Macrodiversity Packet Combining for the IEEE 802.11a Uplink

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Abstract—**This paper proposes and analyzes a packet-level macrodiversity combining scheme for improving the performance of the uplink of IEEE 802.11a networks operating in infrastructure mode. By receiving the mobile station's signal at three equidistant access points, a gain between 6 and 8 dB is observed at a packet error rate of 10^{-2} when the receiver is able to perfectly estimate the channel. A similar gain is found when the receiver operates without channel state information and must estimate the channel. Results are presented showing the improvement in packet error rate and throughput for several different mobile station positions. It is found that the gain due to macrodiversity combining diminishes as the mobile station moves closer to a single access point.**

Keywords: IEEE 802.11a, Macrodiversity, OFDM

I. Introduction

Diversity is a common technique for combating fading in wireless systems [1]. A common form of diversity is *spatial* diversity, which is implemented by using multi-antenna arrays at the transmitter, receiver, or both. Microdiversity is the most prevalent form of spatial diversity and occurs when the antennas are roughly a wavelength apart and connected to the transceiver by high bandwidth, lossless cabling.

Another form of diversity that has attracted recent attention is *macrodiversity* [2]. With macrodiversity, the antennas do not need to be physically located in close proximity. Instead, the antennas can be spread very far apart. For instance, they could be located at different access points. A virtual antenna array is created by pooling the antenna resources of all the participating access points. Macrodiversity has several advantages over microdiversity. First, the antennas are separated so far apart that they are virtually guaranteed to receive the signal over statistically independent channels. This is not the case for microdiversity. Second, the channel to each antenna will not only undergo independent multipath characteristics, but will also experience different path loss and shadowing. This is in contrast with microdiversity, where the path loss and shadowing is the same from the transmitter to each antenna.

The prior work in [2], [3], [4], [5] considered multiuser detection of asynchronous DS-CDMA signals at separate base stations, while [6] considered macrodiversity combining for a simple Bluetooth-based wireless LAN. A key observation in [6] is that macrodiversity is most effective when a MT is located just out of range of several APs. This situation occurs in a cellular-like layout when the MT is right on the border of two cells. Performance at cell boundaries often limits the coverage of wireless networks, but fortunately this is where macrodiversity performs the best. While macrodiversity is often implemented in CDMA cellular communication systems in the form of *soft-handoff* [7] its use in IEEE 802.11-based wireless LANs has been unexplored. Note that while the focus of this paper is on the uplink, a similar benefit can be achieved on the downlink through the use of distributed space-time codes [8].

This paper builds upon preliminary work on macrodiversity for Bluetooth presented in [6]. In particular, the paper proposes a packet-level macrodiversity combining technique for IEEE 802.11a and analyzes its performance through simulation. While Bluetooth is a simple system that lends itself to closed-form analysis, 802.11a is much more complicated and thus the results presented in this paper required the development and execution of an extensive campaign of simulations. The paper considers several practical issues that are critical to the performance of IEEE 802.11a, including channel estimation and ACK signaling.

The remainder of the paper is organized as follows. In Section II the system model is presented along with the proposed macrodiversity combining technique. A discussion on channel estimation for IEEE 802.11a is provided in this section. Next, in Section III extensive simulation results are presented for the proposed scheme. Finally, conclusions are drawn in Section IV.

II. System Model

A. Macrodiversity Combining Technique

Consider an infrastructure-based wireless LAN with topology shown in Fig. 1. K access points are equally spaced along a ring of radius r, and mobile terminals move freely within the ring. In the following discussion, the MT could be in one of three locations: (A) In the middle of the ring and equidistant from the K APs; (B) For the $K = 3$ case only, this is when the MT is halfway between two APs; (C) Halfway between the center of the ring and one of the APs. The access points are connected over a reliable backbone, for instance using Ethernet cabling. In a conventional system, each MT associates with just a single AP (in the absence of shadowing, this will usually be the one closest to the MT). When the MT has a packet to send,

