# Improving Uplink Performance by Macrodiversity Combining Packets from Adjacent Access Points

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*Abstract*— **In this paper, we suggest a postdetection strategy for combining observations made at multiple single-antenna access points in a wireless LAN, using Bluetooth as a running example. The result is a diversity gain that is analogous to a conventional antenna array, only the array is distributed throughout the network. In quasi-static Rayleigh fading and for a target packet error probability of $10^{-2}$, the proposed technique allows a significant (18 dB) reduction in mobile transmit power when as many as six equidistant access points are used. This gain is reduced as the mobile moves closer to any one of the access points or if fewer access points are used. In addition, the role of ARQ and the impact of this reception technique on throughput is investigated.**

Keywords: Macrodiversity, spatial diversity, cooperative diversity, distributed array, Bluetooth, ARQ.

## I. Introduction

Infrastructure-based wireless LANs are composed of fixed access points (APs) and roaming mobile stations (MSs). With current generation technology, each MS communicates with a *single* AP at a time, normally the one that is (initially) closest to it (although the exact one depends on the propagation and interference characteristics). This approach is acceptable if there is an AP within reasonably close proximity, but if the MS is too far away from any one AP, then the MS will not be able to associate with the network. Furthermore, due to mobility and changes in the interference and propagation statistics, the initially associated AP might not always be the best one. If there is an insufficient number of APs, or if some APs are placed too far apart, then there will be "holes" or dead zones in the coverage map. These coverage holes will be at locations that are far from any *one* AP. However, while no one AP is in close proximity to a MS in a coverage hole, there may be several APs that are each just barely out of range. This is the case when the MS is exactly halfway between two (or more) APs. If the MS could *simultaneously* communicate with each of the "just-out-of-range" APs (instead of just one), then with appropriate signal processing it should be possible for it to become associated (despite otherwise being in an apparent coverage hole).

*Diversity* reception is a common technique used in wireless systems to improve performance in the presence of interference and fading. Currently, *spatial* diversity is achieved in typical wireless LANs by using two antennas at each AP and selecting the antenna based on measured packet error rates. This type of diversity reception is called *microdiversity* as antennas at only one AP are used. The technique discussed in this paper can be considered to be a form of *macrodiversity* as it implements diversity across *multiple* APs. It acts like a *distributed* antenna array, since the antenna elements are at neighboring APs rather than localized at a single AP.

Macrodiversity concepts based on maximal ratio combining (MRC) have long been applied to the code division multiple access (CDMA) cellular uplink, mostly in the context of soft handoff [1]. Hanly [2] considers a generalization of soft handoff where each mobile's transmission is received and MRC combined by *all* base stations. This perspective dispenses with the traditional cellular concept by eliminating the need for each mobile to associate with a particular base station. An interesting observation made in [2] is that *as the amount of macrodiversity in the network increases, the system's uplink capacity becomes less sensitive to user location.* Thus, a viable alternative network architecture could consist of a dense distribution of base stations that *collaboratively* receive and process uplink signals, thereby achieving nearly uniform coverage. This work motivated [3], which uses macrodiversity MRC to improve the performance of uplink data transmissions in a more realistic CDMA system. Another technique for macrodiversity combining signals for the cellular uplink, termed multiply-detected macrodiversity, was proposed by Haas and Li and [4].

In [5], Shamai and Wyner present an information theoretic treatment of macrodiversity combining for systems dominated by adjacent cell interference, such as the time division multiple access (TDMA) uplink, and indicate advantages to combining the outputs of adjacent base stations (especially in fading and when users are randomly placed). Supported by these findings and recent advancements in iterative decoding in general, and turbo-multiuser detection in particular, we previously combined the concepts of macrodiversity, multiuser detection, and iterative decoding in a manner suitable for the coded TDMA uplink [6]. An alternative approach to macrodiversity on the uplink is to have two users collaboratively share information while broadcasting to a single base station (e.g. one user could use the other to relay the message) [7], [8].

