Outdoor IEEE 802.11 Cellular Networks: Radio and MAC Design, and Their Performance

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***Abstract* - This paper explores the feasibility of designing an outdoor cellular network based on the IEEE 802.11 standard, which was developed originally for wireless local-area networks. Specifically, the performance of the 802.11 radio and multiple access control (MAC) protocol in outdoor environments is investigated. For channels typical in cellular networks, we study the radio link power budget and the bit-error performance of three kinds of receivers. We also propose a new timing structure for the MAC protocol to handle increased signal propagation delay, and analyze its throughput performance in the outdoor network.**

Our analysis shows that the MAC protocol can handle a cell radius of 6 km without violating the 802.11 standard. However, the link budget reveals that the maximum cell radius in an outdoor 802.11 network ranges from 0.4 to 1.2 km, about *one-third* that supported by W-CDMA and EDGE networks. For an rms delay spread of 1 μs, typical for urban-area cells of this size, our simulation results show that the conventional RAKE receiver can yield a satisfactory performance. Combining these results, we conclude that using ordinary equipment, an 802.11-based cellular network with a cell radius up to 1.2 km is feasible. It is possible to further extend the service range by advanced techniques such as smart antennas.

***Index terms* - Communication system performance, IEEE standards, multi-access communication, multipath channels, radio communication, spread spectrum communication, wireless LAN.**

I. Introduction

While standards bodies, manufacturers and service providers are actively developing, testing and deploying third generation (3G) wireless networks, many companies have started to provide high-speed data services using wireless local-area-networks (WLAN) in places such as airports, convention centers, hotels, coffee shops, etc. Such an approach to providing wireless data services is particularly feasible and attractive due to (a) the maturity and low cost of the IEEE 802.11 technology [1-6], and (b) its operation in unlicensed spectrum (e.g., the 2.4 GHz ISM band). In contrast, the cost per user of a 3G network is likely to be higher than that of an 802.11 WLAN because of higher equipment costs and operation in expensive licensed spectrum. Moreover, even the 802.11b networks, using a relatively early version of the protocol standard, can provide data rates up to 11 Mbps, far exceeding the maximum data rates to be offered by EDGE (Enhanced Data Rates for GSM Evolution) and W-CDMA (Wideband Code Division Multiple Access) 3G networks [7-9]. The recent versions of 802.11a and 802.11g standards can support up to 54 Mbps data rate. Due to popular demand, the 802.11 capability has been included in many laptop computers as standard equipment.

Owing to its limited transmission range of a few hundred meters, however, each 802.11 WLAN serves only a small isolated area, whereas wide-area 3G networks are designed to support cell radii of up to ten kilometers with reliable coverage. As a result, users may continue to use both types of wireless networks: one with excellent coverage, and the other with enhanced performance in isolated areas.

However, there are strong incentives to use the 802.11 technology not only for WLANs, but also for outdoor, cellular data networks. First, much of the low-cost advantage of 802.11 WLANs would translate to an 802.11 cellular network. Second, 802.11 can provide complete, end-to-end IP services, whereas 3G networks are only partially IP-capable. Third, users could use the *same* air interface to obtain wireless services from *both* WLANs *and* outdoor networks.

We particularly focuses on the 802.11b standard here because its physical-layer design is more robust to the harsh radio conditions, when compared with the 802.11a and 802.11g versions. If possible, such 802.11b cellular networks should have cell radii of a few km. Owing to the increased path loss and multipath dispersion associated with such an increased range, however, one might expect some compromises in an outdoor 802.11b network, compared with its WLAN counterpart. For example, the data rate might be lower, some 802.11b features might be unsupported, and additional signal processing and control algorithms might be required. In addition, with increased signal propagation delay in the outdoor network, the multiple access protocol of the

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802.11 standard might not work properly. In this research effort, we explore whether such an 802.11b network is feasible.

The objective of this paper is two-fold. First, we study the impact of increased path loss and multipath dispersion on the performance of the 802.11b *radio design*. Second, we examine the impact of increased propagation delay (also associated with increased range) on the 802.11b *medium access control (MAC) protocol*. We note that there are many other important issues and challenges, not addressed in this paper, with deploying an outdoor 802.11b network. For instance, the use of unlicensed spectrum in 802.11b comes with the "price" of an uncontrolled radio environment, which can adversely affect system capacity. 3G systems, on the other hand, largely avoid this problem through the use of dedicated spectrum and frequency planning.

