A MIMO-Based Collision Mitigation Scheme in Uplink WLANs

Hu Jin, *Student Member, IEEE,* Bang Chul Jung, *Member, IEEE,* Ho Young Hwang, *Member, IEEE,*
and Dan Keun Sung, *Senior Member, IEEE*

Abstract—**Although there exist random backoff schemes in WLANs, a collision problem among stations (STAs) is one of the critical factors that degrade the performance of WLAN systems. To mitigate this collision problem, a MIMO-based uplink collision mitigation scheme is proposed by utilizing additional degrees of freedom through multiple antennas, and, consequently, enhances the system performance. Analysis and simulation results show that there is at least 30% throughput enhancement in a basic service set (BSS) with more than 10 STAs, compared to the performance of conventional WLANs in case of saturation traffic.**

Index Terms—**WLAN, MIMO, multi-user multiplexing, collision mitigation.**

I. INTRODUCTION

As a basic access mechanism in the IEEE 802.11 standard for wireless local area networks (WLANs), a distributed coordination function (DCF) uses a medium access control (MAC) protocol which is based on carrier sense multiple access with collision avoidance (CSMA/CA). A binary random backoff scheme is used as a collision avoidance mechanism. This random backoff cannot completely eliminate collisions, and the throughput of 802.11 DCF is degraded more as the number of STAs increases [1].

Several schemes have been proposed to mitigate the collision problems [2], [3]. These schemes enhanced the performance of IEEE 802.11 WLANs by considering only the MAC layer. However, the throughput performance is limited because of large overhead [4]. Recently, Multiple-Input Multiple-Output (MIMO) transmission techniques have gradually been used in wireless communication systems including WLANs. For example, space-time block code is used to improve link quality and spatial multiplexing can be used to increase transmission data rates in the IEEE 802.11n specification [5]. However, there has been no proposal on multi-user MIMO techniques as a collision mitigation scheme in CSMA/CA-based WLANs. In this letter, we propose a MIMO-based uplink collision mitigation scheme, which can reduce the collision effect at the physical (PHY) layer using a multi-user MIMO detection technique at an access point (AP). To evaluate the performance of this scheme, frame error rate (FER) is analyzed and MAC layer analysis and simulation are performed based on the FER analysis.

The rest of this letter is organized as follows: In Section II, a MIMO-based uplink collision mitigation scheme is proposed. In Section III, FER performance is analyzed considering the distance between an AP and each STA, and the performance of MAC layer is also analyzed. In Section IV, numerical results for the MIMO-based WLANs are shown. Finally, conclusions are presented in Section V.

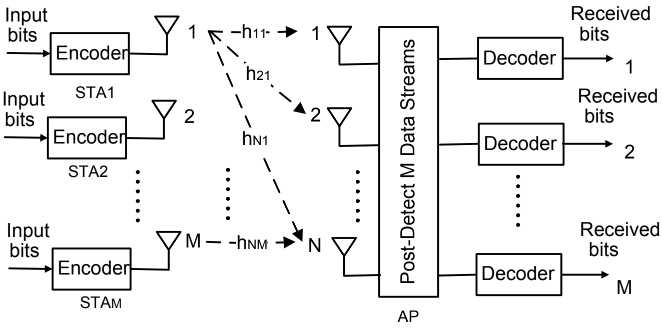

Fig. 1. System model of the proposed MIMO-based uplink collision mitigation scheme.

II. PROPOSED MIMO-BASED UPLINK COLLISION MITIGATION SCHEME

We propose a MIMO-based uplink collision mitigation scheme for an infrastructure-based WLANs in which all the STAs communicate with an AP. Fig. 1 shows a system model of the proposed MIMO-based uplink collision mitigation scheme. If $M (M \geq 2)$ STAs transmit data simultaneously, then a collision occurs in conventional WLAN systems. We assume that each STA has one transmit antenna and the AP has N receive antennas for simplicity since the case of multiple transmit antennas at each STA can be easily extended. Then, the channel matrix $\boldsymbol{H}$ can be expressed as