Macrodiversity combining can also be used on the downlink, again in the context of soft handoff [9]. In [10],

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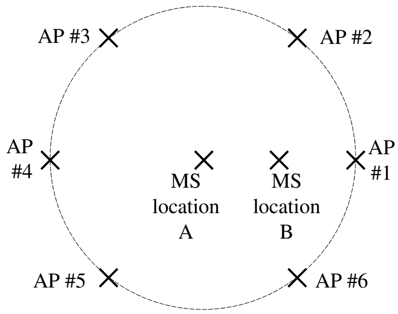

Fig. 1. A dense infrastructure-based network.

transmissions from appropriately power controlled adjacent base stations are used to improve performance of an indoor CDMA downlink. In [11], we proposed a space-time coding approach where the code symbols are transmitted from adjacent single-antenna base stations rather than from multiple antennas at a single base station and then MRC combined at the mobile.

Although optimal (in the absence of interference), MRC is complex as it requires channel estimates and soft decisions for each channel symbol, and these estimates must be transported over the wired backbone to a central processing center [2]. Instead of using MRC, we consider a more practical postdetection approach by combining at the packet-level with the assistance of the error detecting code that is embedded in most wireless LAN packets. The MS transmits an encoded packet to $M$ APs ($M > 1$), and the packet is checked for errors at each AP. All packets that are correct are then forwarded to a central location (e.g. the AP closest to the MS) over a reliable backbone (e.g. Ethernet connection). If the packet was incorrect at the closest AP, then perhaps it was correct at one of the other "supplemental" APs, in which case the system could use this other observation of the transmitted packet. Thus, the system will accept the packet as being correct as long as it was correctly received by *any* of the $M$ APs. Note that this is in strong contrast with a conventional system, where the packet must be correct at a *particular* AP (the one that the MS is associated with).

## II. Potential Performance Improvement

Consider the infrastructure-based topology shown in Fig. 1. A single mobile station is surrounded by a ring of $M$ equally-spaced access points which are connected by a reliable backbone. We assume that the APs have sufficient power to signal the MS over the downlink, and instead turn our attention to the uplink. In a conventional system, the signal transmitted by the MS will be received by only one AP (normally the closest), while in a macrodiversity reception system the signals are received by *all* APs.

The mobile transmits a CRC-encoded packet of length $N$ bits (the CRC is assumed to be strong enough to detect any error pattern) which is received and checked for errors at each AP. Due to the presence of the backbone, the packet will be accepted by the *set* of APs if it is correct at *any* of them. Conversely, the packet will only be rejected if incorrect at *all* APs, in which case a retransmission could be requested. In a practical implementation, the AP closest to the MS could serve as the *head* AP and the other, *supplemental* APs could forward packets to it.

To illustrate the potential transmit power savings, it is informative to associate some realistic values with this example. Let the radius of the ring of APs be 5 m, with the first AP always located at 3 o'clock. Furthermore, assume that the wireless LAN is implemented using the Bluetooth standard [12]. Bluetooth uses Gaussian frequency shift keying (GFSK) modulation with a time-bandwidth product of $BT = 0.5$, modulation index $0.28 \leq h \leq 0.35$, and symbol rate of 1 Megabaud. Time is divided into 625 $\mu$sec slots, and an asynchronous connectionless (ACL) data packet may occupy 1, 3, or 5 consecutive slots. Packets are composed of a 72 bit access code (used for addressing, synchronization, and DC offset compensation), a 18 bit header, and a variable length payload. The header is protected by a triple redundancy code (resulting in 54 symbols). The payload is composed of a 1 or 2 byte payload header, data, and a 16 bit CRC for error detection. While the medium rate (DMx) packets are protected by a Hamming forward error correction code (FEC), we only consider here the high rate (DHx) packets which do not use FEC. In particular, we assume that the highest rate DH5 packet is used (which occupies 5 slots), for which the maximum packet length is $N = 2744$ bits, including 2712 data bits, a 16 bit CRC (for error detection), and a 16 bit payload header (to specify the length of the packet). We assume that the goal is to maximize the uplink throughput, and thus the full length DH5 packet is used on the uplink while the downlink uses DH1 packets, which only occupy 1 slot. Thus, the time-division duplexed channel transports uplink traffic 5/6 of the time and downlink traffic 1/6 of the time and the maximum uplink throughput is $2712/(6 \times 625 \times 10^{-6}) = 723.2$ kbps.