The organization of the rest of this paper is as follows. We provide a brief description of the 802.11b radio design and MAC protocol in Sections II and III, respectively. In Section IV, we present a radio link power budget for 802.11b outdoor networks. We also compare this budget with those for W-CDMA and EDGE networks. Section V studies the link performance in terms of bit-error rate for various receivers operating in multipath dispersive channels typical in outdoor environments. In Section VI, we discuss how the MAC protocol works properly in the outdoor networks. In addition, we project the maximum cell radius in the outdoor networks due to the consideration of MAC protocol. Section VII analyzes the MAC performance for the outdoor networks. Although this paper does not examine the issue of interference among 802.11 networks, we highlight a few solution approaches in Section VIII. Finally, our conclusion and future work on the subject are discussed in Section IX.

II. IEEE 802.11 RADIO DESIGN

IEEE 802.11 [1] specifies three physical layer techniques: direct sequence spread spectrum (DSSS), frequency hopping spread spectrum (FHSS) and infrared (IR). In particular, the DSSS design supports data rates of 1 and 2 Mbps by use of differential binary phase shift keying (DBPSK) and quadrature phase shift keying (DQPSK), respectively. Subsequently, while maintaining the backward compatibility to the DSSS 802.11 specification, 802.11b was adopted to support data rates of 5.5 and 11 Mbps using complementary code keying (CCK) modulation, and like 802.11 DSSS, operates in the 2.4 GHz band (commonly known as the ISM band) [3]. As a result, the 802.11b network can support 1, 2, 5.5 and 11 Mbps, depending on radio conditions. Another extension to the 802.11 specification is 802.11a, which uses an entirely different physical layer known as the orthogonal frequency division multiplexing (OFDM). The 802.11a design can support data rates ranging from 6 to 54 Mbps, and operates in the 5 GHz band (the UNII band) [2]. Furthermore, the relatively new 802.11g standard [4] can provide the same maximum data rate of 54 Mbps using the ISM band, while maintaining backward compatibility with the 802.11b equipment.

We note that while the 802.11b standard is still being supported, the 802.11g and 802.11a capability have been incorporated into many new personal computers and communication devices. For outdoor, cellular environments, radio propagation in the 2.4 GHz band (for the 802.11b and 802.11g standards) is more favorable than in the 5 GHz band (for 802.11a networks). In addition, to overcome the harsh radio conditions in outdoor environments, it is advantageous to use the most robust physical-layer design for the lowest data rate. For both these reasons, our work focuses on the extension of *802.11b* to outdoor networks. Furthermore, although 802.11b can support up to 11 Mbps in WLAN environments, we focus on the *1 Mbps* data rate (DBPSK/DSSS) to most effectively extend the transmission range (a greater range is more viable with a smaller effective noise bandwidth). For brevity, in the following we shall use the terms 802.11 and 802.11b *interchangeably* when referring to the 1 Mbps transmission mode.

According to the 802.11 DSSS specification, the data symbol period is $1\,\mu s$, and each symbol (+1 or –1) is spread using the following 11-bit Barker code:

$$+1\ -1\ +1\ +1\ -1\ +1\ +1\ +1\ -1\ -1\ -1$$

As a result, the chip rate is 11 Mchips/s. Each station in the 802.11b network uses the same Barker code for spreading every symbol. (And each DSSS channel has a radio bandwidth of 22 MHz.) Thus, the network yields a processing gain of 11 (10.5 dB) for 1 Mbps transmission. To achieve a simple radio design for the WLAN environment, the 802.11 standard does not include any training sequence for channel estimation or equalization. We note that a limited amount of channel information—a response with a delay span up to $1\,\mu s$—can be extracted by correlating the received signal with the above Barker sequence. If one desires, the 128 synchronization bits in the packet preamble could be used to estimate channel responses with greater spans.

In typical urban environments (outdoor), root-mean-squared (rms) delay spreads can be several microseconds [10], compared with just fractions of a microsecond in typical indoor WLAN environments. So, inter-symbol interference (ISI) can sometimes span several data symbols. In Sections IV and V, we examine the link power budget and study how the 802.11 radio performs in multipath-dispersive channels, parameterized by a range of delay spread values.

