION

The market for Wireless Local Area Network (WLAN) products is increasing rapidly with the roll out of 802.11b (Wi-Fi) products into the home, public and office environments. With the increasing consumer demand for wireless multimedia, even higher throughput will be required. The IEEE 802.11a standard is designed to accommodate this demand by providing bit rates of up to 54 Mbps in the 5 GHz band.

IEEE 802.11a is a wireless local area network (WLAN) standard powered by Coded Orthogonal Frequency Division Multiplexing (COFDM). The IEEE802.11a system can achieve transmission data rates from 6Mbps to 54Mbps. The highest mandatory transmission rate is 24Mbps. In order to satisfy high volume multimedia communication, higher transmission rates are needed. Yet, because of the hostile wireless channel that the system encounters, to achieve this goal, a higher transmission power and/or strong line of sight path becomes a necessity. Since increasing the transmission power will lead to strong interference to other users, the IEEE 802.11a standard constrains the transmission power to 40mW for transmission working in the range of 5.15-5.25GHz, 200mW for 5.25-5.35GHz and 800mW for 5.725-5.825GHz. Strong line of sight path on wireless channel can only be guaranteed when the transmitter and receiver are very close to each other, which limits the operating range of the system. A new solution to this problem using multiple antennae is provided in this paper.

Current 802.11a receivers incorporate antenna switching as a mechanism to increase the robustness of the received signal [1]. Since OFDM separates the large frequency band into several small sub-bands so that each sub band experiences flat fading, Maximum Ratio Combining (MRC) is most suitable for antenna diversity combining for OFDM system. MRC improves upon antenna switching by combining the symbol modulated on each sub-carrier at the symbol level as the output of the demodulator [2] – [5]. Theoretical analysis [6] shows that with about one half of the wavelength of the carrier frequency separation between the two antenna elements, the correlation of the signal received at these two antennae should be very small, which implies that the two antennae experience different channels. The indoor wireless channel usually shows frequency selective fading for wideband wireless systems, which presents deep fading at different frequency from time to time. Although COFDM systems takes advantage of strong forward error correction (FEC) coding and interleaving that can partly overcome the hostile channel, sometimes it is still not enough for tough indoor channels, especially for the high data rate transmission. With two or more antennae in operation, when one antenna is experiencing deep fading, others have very high chances to be not. Thus when combining the signal coming from different antennae, the back end of the receiver will see a much stable signal than single antenna system. The combining operation can be independent from the FEC decoding. This is the likely scheme that most CE manufactures will pursue in the near future to increase the performance of IEEE 802.11a system with affordable implementation complexity increase.

In the simplest case, after the FFT operation, the received signal on each antenna can be divided by the channel estimation for each sub-carrier. Then the MRC can be performed by adding the signals from both antenna elements. But this method boosts the noise when the sub-carrier meets the deep fading. One of the solutions is to use Channel States Information (CSI) to reduce the noise boosting operation [7]. But since the CSI operation should combine with the Viterbi decoder, it is difficult to be used for MRC that is performed before Viterbi decoder.

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Another way to implement MRC is to combine the signal coming from two antenna elements first and then use Zehavi's sub-optimum decoding method to decode the combined data [8]. The sub-optimum decoding method will be described in more detail in Section II of this paper. This method combines the channel equalization and symbol demapping into one step, which avoids the noise-boosting problem caused by simply dividing the received data on each sub-carrier by the channel estimation for that specific sub-carrier. This is the method to combine the signal at symbol level. Yet this method separates the operation of MRC and decoding, which dose not fully take advantage of the design of convolutional coded COFDM system. This paper presents an optimal receiver diversity combining method for convolutional encoded COFDM system, which can give several dB gain over the conventional symbol level combining technique. The new optimal method combines the MRC, channel equalization and Viterbi decoding into one integrated step, which fulfills the optimum decoding for a two antenna system. With carefully theoretical analysis, we show that the optimal decoding can be implemented simply as combining the signal from two antennae at bit level. First the data from different antenna will use sub-optimum decoding to decode the received data on each sub-carrier separately. Then the decoded "soft" bits will be combined by its corresponding sub-carrier before it is sent to the Viterbi decoder. From implementation complexity point of view, the proposed method has almost the same complexity as the symbol level MRC. But it can provide 2-4dB gain over the sub-optimal symbol level MRC.