$$\boldsymbol{H} = [\boldsymbol{h}_1, \boldsymbol{h}_2, \cdots, \boldsymbol{h}_M], \tag{1}$$

where $\boldsymbol{h}_i = (h_{1i} h_{2i} \cdots h_{Ni})^T$ denotes the channel gain from the i-th STA to the AP with N antennas. With flat Rayleigh fading, $h_{ji}, j = 1, 2, \cdots, N$ is an independent, zero-mean, complex Gaussian random variable with a variance of $2\sigma_i^2$. Since there are many multi-paths in indoor environments, the independence of h_{ji} can be obtained easily. The received signal from M STAs can be written as

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{s} + \boldsymbol{n}, \tag{2}$$

where $\boldsymbol{s} = (s_1 s_2 \cdots s_M)^T$ and $\boldsymbol{r} = (r_1 r_2 \cdots r_N)^T$ denote the transmitted and received symbol vectors, respectively. The term $\boldsymbol{n}$ is a circular symmetric complex Gaussian vector in which each component has zero mean and variance N_0. If the AP can estimate the channel coefficients, it can recover the transmitted data streams from different STAs by using MIMO decoding techniques, such as zero forcing (ZF), minimum mean square error, maximum likelihood, and successive interference cancellation.

We consider OFDM-based WLAN systems. When multiple STAs simultaneously transmit data streams according to the

---

Manuscript received October 11, 2007. The associate editor coordinating the review of this letter and approving it for publication was C.-F. Chiasserini. This research was supported in part by BroMA IT Research Center.

B. C. Jung was with the School of EECS, KAIST, Korea. He is now with KAIST Institute for Information Technology Convergence, Korea (e-mail: bcjung.kaist.ac.kr).

H. Jin, H. Y. Hwang, and D. K. Sung are with the School of EECS, KAIST, Korea (e-mail: {jinhu, hyhwang}@cnr.kaist.ac.kr; dksung@ee.kaist.ac.kr).

Digital Object Identifier 10.1109/LCOMM.2008.071672.

TABLE I
SYSTEM PARAMETERS

Path loss at 1m	44.2 dB
Path-loss exponent	4
Transmit power of STA	200 mW
N_0	-199 dBW/Hz
Data size	1000 bytes

CSMA/CA protocol, the received time of each data stream at an AP may be different due to the different distances between each STAs and the AP. However, if the time mismatch is smaller than the guard time of the OFDM symbol, then it does not degrade the signal detection performance [7], [8]. For example, the guard time specified in the IEEE 802.11a specification is set to $0.8\mu s$ and this synchronization problem does not occur if a difference in distances between transmitting STAs from the AP is smaller than 240m. Since most WLAN APs cover an area within a radius of 100m, the synchronization between the data streams experiencing collisions is assumed to be guaranteed.

In this letter, each STA is assumed to have a unique preamble chosen from an orthogonal preamble sequence set. Hence, the AP knows which STA transmits its data and estimates the channel coefficients of each STA.

III. PERFORMANCE ANALYSIS OF A WLAN SYSTEM WITH THE PROPOSED MIMO-BASED UPLINK COLLISION MITIGATION SCHEME

A. FER Analysis in PHY Layer

We use a ZF receiver in which the post-detection signal-to-noise ratio (SNR) for the i-th STA, γ_i is expressed as

$$\gamma_i = \frac{E[|s_i|^2]}{[(\boldsymbol{H}^H\boldsymbol{H})^{-1}]_{ii}N_0} = \frac{\gamma_0}{[(\boldsymbol{H}^H\boldsymbol{H})^{-1}]_{ii}}, \qquad (3)$$

where γ_0 is the transmitted SNR defined as $E[|s_i|^2]/N_0$. $[\boldsymbol{A}]_{ii}$ denotes the i-th row and i-th column component of the matrix $\boldsymbol{A}$ and $\boldsymbol{H}^H$ denotes the conjugate transpose of the matrix $\boldsymbol{H}$.