The DH5 uplink packet will be considered incorrect at any one AP if any of the following three events occurs: (1) The packet is not synchronized; (2) The packet header is not correctly decoded; (3) The CRC check on the payload fails. The probabilities of each of these three events as a function of the instantaneous channel symbol SNR ($E_s/N_o$) are specified in [13] and not repeated here. Note that while this analysis assumes noncoherent detection, it does not account for intersymbol interference (due primarily to the Gaussian pulse shaping), and therefore is a lower bound on the packet error probability of a practical noncoherent receiver. The synchronization threshold that we use here is $T = 66$, i.e. the packet will be synchronized provided that at least 66 of the 72 bits in the access code are received correctly.

Because of the frequency-hopping nature of Bluetooth, it is reasonable to assume a quasi-static fading channel (i.e. the channel SNR is constant for the duration of a single packet, but varies from packet to packet). More specifically, we assume *quasi-static Rayleigh* fading (i.e. the envelope of the signal is Rayleigh distributed from packet-to-packet, and thus the SNR is exponentially distributed) and that the channels from the MS to each of the $M$ APs are uncorrelated (due to their wide spatial separation). The noise spectral density is $N_o = 10^{-18}$ W/Hz and the average received power at the $m^{th}$ AP is $P_r = K_o\,(d_m/d_o)^{-n}\,P_t$, where $d_o = 1$ m is a reference distance, $d_m$ is the distance from MS to AP, $n$ 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, $n = 3$ [14], [15], and for the 2.4 GHz ISM band, $K_o = (c/4\pi d_o f_c)^2 \approx 10^{-4}$.

If we denote the instantaneous packet error probability at the $m^{th}$ AP by $p_e(\gamma_m)$, then the corresponding average packet error rate in fading is found by taking the expected value of $p_e(\gamma_m)$ with respect to the SNR [16]. For quasi-static Rayleigh fading, the SNR is exponentially distributed, i.e. its pdf is $f_{\gamma_m}(\gamma_m) = \exp(-\gamma_m/\Gamma_m)/\Gamma_m$, and thus the average packet error rate is:

$$\bar{p_e}(\Gamma_m) = \int_0^\infty f_{\gamma_m}(\gamma_m) p_e(\gamma_m) d\gamma_m \quad (1)$$

$$= \int_0^\infty \frac{1}{\Gamma_m} e^{-\gamma_m/\Gamma_m} p_e(\gamma_m) d\gamma_m, \quad (2)$$

where $\Gamma_m$ is the average SNR of the channel between the mobile and $m^{th}$ AP. With the proposed macrodiversity scheme, the packet will be rejected by the *system* only if it is incorrect at *all* $M$ APs. Because the $M$ channels are uncorrelated, the system-wide average packet error probability is simply:

$$\bar{p_e} = \prod_{m=1}^{M} \bar{p_e}(\Gamma_m). \quad (3)$$

Fig. 2 shows the average packet error probability ($\bar{p}_e$) versus the average received SNR per channel symbol ($\mathcal{E}_s/N_o$) at each receiver[1] when the MS is at location A (Fig. 1). The $M = 1$ case corresponds to a conventional system where the mobile communicates with just a single AP. Note that by merely increasing $M$ to 2 yields a substantial 10 dB gain when $\bar{p}_e = 10^{-2}$. Additional gains are achieved by using more than two APs (e.g. 18 dB for $M = 6$), although each additional AP yields diminishing returns. The corresponding transmit power requirements are shown in Table I, which indicates that by using just two APs the required power is reduced from 2.95 mW to 282 $\mu$W, and by using six it is cut to just 47 $\mu$W.

When the MS is in the center of the circular cell, the system behaves as if the transmission was received by a single AP with an $M$ element antenna array with sufficient element spacing to ensure decorrelated channels (assuming the same packet diversity combining technique used by the proposed macrodiversity system). The main benefit of the macrodiversity approach is that instead of requiring a large antenna array at a single AP, a *virtual* array can be created across the network by combining signals at widely separated APs. It is noted that by combining on a packet level, rather than on a symbol level (with soft decisions), the burden on the backbone is greatly reduced.

[1]Because each AP is equidistant from the mobile, the average SNR is the same for all $M$ channels.