The rest of the paper is organized as following. Section II gives an overview of channel model, IEEE 802.11a transceiver and Zehavi's soft metrics calculation algorithm. Section III introduces the conventional and the new optimal diversity combining technique that use Zehavi's algorithm. Theoretical analysis is given to show the reason why the optimal combining performs better than the conventional combining technique. Simulation results comparing the optimal bit level combining, conventional symbol level combining and single antenna system are given in Section IV. Conclusion is given in Section V.

II. CHANNEL MODEL AND SUBOPTIMAL DECODING METHOD FOR OFDM SYSTEM

A simple and effective way to simulate the channel is by using its impulse response. A model based on a tapped delay line is usually used for this purpose.

$$h(t,\tau,d)=\sum_{k=1}^{N_d} a_k(t)b_k(\varphi)\delta[\tau-\tau_k(t)]e^{j\theta_k(t)} \qquad (1)$$

Where t, τ and d are the observation time, impulse delay and the location of the receiver, respectively; other parameters are defined as:

N_d: the number of multipath components, which is related to the location of the receiver;

$a_k(t)$: time-varying amplitude of the kth path;

$\tau_k(t)$: time of arrival (TOA) of the kth path;

$\theta_k(t)$: phase sequence of the kth path;

$b_k(\varphi)$: angle of arrival (AOA) of the kth path.

A transmitted signal passing through the channel can be modeled as the convolution of the input signal and the channel impulse response.

In the following work, we use the so called exponential Rayleigh fading channel model that has been adopted by IEEE 802.11 working group as the baseline for predicting performance results for a given implementation. It is composed of complex samples with random uniformly distributed phase and Rayleigh distributed magnitude with average power decaying exponentially with time. The mathematical model for the channel is as follow [1]

$$h_k = N(0,\frac{1}{2}\sigma_k^2)+jN(0,\frac{1}{2}\sigma_k^2) \qquad (2)$$

where $N(0,\frac{1}{2}\sigma_k^2)$ is a zero mean Gaussian random variable with variance of $\frac{1}{2}\sigma_k^2$ and $\sigma_k^2=\sigma_0^2 e^{-kT/\tau_{rms}}$,where T is the OFDM symbol period.

The basic principle of OFDM is to split a high-rate data stream into a number of lower rate streams that are transmitted simultaneously over a number of sub-carriers. Because the symbol duration increases for the lower rate

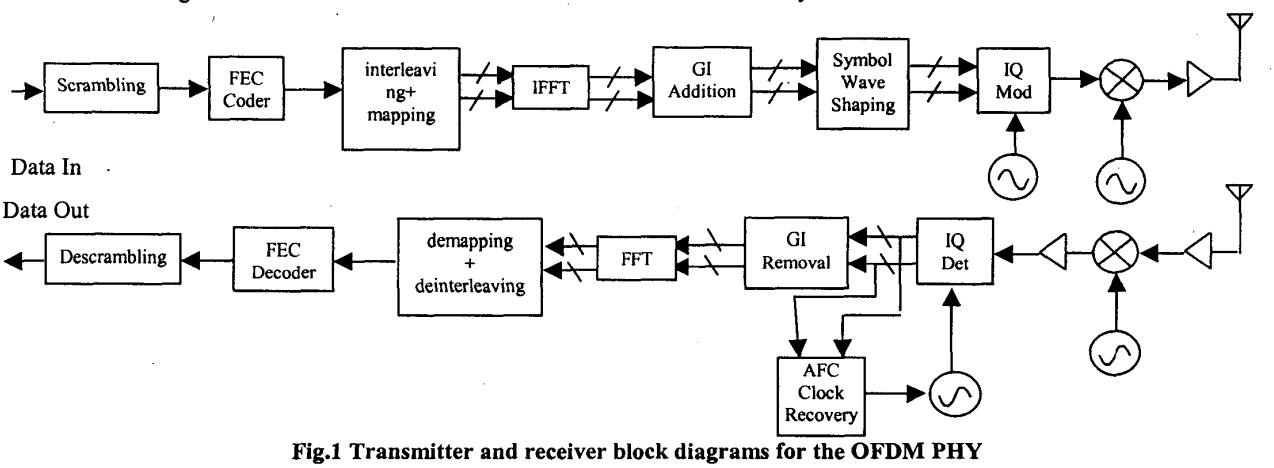


Fig.1 Transmitter and receiver block diagrams for the OFDM PHY

parallel sub-carriers, the relative amount of dispersion in time caused by multipath delay spread is decreased. Intersymbol interference is eliminated almost completely by introducing a guard interval in every OFDM symbol. Within the guard interval, the OFDM symbol is cyclically extended to avoid inter-carrier interference. The generated OFDM signal in baseband can be expressed as