Although the variance of each column of $\boldsymbol{H}$ is different, $1/[(\boldsymbol{H}^H\boldsymbol{H})^{-1}]_{ii}$ is Chi-square distributed with $2(N-M+1)$ degrees of freedom and variance σ_i^2 [9]. Consequently, when a ZF receiver is used, each $\gamma_i(1 \le i \le M)$ has a cumulative distribution function given as

$$F_{2(N-M+1)}(\gamma_i, \sigma_i) = 1 - \sum_{k=0}^{N-M} \frac{1}{k!}\left(\frac{\gamma_i}{2\sigma_i^2\gamma_0}\right)^k e^{-\frac{\gamma_i}{2\sigma_i^2\gamma_0}}. \qquad (4)$$

Hence, the SNR distribution for the i-th STA only depends on its own channel variance σ_i^2 and it is not affected by the variances of other colliding STAs. However, a large number of simultaneously transmitting STAs, M, decreases the degrees of freedom.

For a slow flat-fading channel, the FER for the i-th STA with distance D_i from the AP is

$$\eta_l(D_i) = \int_0^\infty \eta_{AWGN}(\gamma) f_l(\gamma, \sigma(D_i)) d\gamma, \qquad (5)$$

where $\eta_{AWGN}(\gamma)$ and $f_l(\gamma, \sigma(D_i))$ denote the FER for the STA with a received SNR value of γ in the AWGN channel and the probability density function of the post-detection SNR γ, at the AP, respectively. The subscript l represents the degrees of freedom expressed as $2(N-M+1)$. Considering the path loss, the relationship between D_i and $\sigma(D_i)$ can be obtained as

$$2\sigma^2(D_i)(dB) = -44.2 - 40\log_{10} D_i \ \ (dB), \qquad (6)$$

where the path loss at 1m is set to $44.2dB$ [10] and the path-loss exponent is set to 4 as shown in Table I . A transmit power of 200mW is recommended by IEEE 802.11a specification.

We assume that a frame error occurs if the post-detection SNR value is smaller than a reference value γ_{ref} at the AWGN channel. Hence, we approximate $\eta_{AWGN}(\gamma)$ as

$$\eta_{AWGN}(\gamma) \approx \begin{cases} 1, & \gamma \le \gamma_{ref} \\ 0, & \gamma > \gamma_{ref} \end{cases} \qquad (7)$$

and then rewrite Eq. (5) as

$$\eta_l(D_i) \approx \int_0^{\gamma_{ref}} \eta_{AWGN}(\gamma) f_l(\gamma, \sigma(D_i)) d\gamma = F_l(\gamma_{ref}, \sigma(D_i)), \quad (8)$$

where $F_l(\gamma_i, \sigma(D_i))$ is described in Eq. (4). It means that as the number of simultaneously transmitting STAs increases, the achieved degrees of freedom $2(N-M+1)$ becomes lower and, consequently, the FER performance becomes worse. We have set the value γ_{ref} to an SNR value which yields an FER value of 10^{-3} in the AWGN channel. For example, based on the system parameters in Table I, the γ_{ref} value is set to 13.99dB, which is derived from [6], in case of data rate 24 Mbps in 802.11a WLANs.

B. Performance Evaluation Model in MAC Layer

Bianchi [1] proposed a simple discrete time Markov chain (DTMC) model to compute the saturation throughput in an error-free channel. We here extend this model to analyze the MAC layer performance of the proposed MIMO-based WLANs in an error-prone channel. For simplicity, we assume there is only uplink transmission and no downlink transmission.

Consider n contending STAs in a BSS. Let τ_i and p_i denote the transmission and backoff stage transition probability of the i-th STA, respectively. Equipped with N antennas, an AP can receive maximum N data streams simultaneously. Let $Ps_{i,m}$ be the successful transmission probability of the i-th STA when m STAs simultaneously transmit their data streams to the AP, and $Ps_{i,m}$ is given by $1 - F_{2(N-m+1)}(\gamma_{ref}, \sigma(D_i))$. The relationship between the transmission and stage transition probability from the viewpoint of system is obtained as