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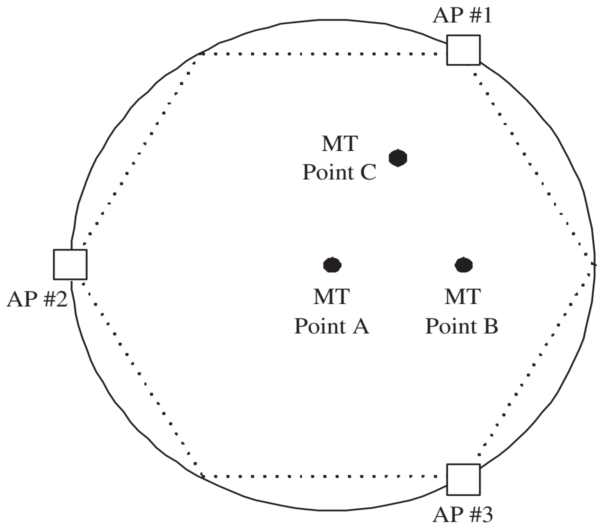

Fig. 1. A dense infrastructure-based wireless network

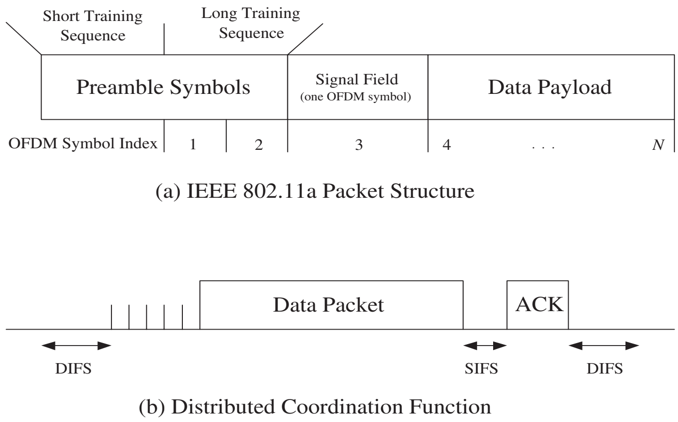

Fig. 2. IEEE 802.11a packet structure and DCF protocol

only that particular AP is permitted to receive it.

In the proposed macrodiversity scheme, *all* of the APs along the ring are permitted to receive the packet. The AP which is closest to the MT is elected to be the *master* AP, and will be the one to reply to the MT with an ACK packet. Each packet is encoded by a CRC error detecting code, and thus each AP can determine if it received the packet correctly or not. After the packet has been received by the K access points, each AP will send a short packet to the master AP telling the master if it has received the packet correctly or not. If any of the K AP receives the packet correctly, then the master AP will send an ACK back to the MT (even if the master did not itself receive the packet correctly). In the case that the master AP did not receive the packet correctly but one of the other APs did, then the master will ask that AP to forward the packet to the destination on its behalf. Using this protocol, the packet will be forwarded towards its destination whenever *any* AP successfully decodes the packet.

B. Packet Format

A brief overview of the IEEE 802.11a packet structure is given in Fig. 2(a). Since a complete description goes beyond the scope of this paper, the interested reader is referred to the standard [9]. The preamble consists of (1) a short training sequence which is repeated 10 times and used for Automatic Gain Control(AGC) convergence, timing, and coarse frequency acquisition in the receiver, followed by (2) a long training sequence which is repeated twice and used for channel estimation at the receiver. We assume that perfect synchronization is achieved after the short training sequence is received, though we do not assume that the channel is perfectly estimated. Following the preamble field is the signal field, which contains the length of the payload as well as the transmission rate. IEEE 802.11a provides a payload length between 1 and 4095 bytes, and eight transmission rates ranging from 6 Mbps to 54 Mbps, associated with modulation ranging from BPSK to 64QAM and convolutional coding rates 1/2, 2/3, and 3/4. The signal field uses BPSK modulated OFDM concatenated with rate 1/2 convolutional encoding, which is same modulation-coding type used by the 6 Mbps payload.