$$s(t) = \sum_{i=-\frac{N_s}{2}}^{\frac{N_s}{2}-1} d_{i+N_s/2} e^{j2\pi\frac{i}{T}(t-t_s)}, t_s \le t \le t_s + T \quad (3)$$

$$s(t) = 0, t < t_s, t > t_s + T$$

This is nothing more than the inverse Fourier transform of N input symbols. The implementation of generating the signal in the digital domain can be simplified by using the fast inverse Fourier transform according to

$$s(n) = \sum_{k=0}^{N-1} d_k \exp(j2\pi kn/N) \quad (4)$$

The diagram of transceiver of the IEEE 802.11a system is shown in detail in Fig. 1 [9].

In a single carrier system, since a time-disperse channel (frequency selective fading channel) brings the channel memory into the system, joint maximum likelihood equalization and decoding is not realistic because of the high computation cost. The general practice is to first use MMSE as the criteria to equalize the channel. Then the equalized signal is sent to a maximum likelihood detector for further decoding. This is a sub-optimal system. In an OFDM system, since the system is designed to let each sub-carrier experience flat fading channel, the real maximum likelihood equalization and decoding can be implemented with affordable computational cost.

The symbol-to-bit mapping in the soft decoding process is done by calculating the metrics according to the largest probability for each bit using the received symbol. The initial work related to this method has been done by E. Zehavi [8]. At the receiver, the faded, noisy version of the transmitted channel symbol is passed through metric computation units according to equation (5):

$$m_i^p(n) = \min_{x \in C^p} \| y - hx \|^2, p = 0,1 \quad (5)$$

where m_i^p is the metric for bit b_i in a symbol to be p, where p is either 0 or 1, y is the received symbol, h is the channel estimation, x is the symbol constellation, and C^p represents the subset of the constellation points such that bit $b_i = p$. The physical meaning of this equation is to find the shortest distance between the received symbol and projection of the constellation points in the channel for a certain bit. The idea is illustrated with a QPSK signal in Fig.2.

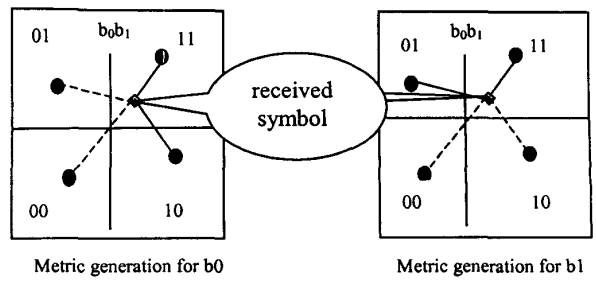


Fig.2 Illustration of metric calculation.

The metrics calculated for bit b_0 and b_1 are obtained via the following operations:

$$m_0^0 = \min(d_{00}, d_{01}), m_0^1 = \min(d_{10}, d_{11})$$
$$m_1^0 = \min(d_{00}, d_{10}), m_1^1 = \min(d_{01}, d_{11}) \quad (6)$$

where d_{ij} represents the Euclidean distance between the received symbol and the faded constellation point (i, j). The pair (m_0^0, m_0^1) is sent to the Viterbi decoder as the possibility for b_0 in each symbol being '1' or '0' for soft decoding. The same method can be applied to obtain metrics for b_1 except the pair (m_1^0, m_1^1) is used. This method can obviously be extended to other modulation schemes, such as BPSK or QAM with different complexity.

III. ANTENNA DIVERSITY COMBINING

Maximum Ratio Combining (MRC) is an antenna diversity technique for reducing the depth and duration of the fading experienced by a receiver in a flat fading channel. In MRC, the voltage signals from each of the antenna diversity branches are co-phased to provide coherent voltage addition and are individually weighted to provide optimal SNR. In an OFDM system, signal transmitted on each sub-carrier experiences flat fading, so the received signal on each antenna branch for the same sub-carrier is suitable to be combined with MRC.

A. Conventional Symbol Level Diversity Combining

MRC is usually implemented as in Fig. 3 [2]-[5], where the combining is performed before the calculation of the bit metrics for the soft Viterbi decoding for each sub-carrier; this is so called "symbol level diversity combining".