$$p_i = 1 - \sum_{m=0}^{N-1} Ps_{i,m+1} \boldsymbol{T}(\{\tau_1, \cdots, \tau_{i-1}, \tau_{i+1}, \cdots, \tau_n\}, m), \ (9)$$

where the probability that m STAs transmit simultaneously among a station set of $\{1, 2, \cdots, i-1, i+1, \cdots, n\}$ is expressed as

$$\boldsymbol{T}(\{\tau_1, \cdots, \tau_{i-1}, \tau_{i+1}, \cdots, \tau_n\}, m) = \sum_{l_1=1, l_1 \neq i}^{(n-m+1)} \tau_{l_1}$$
$$\sum_{l_2=l_1+1, l_2 \neq i}^{(n-m+2)} \tau_{l_2} \cdots \sum_{l_m=l_{m-1}+1, l_m \neq i}^{n} \tau_{l_m} \prod_{l=1, l \neq l_1, l_2, \cdots, l_m, i}^{n} (1-\tau_l).$$

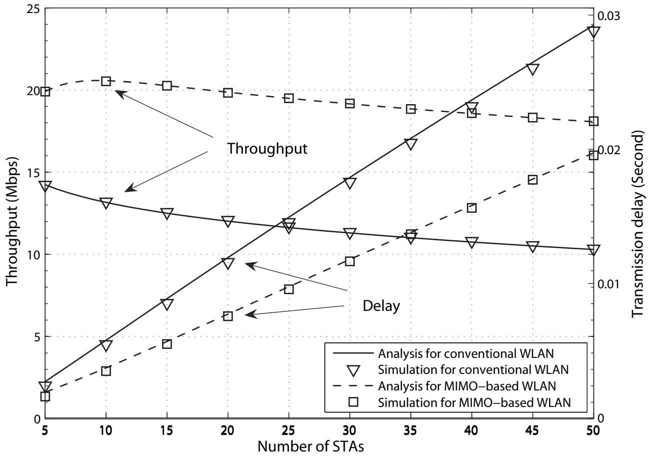

Fig. 2. Throughput and transmission delay in an error-free channel

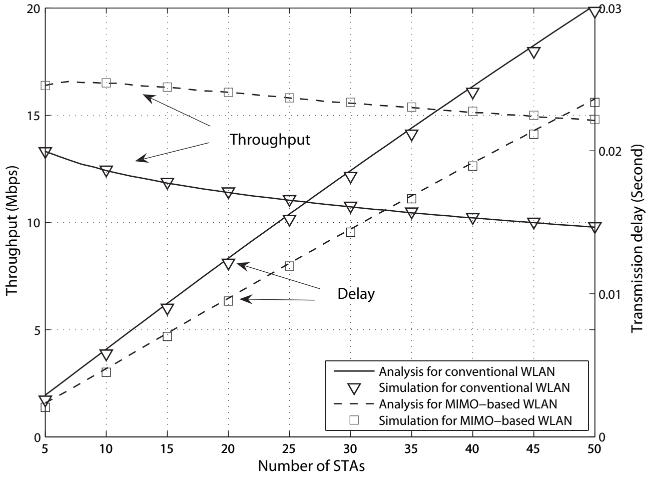

Fig. 3. Throughput and transmission delay in an error-prone channel

From the viewpoint of backoff procedure considering the retry limit R, we can obtain another relationship between τ_i and p_i $(i = 1, \cdots, n)$, based on the DTMC model,

$$\tau_i=\frac{2(1-p_i^{R+1})}{W(1-2^L p_i^{R+1})+Wp_i[\sum_{k=0}^{L-1}(2p_i)^k]+(1-p_i^{R+1})}, \quad (10)$$

where W represents the minimum contention window size. The term L is the number of backoffs to reach the maximum contention window size in the backoff procedure. Numerically solving Eqs. (9) and (10), the values τ_i and p_i $(i = 1, \cdots, n)$ can be obtained. Based on these values, the throughput and transmission delay can be calculated as in [1] and [11].