C. Channel Model

The wideband OFDM signal used by IEEE 802.11a undergoes frequency selective multipath fading. We assume here that the channel is quasi-static, i.e. the fading coefficients are constant over an entire packet but vary independently from packet to packet. The time-domain channel impulse response is given by a standard tapped delay-line model:

$$h(t) = \sum_{\ell=0}^{L-1} \alpha_\ell \delta(t - \ell T) \qquad (1)$$

where L is the number of multipath components, T is the tap spacing (sometimes called the chip period), and α_ℓ is the ℓ^{th} channel coefficient. For 802.11a, the tap spacing is set to 50 nsec. We assume an exponentially decaying Rayleigh multipath delay profile, which implies that the α_ℓ are independent complex Gaussian random variables with zero mean[1] and variance

$$\sigma_\ell^2 = \frac{e^{-\frac{\ell T}{\tau_{rms}}}\left(1 - e^{-\frac{T}{\tau_{rms}}}\right)}{1 - e^{-\frac{LT}{\tau_{rms}}}} \qquad (2)$$

where τ_{rms} is the rms delay spread [1].

After the transmitted signal propagates through the channel with impulse repsonse $h(t)$, it is matched-filtered and then transformed using the Discrete Fourier Transform (DFT). The resulting signal is

$$\mathbf{y}_i = \mathbf{X}_i \mathbf{h} + \mathbf{w}_i \qquad i = 1, 2, ..., N \qquad (3)$$

where $\mathbf{X}_i$ is a 52×52 (corresponding to 48 data subcarriers plus 4 pilot subcarriers [9]) diagonal matrix, whose elements are the modulated and encoded output of the original information $\mathbf{u}$, $\mathbf{h}$ is a 52×1 complex fading vector in

[1] If the mean were nonzero, then the fading would be Rician. Rician fading is common when there is a line-of-site (LOS) component present.

frequency domain, which remains constant over the whole packet, and has zero mean and correlation matrix $\mathbf{R}_{hh}$, $\mathbf{w}_i$ is the independent additive white Gaussian noise, with zero mean and correlation matrix $\sigma_w^2\mathbf{I}$, and N is the number of OFDM symbols(counting from the long training sequence). The channel correlation matrix $\mathbf{R}_{hh}$ can be found from the channel's impulse response as follows

$$\mathbf{R}_{hh}[m,n] \quad = \quad r(m-n) \tag{4}$$

with

$$r(k) \quad = \quad \sum_{l=0}^{L-1} \sigma_l^2 e^{-\frac{j2\pi kl}{64}}. \tag{5}$$

D. Error Performance

If the channel state information(CSI) is known to the receiver, it is easy to calculate the a posterior probabilities of the modulated symbols for each subcarrier. By demapping the modulated symbols, the binary log likelihood ratios (LLRs) are then forwarded into a Viterbi or BCJR decoder [10]. An error event is generated if the CRC check fails, which occurs if the receiver is unable to decode the payload or signal fields. The probability of average packet error is then

$$\bar{p}_e \quad = \quad \int_{\mathbf{h}}\int_{\mathbf{z}} Pr(\hat{\mathbf{u}} \neq \mathbf{u}|\mathbf{h},\mathbf{z}) f_h(\mathbf{h}) f_z(\mathbf{z}) d\mathbf{z} d\mathbf{h} \tag{6}$$

with

$$f_h(\mathbf{h}) = \frac{1}{\pi^N |\mathbf{R}_{hh}|} e^{-\mathbf{h}^H \mathbf{R}_{hh}^{-1}\mathbf{h}}$$

$$\mathbf{z} = [\mathbf{w}_1^T, \mathbf{w}_2^T, ..., \mathbf{w}_N^T]^T$$

$$f_z(\mathbf{z}) = \frac{1}{\pi^N |\mathbf{R}_{zz}|} e^{-\mathbf{z}^H \mathbf{R}_{zz}^{-1}\mathbf{z}}$$