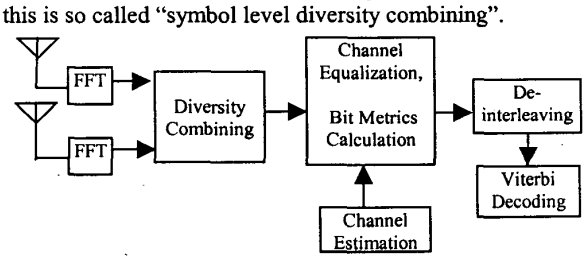


Fig.3 Conventional Symbol Level Diversity Combining

The received signal on each antenna branch can be expressed as

$$r_{1k} = h_{1k}s + n_{1k}, r_{2k} = h_{2k}s + n_{2k} \quad (7)$$

Where

$$h_{1k}(t) = h_{1k}(t+T) = \alpha_{1k}e^{j\theta_{1k}}$$
$$h_{2k}(t) = h_{2k}(t+T) = \alpha_{2k}e^{j\theta_{2k}} \quad (8)$$

where h_{ik} represents the channel coefficient for kth subcarrier from antenna i; T is the OFDM symbol period; α_{ik} and θ_{ik} represent the amplitude and phase respectively of the flat fading channel for kth subcarrier from antenna i. The combining is done as follow

$$r_k = w_{1k}r_{1k} + w_{2k}r_{2k} \quad (9)$$

where w_{ik} is the summation weight which are calculated from the SNR of the received signal at each antenna, i =0,1. Decoding is done by calculating the bit metrics for each bit according to following equation

$$s_{0,i} = \min_{x\in C_i^0} |r_k - (h_{1k}w_{1k} + h_{2k}w_{2k})x|^2$$
$$s_{1,i} = \min_{x\in C_i^1} |r_k - (h_{1k}w_{1k} + h_{2k}w_{2k})x|^2 \quad (10)$$

where C_i^p is the subset of constellation points such that bit i equal to p, where p is either 0 or 1; $s_{p,i}$ is the bit metrics for bit i to be p. Zehavi's metrics calculation method then can be used to find the bit metrics for each bit in a symbol carried on each sub-carrier.

This method, as shown in the analysis below, is not the optimum maximum likelihood decoding for COFDM system in multipath fading channel.

B. Theoretical analysis of the optimal decoder for antenna diversity combining

In optimum maximum likelihood decoding for two received signals of a coded system, the bit metrics in each symbol should be calculated as

$$s_{p,i} = \min_{x\in C_i^p} \|\mathbf{r} - \mathbf{h}x\|^2 = \min_{x\in C_i^p} \left\| \begin{pmatrix} r_1 \\ r_2 \end{pmatrix} - \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} x \right\|^2$$
$$= \min_{x\in C_i^p} (\|r_1 - h_1x\|^2 + \|r_2 - h_2x\|^2) \quad (11)$$
$$\approx \min_{x\in C_i^p} (\|r_1 - h_1x\|^2) + \min_{x\in C_i^p} (\|r_2 - h_2x\|^2)$$

This is equivalent to finding the bit metrics for each received symbol stream separately and then combining the bit metrics afterward. Equation (11) tells us that to implement MRC for COFDM system, the combining should be performed after the bit metrics calculation (demapping) for each antenna.

C. Optimal diversity combining for coded OFDM system

According to above analysis, the optimal decoder that combines the equalization, demodulation and diversity combining is given in Fig.4.

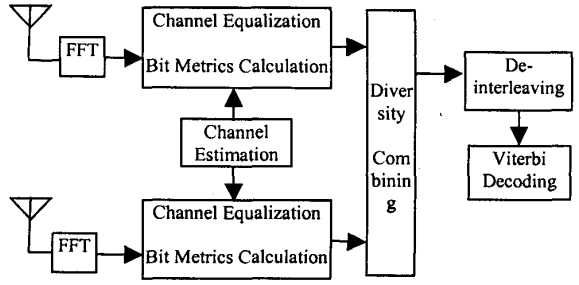
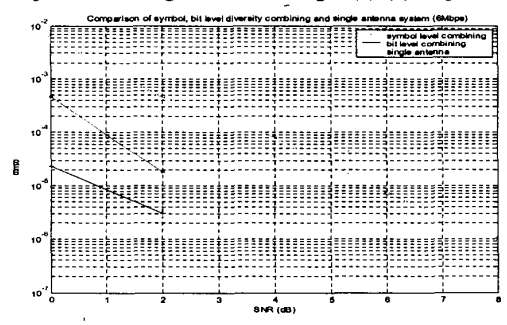