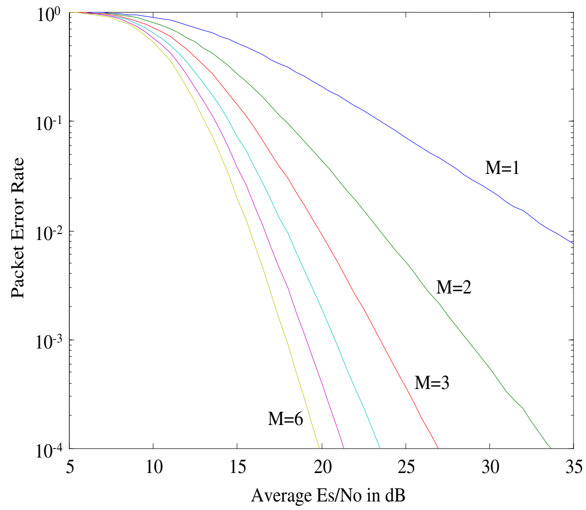


Fig. 2. Average packet error rate of macrodiversity combining ($M$ APs) in quasi-static Rayleigh fading when MS at location A and the Bluetooth DH5 packet is used.

| No. APs | loc. A | loc. B |
|---|---|---|
| 1 | 2.95 mW | 372 $\mu$W |
| 2 | 282 $\mu$W | 96 $\mu$W |
| 3 | 121 $\mu$W | 58 $\mu$W |
| 4 | 78 $\mu$W | 43 $\mu$W |
| 5 | 58 $\mu$W | 36 $\mu$W |
| 6 | 47 $\mu$W | 31 $\mu$W |

Table I: Transmit power required to obtain $\bar{p}_e = 10^{-2}$ from locations A and B.

When the mobile is not equidistant from the access points, the diversity gains will be diminished since the received signal powers at the supplemental APs will be smaller than at the head AP. For example, let the mobile be in location B (Fig. 1), which is 2.5 m away from AP #1. Fig. 3 shows $\bar{p}_e$ versus the average ($\mathcal{E}_s/N_o$) measured at AP #1 (the average SNR will be reduced to $(d_1/d_m)^n \mathcal{E}_s/N_o$ at the other APs). The required received SNR when $M = 1$ is exactly the same as when the mobile was centered, since the MS is still just communicating with the closest AP. However, now the incremental diversity gain is reduced. At $\bar{p}_e = 10^{-2}$ this gain is 5.9 dB for $M = 2$ and 10.8 dB for $M = 6$. While these *absolute* gains are not as dramatic as when the MS was at location A, it should be noted that the *incremental* gains of using more APs do not diminish as quickly as when the AP is centered. This is because as more equally-spaced APs are added to the ring, the nearest supplemental AP moves closer to the mobile. For instance, when $M = 2$ the supplemental AP is located 7.5 m from the mobile, but when $M = 6$ the closest supplemental AP is located just $5\sqrt{3}/2 \approx 4.3$ m away (and there are two at that distance). This is encouraging, because in a densely deployed infrastructure there are likely to be many supplemental APs. Table I shows the required transmit power when the MS is at location B and indicates that it can be

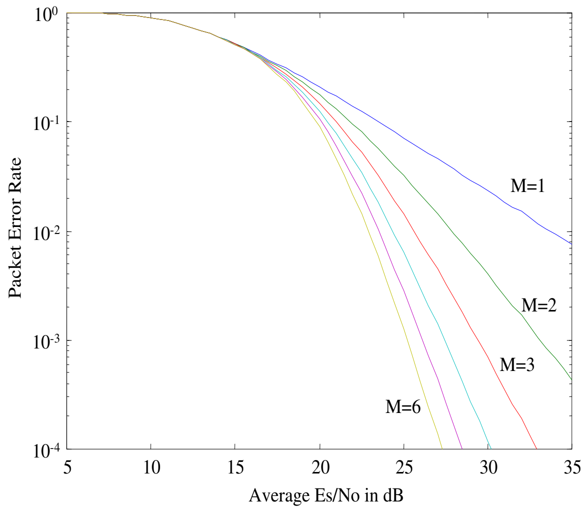


Fig. 3. Average packet error rate of macrodiversity combining in quasi-static Rayleigh fading when MS at location B and the Bluetooth DH5 packet is used.