where $\mathbf{R}_{zz} = \sigma_w^2 \mathbf{I}_{52N\times 52N}$ and $\hat{\mathbf{u}}$ is the receiver's estimate of the original uncoded information. Clearly, $\bar{p}_e$ is only a function of the noise power σ_w^2. If the average carrier power is fixed, $\bar{p}_e$ is also a function of average Carrier to Noise Ratio(CNR)[2]. By letting Γ_k be the average CNR at AP $\#k$, the average packet error rate under packet-level combining is

$$\bar{P}_e \quad = \quad \prod_{k=1}^{K} \bar{p}_e(\Gamma_k) \tag{7}$$

E. Channel Estimation

When the CSI is unknown to the receiver, all of the known symbols, i.e. the two repetitions of the long training sequence and the pilots throughout the packet, are used to estimate the channel. Although the exact CSI is unknown, the channel's statistical correlation matrix $\mathbf{R}_{hh}$ is helpful to produce the MMSE channel estimate [11],

$$\hat{\mathbf{h}}_{MMSE} \quad = \quad \mathbf{R}_{hh}\left(\mathbf{R}_{hh} + \sigma_w^2 \mathbf{U}\right)^{-1} \mathbf{h}_{LS} \tag{8}$$

where $\mathbf{h}_{LS}$ is the Least Square channel estimate output, which comes from the stacking and processing of all pilot subcarriers,

$$\mathbf{h}_{LS}[m] \quad = \quad \frac{1}{N}\sum_{i=1}^{N} \frac{\mathbf{y}_i[m]}{\mathbf{X}_i[m,m]} \quad m \in \mathcal{P} \tag{9}$$

as well as the stacking and processing of the long training sequece

$$\mathbf{h}_{LS}[m] \quad = \quad \frac{1}{2}\left(\frac{\mathbf{y}_1[m]}{\mathbf{X}_1[m,m]} + \frac{\mathbf{y}_2[m]}{\mathbf{X}_2[m,m]}\right) \quad m \in \mathcal{D} \tag{10}$$

with $\mathcal{P}$ and $\mathcal{D}$ are the set of subcarrier indexes for pilot and data subcarriers, respectively. The underlying reason for (9) and (10) is that symbols of both pilots and the long training sequence have unitary power. Thus $\mathbf{U}$ is a diagonal matrix with its elements equal to $\frac{1}{N}$ if it corresponds to a pilot subcarrier, or $\frac{1}{2}$ otherwise. It is obvious that the receiver never learns the packet length until the signal field is successfully decoded, which only permits us to use $N = 3$ to estimate CSI for signal field detection.

III. Simulation Results

This section considers the packet error rate (PER) performance of the proposed macrodiversity combining technique. All results are found using Monte Carlo simulation with enough trials to generate 200 independent packet errors. All data packets are 1500 bytes long. In each case, the office non-line of site (NLOS) model from [12], [13] was used, which has exponentially decaying multipath Rayleigh fading with rms delay spread $\tau_{rms} = 50$ nsec and number of multipath components $L = 10$. The channel is quasi-static in the sense that it is constant for a single packet and independent from packet to packet. We consider both the case that the receiver has perfect CSI available as well as the case that the receiver has no CSI and therefore must estimate the channel. We let the number of access points range from $K = 1$ to $K = 3$, with $K = 1$ corresponding to the conventional (non-macrodiversity) case.

A. Packet Error Rate Performance

The first result, which is shown in Fig. 3, is for the 6 Mbps data rate and the MT at location A (equidistant from the K APs). In particular, the PER is plotted against the average CNR at AP #1 (all APs have equal average CNR in this case). By increasing the number of AP from $K = 1$ to $K = 2$, there is a 4dB gain with CSI and a 5 dB gain without CSI at $\bar{P}_e = 10^{-2}$ achieved by packet combining. When the third AP joins the receiving group, the gain increases to about 6 dB and 7 dB, for CSI and no CSI, respectively. Fig. 3 also shows the PER of Maximal Ratio Combining (MRC) for $K = 3$. Although MRC can get an extra gain by doing soft value combining, it requires exchanging about 100K bits (4-bit level quantization) per packet for each additional AP, which is a much heavier burden to the backbone compared with our packet-level combining scheme.