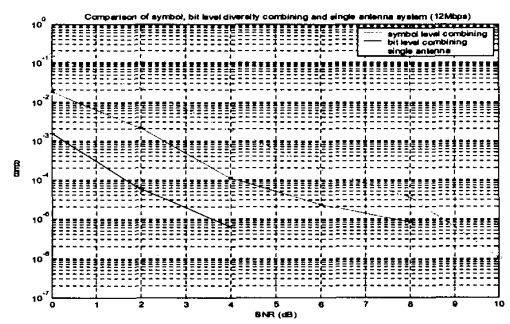
Fig.4 Optimal Bit Level Diversity Combining

IV. SIMULATIONS

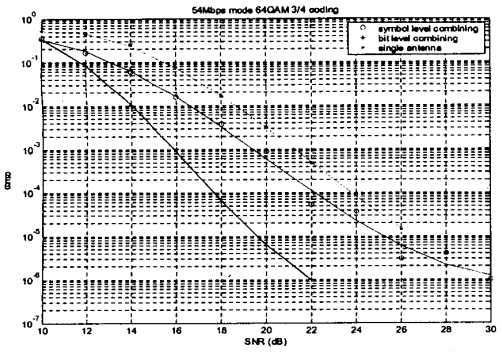
Simulations for IEEE 802.11a system have been done to compare the performance of the conventional symbol level combining, proposed optimal combining and single antenna system. Transmission modes from 6 Mbps to 54 Mbps have been simulated. The simulated multipath channel is the exponential Rayleigh fading channel defined in [1] with 40ns rms delay spread. For each data point in the SNR vs. BER curve, 1M bits that are equally distributed in 250 packets were simulated. It is reasonable to assume that the wireless channel for each antenna element will be the same for each packet, while it is different for different packets. In all the simulations, ideal frequency and timing synchronization is assumed. Simulation results for all the transmission modes are available. To save space, only the results for 6, 24, 54Mbps modes are given here in Fig.5 (a)-(c) respectively.



(a)



(b)



(C)

Fig.5 Performance comparison for single antenna, conventional and proposed optimal combining receiver for (a) 6Mbps (b) 24Mbps and (c) 54 Mbps transmission modes.

The results show that the proposed optimal MRC can have about 4-6 dB gain over a single antenna reception and 2-4 dB gain over a conventional symbol level MRC at BER of 10^{-4} level.

V. CONCLUSIONS

For convolutional coded COFDM system, the optimal decoding for receiver diversity combining should be performed at bit level instead of symbol level. The bit level optimal MRC integrates the channel equalization, demapping (bit metrics calculation) and diversity combining in decoder, which actually is the maximum likelihood decoding method for diversity combining method for COFDM system. The novel bit level combining technique can provide about 4-6 dB gain over a single antenna system and 2-4 dB gain over a conventional symbol level diversity combining system. The implementation complexity of proposed optimal MRC is almost the same as conventional MRC. The improvement in IEEE 802.11a receiver performance allows more robust multimedia streaming over a wireless link.

References

[1] Bob O'Hara, Al Petrick; The IEEE 802.11 Handbook: A designer's Companion, December 1999.

[2] Y.G. Li and N.R. Sollenberger, "Adaptive antenna arrays for OFDM systems with cochannel interference," IEEE Trans. Comm, Vol.47, No. 2, Feb., 1999.

[3] Slimane, S.B., "A low complexity antenna diversity receiver for OFDM based systems," IEEE ICC 2001, Vol. 4, 2001.

[4] Dammann, A.; Kaiser, S., "Standard conformable antenna diversity techniques for OFDM and its application to the DVB-T system," IEEE GLOBECOM '01., Vol. 5 , 2001.

[5] Lee, D.; Saulnier, G.J.; Zhong Ye; Medley, M.J., "Antenna diversity for an OFDM system in a fading channel," IEEE MILCOM 1999, Vol. 2, 1999.

[6] Theodore S. Rappaport, Wireless communication – principles and practice, Printice Hall, 1996.

[7] Weon-cheol Lee, Hyung-Mo Park and Jone-Seok Park, "Viterbi decoding method using channel state information in COFDM system," IEEE Transactions on Consumer Electronics, Volume: 45 Issue:3,Aug.1999 pp 533 –537.

[8] E. Zehavi, "8-PSK trellis codes for a Rayleigh channel," IEEE Trans. Comm., Vol. 40, pp873-884, May 1992.

[9] Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) specifications: High-speed Physical Layer in the 5 GHz Band, IEEE Std 802.11a-1999.
1999.

BIOGRAPHIES

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