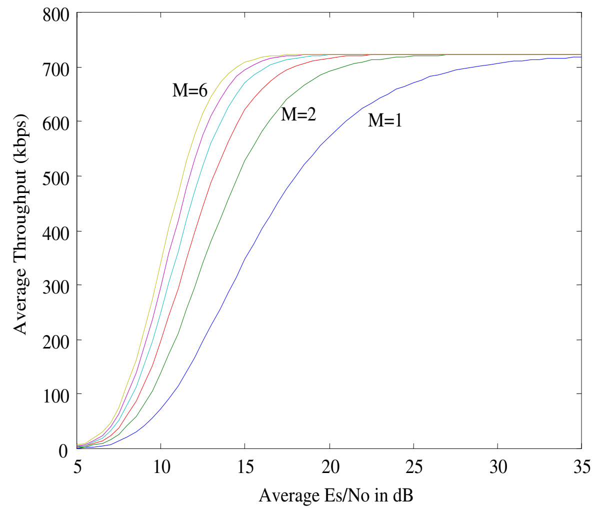


Fig. 4. Average throughput of macrodiversity combining in quasi-static Rayleigh fading when MS at location A, the Bluetooth DH5 packet is used, and a perfect ARQ return channel is assumed.

cut from 372 $\mu W$ to 96 $\mu W$ by using two APs and to 31 $\mu W$ by using six APs.

## III. Throughput Analysis

While packet error rates provide some insight into the potential gains of the proposed macrodiversity reception system, another performance measure that should be considered is the average throughput, which is a function of the number of automatic repeat request (ARQ) retransmissions. Bluetooth uses a simple stop-and-wait ARQ protocol. If the DH5 uplink packet is received correctly (by any of the $M$ APs), then an ACK message is sent (as part of the packet header) within the DH1 downlink packet transmitted during the next slot. Note that while the uplink packet is simultaneously received by all $M$ APs, only a single AP can transmit the downlink packet. Although it would be preferable to use the AP with the best instantaneous SNR to the MS, in practice the AP with the best average SNR could be used (in the absence of shadowing this would be the AP closest to the MS). If the MS does not receive the proper ACK message during the downlink slot, then it will retransmit the entire DH5 packet during the next uplink slot.

For ARQ systems, the throughput $R$ depends on the number $N$ of total data-bearing packets that must be transmitted per successful packet reception. For Bluetooth [13],

$$R = \frac{K}{(DN)(625 \times 10^{-6})}, \tag{4}$$

where $D$ is the number of occupied slots per transmission including the return packet ($D = 6$ for our system which uses DH5 for the uplink transmission and DH1 for the return packet) and $K$ is the number of data bits in the packet ($K = 2712$ for DH5). The average throughput $\bar{R}$ is found by taking the expected value of R with respect to N,

$$\bar{R} = E_N\{R\} \tag{5}$$

$$= \frac{K}{(D\bar{N})(625 \times 10^{-6})}, \tag{6}$$

Thus in order to determine the average throughput, the average number of transmissions $\bar{N}$ must first be determined.

Assume an idealized ARQ system, in the sense that the uplink packets can be decoded before the downlink slot begins and the ACK messages sent on the downlink channel are always received intact. In this case, $N$ is merely a geometric random variable and the average number of uplink transmissions required per correctly received DH5 packet is $\bar{N} = 1/(1 - \bar{p_e})$. Fig. 4 shows the average throughput for the proposed macrodiversity combining system when the mobile is at location A under the perfect ARQ assumptions. From this figure, it appears that the *throughput* gains are less dramatic than the *packet error rate* gains, especially at lower throughput. This is because *low* throughput corresponds to relatively *high* packet error rates, and as shown in Fig. 2 the macrodiversity advantage grows with *decreasing* packet error rates. At low $\bar{p_e}$, the gains are more modest. For instance, a throughput of 145 kbps is achieved with a packet error probability of only $\bar{p_e} = 0.2$, at which point the advantage is 1.5 dB when using $M = 2$ APs and 3 dB when using $M = 6$ AP. However, at a throughput of 716 kbps the gains reported in the last section for $\bar{p_e} = 10^{-2}$ are obtained, and for higher throughput these gains are even larger.