III. IEEE 802.11 MAC PROTOCOL

We provide a brief description of the 802.11 MAC protocol here; readers are referred to [1-5] for details. The 802.11 specification define five timing intervals for the MAC protocol. Two of them are considered to be basic

ones that are determined by the physical layer: the short interframe space (SIFS) and the slot time. The other three intervals are defined based on the two basic intervals: the priority interframe space (PIFS) and the distributed interframe space (DIFS), and the extended interframe space (EIFS). The SIFS is the shortest interval, followed by the slot time. The latter can be viewed as a time unit for the MAC protocol operations, although an 802.11 channel as a whole does not operate on a slotted-time basis. For the 802.11b networks (i.e., with DSSS physical layer), the SIFS and time slot are 10 and 20 μs, respectively. The slot time of 20 μs is chosen to account for the signal propagation delay, the switching time from the receiving to the transmitting state at a receiver, and the latency in sending signal from the physical layer to the MAC layer. The PIFS is equal to SIFS plus one slot time, while the DIFS is the SIFS plus two slot times. The EIFS is much longer than other four intervals, and is used when a data frame containing errors is received by the MAC.

The 802.11 MAC supports two modes of operation: the *Point Coordination Function* (PCF) and the *Distributed Coordination Function* (DCF). The PCF is to provide contention-free access, while the DCF uses the well-known carrier sense multiple access with collision avoidance (CSMA/CA) mechanism for contention based access. According to the specification, the two modes are used alternately in time. That is, a contention-free period by the PCF is followed by a contention period of the DCF. However, to our knowledge, the PCF has not been implemented and only the DCF is available in commercial products.

A. The PCF Protocol

In essence, the PCF employs a standard polling scheme where an AP polls its associated mobile stations one after another by sending polling messages. If the AP has data to send to a station being polled, the data can be included in the polling message. If the polled station has data for the AP, it is sent in the response message. When applicable, an acknowledgment (indicating receipt of a previous data frame from the AP) can also be included in the response message.

As an illustrative example in Figure 1, the AP first sends the polling message and data, if any, to mobile station 1 (denoted by S1). According to the standard, the station 1 should immediately send an acknowledgment or a data frame, if any, to the AP within the SIFS interval. After receiving ACK or data from station 1, the AP polls mobile station 2 within the SIFS interval. In this illustration, station 2 does not respond, either because the polling message is lost or station 2 has no data to send to the AP. In this case, as a response is not received from station 2 before the SIFS expires, the AP polls a station 3 within the PIFS interval, which starts from the end of the last polling message for station 2.

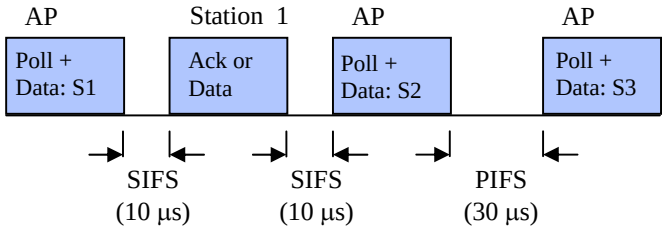

Figure 1. The PCF of the 802.11 MAC Protocol

B. The DCF Protocol

The DCF employs the CSMA/CA mechanism, and works as follows. A station (including the AP) with a new packet ready for transmission senses whether or not the channel is busy. Specifically, if the channel is detected idle for a DIFS interval (i.e., 50 μs for the 802.11b networks), the station starts the packet transmission. Otherwise, the station continues to monitor the channel busy or idle status. After finding the channel idle for a DIFS interval, the station: a) starts to treat channel time in unit of slot time, b) generates a random backoff interval in unit of slot time, c) continues to monitor whether the channel is busy or idle. In the latter step, for each slot time where the channel remains idle, the backoff interval is decremented by one. When the interval value reaches zero, the station starts the packet transmission. During this backoff period, if the channel is sensed busy in a slot time, the decrement of backoff interval stops (i.e., frozen) and the decrement resumes only after the channel is detected idle continuously for the DIFS interval and the following one slot time. Again, the packet transmission is started when the backoff interval reaches zero. The random backoff mechanism helps avoid packet collision as the channel has been detected to be busy recently. Further, as a means to avoid channel capture a station must wait a backoff interval between two consecutive new packet transmissions, even if the channel is sensed idle in the DIFS interval. The operations are depicted in Figure 2.