[2]Carrier to Noise Ratio can be calculated by $CNR = \frac{E_c}{N_0}$, where E_c is the average energy per chip(there are 80 chips in one IEEE 802.11a OFDM symbol), N_0 is the noise power spectral density.

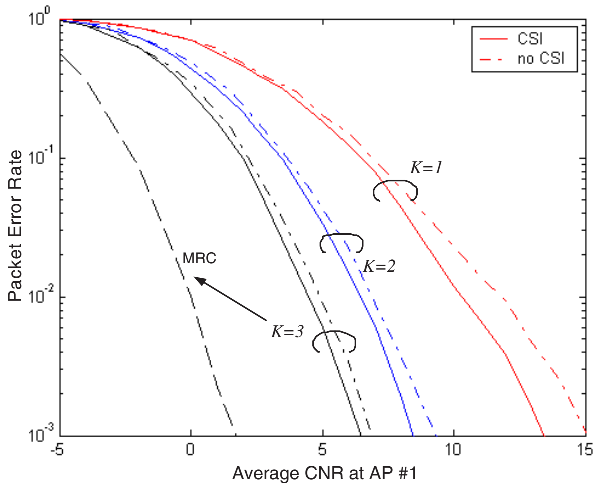

Fig. 3. Packet error rate of IEEE 802.11a at location A using the 6 Mbps packet. The channel is quasi-static exponentially Rayleigh faded with rms delay spread of 50 nsec and the data packet length is 1500 bytes.

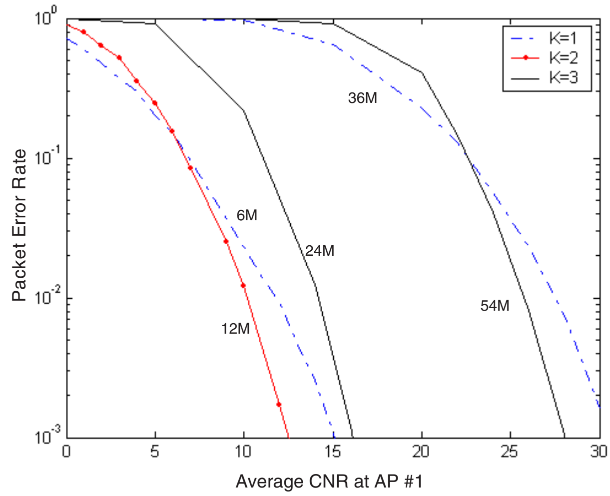

Fig. 4. Packet error rate at location A for several different data rates and number of receiving APs K. The receivers do not have CSI and must estimate the channel.

Fig. 4 shows the PER performance for several different rate options and number of access points. It is assumed that the APs do not have CSI and must estimate the channel. From this plot, it can be seen that by increasing the number of APs from $K = 1$ to $K = 2$, the data rate can be increased from 6 Mbps to 12 Mbps and that the faster macrodiversity system will actually outperform the slower conventional system for $\bar{P}_e < 0.1$. If a third AP joins the group, the data rate can be increased to 24 Mbps, thought this requires slightly more transmit power than the conventional system operating at 6 Mbps. We can also see that by increasing $K = 1$ to $K = 3$ the data rate could be increased from 36 Mbps to 54 Mbps, with the macrodiversity system outperforming the conventional system at $\bar{P}_e < 0.1$ From this figure, it is apparent that the proposed macrodiversity combining technique offers the potential to increase the transmission rate while keeping the PER at the same level (or better).