In practice, the return channel is not perfect as it also experiences fading. In particular, we assume that the return packet also undergoes quasi-static Rayleigh fading and that the instantaneous SNR of the return packet transmitted over the downlink is independent of the instantaneous SNR of the uplink packet. However, the average SNR of both uplink and downlink packets are assumed to be equal.

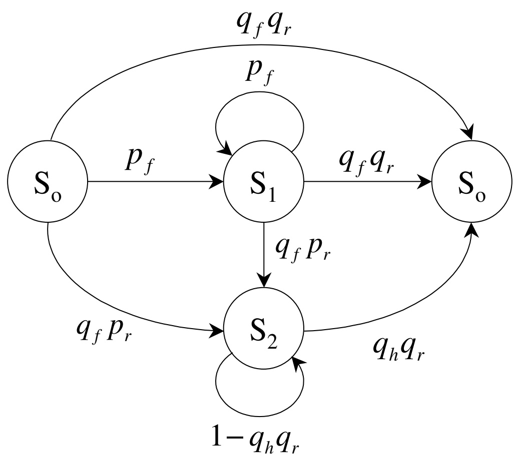


Fig. 5. State diagram representation of Bluetooth stop-and-wait ARQ protocol using macrodiversity reception.

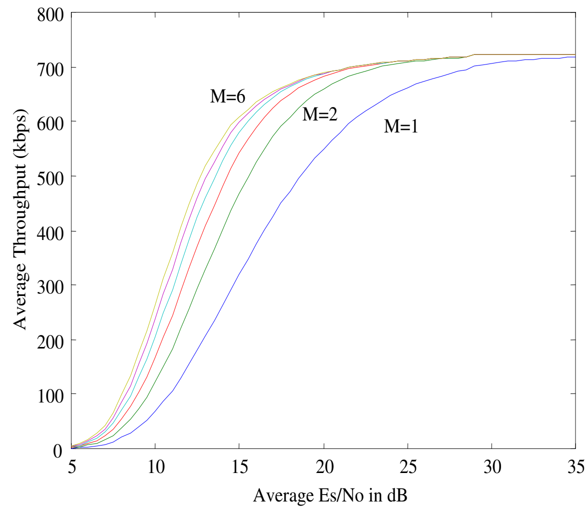


Fig. 6. Average throughput of macrodiversity combining in quasi-static Rayleigh fading when MS at location A, the Bluetooth DH5 packet is used, and the return channel is imperfect.

In [17] we derived the throughput of Bluetooth in quasi-static fading when using a single receiver ($M = 1$) when the return channel is imperfect. This derivation involved the analysis of a state transition diagram that describes the stop-and-wait ARQ protocol. In Fig. 5, the branches of the state transition diagram have been relabeled with new transition probabilities to account for the macrodiversity reception on the uplink. In this figure, $p_f = \bar{p_e}$ is the probability that the forward (uplink) packet is not received correctly by any of the $M$ APs, while $p_h$ is the probability that only the packet header on the uplink is not received correctly by any of the APs. For each error probability $p$, $q = 1 - p$ is the corresponding probability that the packet (or header) is received correctly. Finally, $p_r$ is the probability that the header of the return packet, which is transmitted by a particular AP (assumed to be the one closest to the MS), is received incorrectly at the MS.

The system starts in state $S_o$ with the MS transmitting a new DH5 packet. If at any time both the DH5 (forward) packet transmitted by the MS over the uplink is received correctly by any of the $M$ APs and the packet header of the DH1 (return) packet transmitted by an AP over the downlink is received correctly by the MS, then the system returns to state $S_o$ and the MS transmits the next packet. If the forward DH5 packet is incorrect, the system moves to state $S_1$ and the DH5 packet is retransmitted by the MS. The system will remain in state $S_1$ until one of the APs correctly decodes the DH5 packet. If at any time the forward DH5 packet is received correctly by an AP, but the header of the corresponding return DH1 packet is incorrect (an hence the ARQ flag not received by the MS), then the system will move to state $S_2$. While in state $S_2$, the APs will only examine the header of the DH5 forward packet (since the payload data has already been correctly decoded) and thus the system will only move back to state $S_o$ if the headers of both the forward (DH5) and return (DH1) packets are correctly decoded (it now does not matter if the payload data of the forward packet is correct).