IV. NUMERICAL EXAMPLES

MAC layer parameters, such as minimum contention window size and retry limit, are set according to the IEEE 802.11a specifications. We evaluate the performance of a MIMO-based WLAN system in terms of throughput and delay in the case of saturated traffic. The data rate is fixed to a single rate of 24Mbps and the frame size is 1000 bytes. STAs are uniformly distributed with varying distances between 27m and 32m from an AP. The FER for each STA is obtained from Eq. (8) as a function of distance. The number of antennas at the AP is set to 2. In the case of conventional WLAN, we assume the AP uses 2 antennas to perform maximum ratio combing to achieve better FER performance.

Fig. 2 shows the throughput and transmission delay performance obtained by both analysis and simulation in an error-free channel. The analytical results agree well with simulation resutls. The proposed MIMO-based WLAN yields a much higher throughput enhancement by at least 60% in case of more than 10 STAs, and smaller transmission delay, compared with the performance of conventional WLAN systems.

Fig. 3 shows the throughput and transmission delay performance in an error-prone channel under a flat Rayleigh fading environment. The proposed MIMO-based uplink collision mitigation scheme yields at least 30% throughput enhancement in case of more than 10 users and smaller transmission delay, compared with the performance of the conventional WLAN. Simultaneous transmissions among STAs cause worse FER performance due to the collisions among data streams. Therefore, the performance enhancement is reduced compared to that of the error-free channel case.

V. CONCLUSION

In this letter, we have proposed a MIMO-based uplink collision mitigation scheme in uplink WLANs in order to mitigate a collision problem which is one of the most critical factors degrading the overall system performance. The proposed MIMO-based uplink collision mitigation scheme yields much better performance than the conventional scheme. We leave the effect of the downlink transmission on the proposed scheme and the performance comparison between the IEEE 802.11n system and the proposed scheme for further studies.

REFERENCES

[1] G. Bianchi, "Analysis of the IEEE 802.11 distributed coordination function," *IEEE J. Select. Areas Commun.*, vol. 18, pp. 535-547, Mar. 2000.

[2] C. Wang, B. Li, and L. Li, "A new collision mitigation mechanism to enhance the performance of IEEE 802.11 DCF," *IEEE Trans. Veh. Technol.*, vol. 53, no. 4, pp. 1235-1246, July 2004.

[3] J. Choi, J. Yoo, S. Choi, and C. Kim, "EBA: an enhancement of the IEEE 802.11 DCF via distributed reservation," *IEEE Trans. Mobile Comput.*, vol. 4, no. 4, pp. 378-390, July/Aug. 2005.

[4] Y. Xiao and J. Rosdahl, "Throughput and delay limits of IEEE 802.11," *IEEE Commuun. Lett.*, vol. 6, no. 8, pp. 355-357, Aug. 2002.

[5] IEEE P802.11n/D1.0, "Draft amendment to wireless LAN media access control (MAC) and physical layer (PHY) specifications: enhancements for higher throughput," Mar. 2006.

[6] D. Qiao, S. Choi, and K. G. Shin, "Goodput analysis and link adaptation for IEEE 802.11a wireless LANs," *IEEE Trans. Mobile Comput.* vol. 1, no. 4, pp. 278-292, Oct.-Dec. 2002.

[7] J. Heiskala and J. Terry, *OFDM Wireless LANs: A Theoretical and Practical Guide*. SAMS Publishing, 2002.

[8] K. Fazel and S. Kaiser, *Multi-Carrier and Spread Spectrum Systems*. Wiley, 2003.

[9] J. H. Winters, J. Salz, and R. D. Gitlin, "The impact of antenna diversity on capacity of wireless communication systems," *IEEE Trans. Commun.*, vol. 42, no. 2/3/4, pp. 1740-1747, Feb. 1994.

[10] J. Foerster, "Channel modeling sub-committee report final," IEEE P802.15-02/368r5-SG3a, Dec. 2002.

[11] P. Chatzimisios, A. C. Boucouvalas, and V. Vitsas, "Performance analysis of IEEE 802.11 DCF in presence of transmission errors," in *Proc. IEEE International Conference on Communications*, vol. 7, pp. 3854-3858, June 2004.