Now consider how much power must be transmitted by the MT to meet a target average PER of, say, $\bar{P}_e = 10^{-2}$. In order to determine this power, we must make some more assumptions about the operational environment. Let the radius r of the ring in Fig. 1 be 10m, and the transmit antenna gain be 6dBi. The noise spectral density is $N_o = 10^{-19}$ W/Hz and the average received power at the AP $\#k$ is $P_k^{(r)} = K_o \left(d_k/d_o\right)^{-\alpha} P^{(t)}$, where $d_o = 1$ m is a reference distance, d_k is the distance from MT to AP $\#k$, α is the path loss exponent, K_o is the channel power gain at the reference distance, and $P^{(t)}$ is the transmitted power. Corresponding to a typical indoor channel, $\alpha = 3$ [14], [15], and for the 5 GHz band, $K_o = (c/4\pi d_o f_c)^2 \approx 2.28 \times 10^{-5}$. Table I shows the transmit power required to reach $\bar{P}_e = 10^{-2}$ when the MT is in location A for the $K = 1$ and $K = 3$ cases, both with and without CSI. The gain achieved by macrodiversity combining across three APs is between 6 dB to 8 dB for both the CSI and no CSI cases. From this table, it can be seen that by using $K = 3$ it is often possible to increase the data rate while simultaneously reducing the required transmit power.

TABLE I

Transmit Power to $\bar{P}_e = 10^{-2}$ for 1500-byte-packet under $50ns$ rms multipath fading channel when MT is at point A

	CSI		no CSI	
	$K = 1$	$K = 3$	$K = 1$	$K = 3$
6M	240 μW	61 μW	340 μW	68μW
9M	1.1 mW	210 μW	1.5 mW	227 μW
12M	493 μW	134 μW	650 μW	153 μW
18M	2.0 mW	420 μW	3.1 mW	493 μW
24M	1.7 mW	450 μW	2.5 mW	589 μW
36M	8.8 mW	1.8 mW	12.4 mW	2.3 mW
48M	12.1 mW	2.7 mW	18 mW	4.2 mW
54M	30 mW	4.8 mW	41.4 mW	8.2 mW

Alternatively, when the transmit power of MT at location A is fixed, the radius of the ring of APs can then be enlarged while maintaining the same PER as in a conventional system. This implies that access points could be more widely separated, which is appealing for environments that are limited by coverage rather than user density. For example, let the transmit power of the MT be 10 mW. In a convectional system, the distance between AP #1 and the MT when using a 6 Mbps packet with target $\bar{P}_e = 10^{-2}$ is 35 m for CSI and 31 m for the no CSI case. By using two supplemental APs, the radius of the ring can be enlarged to 55 m and 53 m, respectively. It is easy to find that the radius of the ring can be enlarged by $G^{1/\alpha}$ times, where G is the gain of CNR.

The previous results have been for when the MT is at location A, i.e. equidistant from the K APs. But what happens if the MT is at a different location? The impact of location is shown in Fig. 5 for the $K = 3$ case and when the receivers have CSI. As expected, the performance is

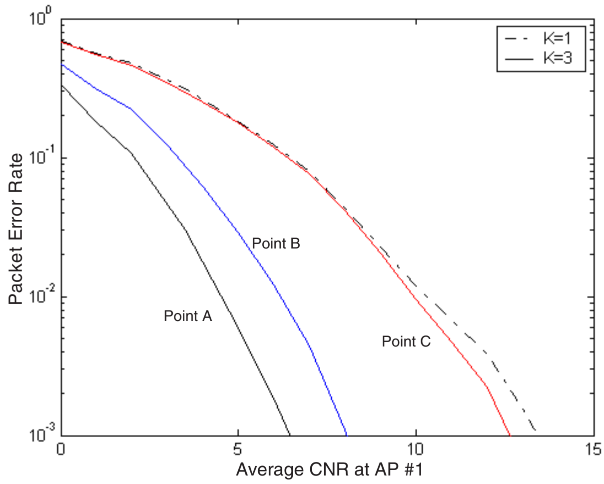

Fig. 5. Packet error rate at point A B and C, with IEEE 802.11a 1500 byte rate 6Mbps packet and known CSI at receivers