The average number of transmissions can be found by analyzing Fig. 5. Each branch must be multiplied by the variable T, which indicates the amount of time required to make a state transition [18]. Mason's gain rule is used to obtain the graph's generating function $G(T)$. Finally, the average number of state transitions required for the system to move from state $S_o$ back to state $S_o$ is found by taking the partial derivative of $G(T)$ with respect to T and setting $T = 1$. This result gives the average number of ARQ transmissions

$$\bar{N} = \frac{1}{q_f} + \frac{p_r}{q_r q_h}. \tag{7}$$

The throughput when the MS is at location A (Fig. 1) and the return channel is imperfect is shown by Fig. 6. Note that the throughput gains due to using macrodiversity are reduced slightly with respect to the perfect ARQ case. For instance, at a throughput of 500 kbps, the gain of using $M = 2$ APs is 3.4 dB with perfect ARQ but only 3.2 dB when accounting for imperfect ARQ. Likewise, for $M = 6$ the gain is 6.7 dB with perfect ARQ but only 6 dB with imperfect ARQ. The reason that the loss due to return channel effects is more pronounced when more APs are used is that the return channel does not enjoy diversity benefits (i.e. only one AP transmits the return packet). The average throughput in the presence of an imperfect return channel is shown for location B in Fig. 7. Here, there is essential no gain due to macrodiversity reception for throughputs less than about 350 kbps.

## IV. Conclusion

This paper has discussed the general benefits of macrodiversity reception in the wireless LAN uplink, and suggests a practical implementation involving the postdetection combining of the outputs of spatially separated access points. Using Bluetooth as an example, it is shown that an order-

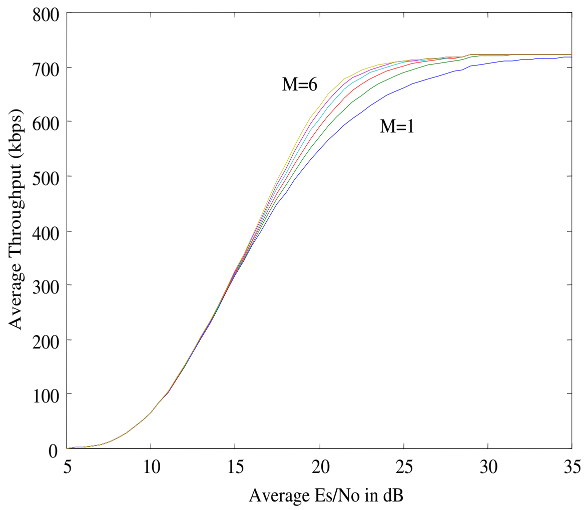


Fig. 7. Average throughput of macrodiversity combining in quasi-static Rayleigh fading when MS at location B, the Bluetooth DH5 packet is used, and the return channel is imperfect.

of-magnitude reduction in transmit power is possible for a target packet error probability of $10^{-2}$ by using just two APs each located the same distance from the MS. The gain is highly dependent on the location of the MS, and is reduced when the MS moves closer to one AP (and further away from the other APs). It should be noted, though, that the biggest gains occur at locations where they are needed most, i.e. when the MS is far away from any one AP but equidistant from two or more APs (as occurs when the MS is between coverage cells). Throughput is also considered, and performance gains are reduced at low throughput (since at low throughput the corresponding packet error probabilities are too high for macrodiversity reception to have a significant impact). In addition, the lack of diversity in the ARQ return channel diminishes the gains further. However, at a moderate throughput (500 kbps) gains of 3 dB are still readily achievable when the MS is equidistant from just two APs.

While this paper has indicated some promising initial results, significant work remains before the proposed macrodiversity concepts can be embedded into practical systems. First, the analysis should be expanded to consider channels other than just Rayleigh fading (e.g. Rician/Nakagami fading, log-normal shadowing), and the possibility of local antenna microdiversity should be taken into account (i.e. what if each AP has two antennas?). Furthermore, interference issues need to be taken into account by the analysis. Finally, while the application to Bluetooth has been discussed here primarily to the tractability of its time synchronous transmissions, the application to the IEEE 802.11 family of standards could be of more widespread appeal.

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