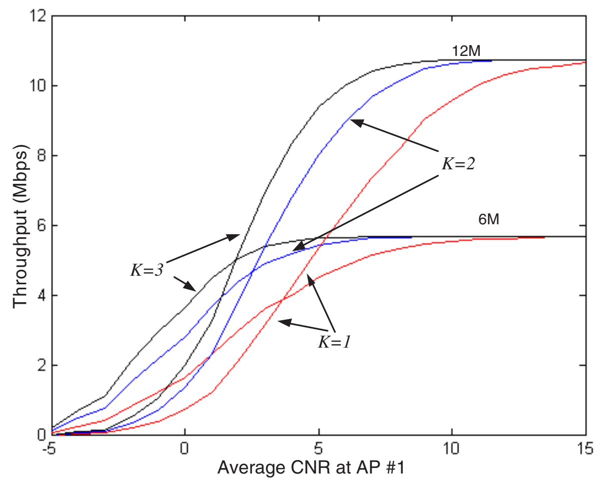

Fig. 6. Maximum throughput at point A with 6 Mbps and 12 Mbps packets, no CSI at receivers, and imperfect ACK channel

best at location A. As the MT moves closer to one AP, and further away from others, the gain introduced by macrodiversity scheme goes down. When the MT moves to point B, although AP #2 is far, AP #1 and #3 are equidistant, which still accounts for a diversity gain about 4 dB at $\bar{P}_e = 10^{-2}$. But when MT moves to C, the supplemental APs #2 and #3 are equally far away, which reduces the gain to only 0.4dB at $\bar{P}_e = 10^{-2}$. Thus, when the MT is close to one AP, it is probably not worth macrodiversity combining transmissions (of course if it is close to an AP then it will have good coverage and won't need the benefit of macrodiversity).

B. Throughput Performance

As is shown above, the PER performance is improved by macrodiversity reception. In this section, we use another important parameter, maximum throughput, to describe the proposed macrodiversity approach. Fig. 2(b) shows the timing of the Distributed Coordination Function(DCF), the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol used by 802.11a. Before transmitting a packet, an MT must wait for the medium be idle for at least a Distributed Interframe Space (DIFS) period, or an Extended Interframe Space (EIFS) period immediately after receiving a "bad" frame. A back-off procedure is adopted after the IFS to allow contention among MTs. Once an MT successfully gets the opportunity to access the medium, the other MTs must wait until the transmission and ACK cycle is over. If an error occurs in this cycle, i.e., either the AP fails to receive the data packet or the MT fails to receive the ACK, the terminal will retransmit the packet up to a certain number of times. A Short Interframe Space (SIFS) is used between a data packet and the ACK. RTS/CTS (Request to Send/Clear to Send) handshaking can optionally be used to improve reliability when using long packets [16].

The packet transmission is successful only after the MT

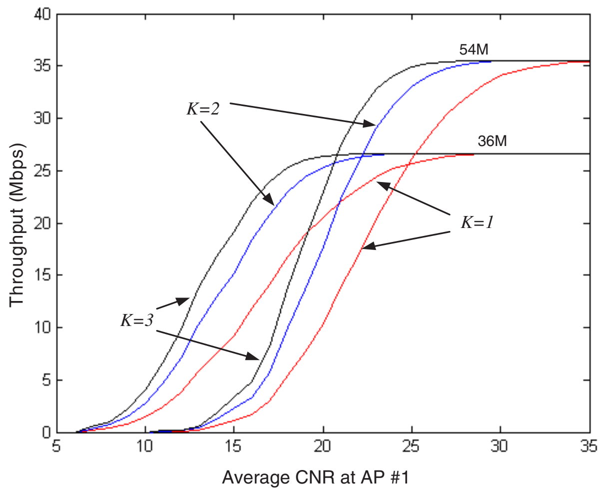

Fig. 7. Maximum throughput at point A, with 36 Mbps and 54 Mbps packets, no CSI at receivers, and imperfect ACK channel

get a correct ACK frame. However, when macrodiversity is used, the packet could be received by multiple access points, so who sends the ACK? This is why it is wise to elect one AP to serve as a "master". Ideally, the master should be the AP that receives the strongest signal from the MT, and usually this is the one that is closest to it. This is the assumption we make in the following discussion.

Fig. 6 and Fig. 7 show the maximum throughput performance on the uplink when the MT is at location A for rates 6 Mbps, 12 Mbps, 36 Mbps and 54 Mbps. This and all subsequent figures take into account the possibility of a lost ACK frame on the return channel. If we fix the rate at 6 Mbps, the required CNR to achieve a throughput of 4 Mbps is 4 dB, 1.5 dB and 0.4 dB for $K = 1$ AP, $K = 2$ APs, and $K = 3$ APs respectively. The gains of 2.5 dB and 3.6 dB are increased to 4 dB and 5.8 dB respectively, if we want to reach a high throughput of 5.5 Mbps. Alternately, if the CNR is fixed at 0dB, the conventional system

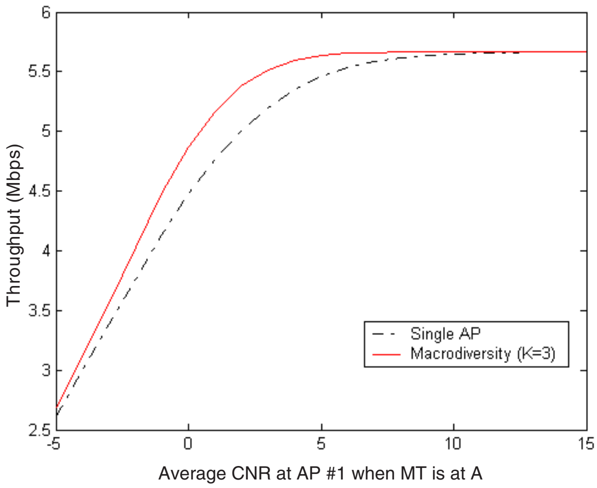

Fig. 8. Maximum throughput when MT is at random locations with a 6Mbps packet, no CSI, and imperfect ACK channel

can achieve a throughput of 1.6 Mbps. If a second AP is used at the packet-level combining, the throughput can be increased by 71%. If 3 APs work together, as in Fig. 1, a 3.6 Mbps throughput can then be achieved, which is about 120% higher than that of the conventional system.

While a great gain can be achieved when the MT is at the center of the ring, Fig. 8 shows a much smaller gain if the MT changes its location randomly within the hexagon shown in Fig. 1 after each transmission and ACK cycle. This model is also suitable when the media is randomly accessed by MTs uniformly distributed in the hexagon. Suppose the transmit power is fixed when the MT moves, and in accordance with the above simulation results, the x axis of Fig. 8 is indexed by the average received CNR at AP #1 when the MT is at the center of the ring. In the case that the MT is much closer to a single AP than to the others, the average received CNR at the supplemental APs are much lower, which accounts for very little or even no gain at all. As a result, such locations cause the least gain for the whole hexagon. Here, we remind the readers that the objective of the packet-level macrodiversity scheme is to improve the uplink performance when the MT is at the center of the ring, or almost equidistant to several APs.

IV. Conclusion

In this paper, we have considered the macrodiversity scheme to improve the uplink performance in IEEE 802.11a. We have shown the diversity gain achieved by combining the received information from adjacent APs at a packet-level, which does not add much burden to the backbone. The proposed macrodiversity technique allows a higher rate option to be employed without any loss in PER performance. It was shown that an average 6 to 8 dB gain can be achieved by using $K = 3$ equidistant APs compared to the conventional single AP. However, the gain becomes less when the MT moves closer to one AP and further away from others.

It should be noted that there are some additional issues that should be taken into account when considering a macrodiversity deployment. The packet-level combining must occur within the SIFS period, which requires efficient real time signal processing. Also, most wireless networks reuse frequencies in such a way that adjacent access points are tuned to different channels. However, in order to use macrodiversity, adjacent access points must be able to receive signals transmitted within the same channel. This suggests that APs suitable for macrodiversity combining could require two or more receivers on board or must be able to rapidly tune to different frequencies.

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