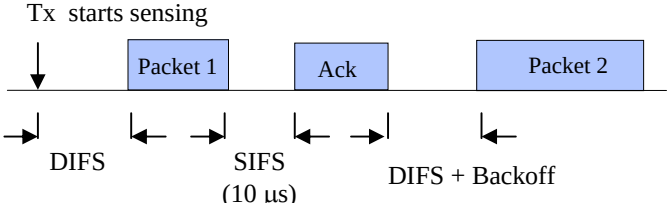

Figure 2. The DCF of the 802.11 MAC Protocol

The backoff mechanism for the DCF is an exponential one. That is, for each packet transmission, the backoff time in unit of slot time (i.e., an integer) is uniformly chosen from 0 to n-1, where n is called the contention window and its actual value depends on the number of failed transmission for the packet. At the first transmission attempt, n is set to a value CW_{min}=32, the so-called minimum contention window. After each

unsuccessful transmission, n is doubled, up to a maximum value CW_{max}=1024.

During a packet transmission, a station cannot listen to find out if the transmission collides with other transmissions. The 802.11 specification require a receiver to send an ACK for each packet that is successfully received. Furthermore, to simplify the protocol header, an ACK contains no sequence number, and is used to acknowledge receipt of the immediately previous packet sent on the channel. That is, each pair of sending and receiving stations exchange data based on a stop-and-go protocol. As shown in Figure 2, the sending station is expected to receive the ACK within the 10 μs SIFS interval after the packet transmission is completed. If the ACK does not arrive at the sending station within a specified ACK_timeout period, or it detects transmission of a different packet on the channel, the original transmission is considered to be failed and subject to retransmission.

In addition to the physical channel sensing mentioned above, the 802.11 MAC protocol implements a network allocation vector (NAV), which is a value to indicate to each station the amount of time that remains before the channel will become idle. All packets in the MAC protocol contain a duration field and the NAV is updated according to the value in the field of each packet being transmitted. The NAV is thus referred to as virtual carrier sensing mechanism. Combining the physical and virtual sensing operations, the MAC provides the collision avoidance feature.

The protocol described above is called the two-way handshaking mechanism. In addition, the MAC also contains a four-way frame exchange protocol. Essentially, the four-way protocol requires a station send to the AP a special, Request-to-Send (RTS) message, instead of the actual data packet, after gaining the channel access through the contention process described above. In response, if the AP sees appropriate, it sends a Clear-to-Send (CTS) message within the SIFS interval to instruct the requesting station start the packet transmission immediately. The main purpose of the RTS/CTS hand-shake is to resolve the so-called hidden terminal problem (i.e., some stations cannot receive signal from all other stations, thus possibly causing severe interference) and to maintain high channel throughput, especially for long packet transmission in light of lack of collision detection in the wireless networks.

IV. Radio Link Power Budget for Outdoor 802.11 Networks

Table 1 presents a link budget for an outdoor 802.11 network, and for comparison, link budgets for 384 kbps non-real-time data services in W-CDMA networks and EDGE networks with 1/3 frequency reuse.

Table 1. Radio link power budgets.

		802.11b				WCDMA		EDGE	
a	Thermal noise (dBm/Hz)	-174				-174		-174	
b	Channel BW* (dB)	73.4				65.8		53	
c	Noise factor (dB)	5				5		5	
d	**Noise power (dBm)**	-95.6				-103.2		-116	
e	Interference margin (dB)	3				3		3	
f	Minimum SINR (dB)	0				-5		10	
g	**Min. RX sig. power (dBm)**	-92.6				-105.2		-103	
h	Transmitter EIRP (dBm)	30	30	30	30	30	30	30	30
I	Sector gain (dBi)	6	6	17	17	17	17	17	17
j	Shadowing margin (dB)	-8	-8	-8	-8	-8	-8	-8	-8
k	Building penetration (dB)	-15	0	-15	0	0	-15	0	-15
l	**Allowable path gain (dB)**	-105.6	-123.6	-116.6	-131.6	-129.2	-144.2	-127	-142
m	Med. path gain. @100m (dB)	-80	-80	-80	-80	-80	-80	-80	-80
n	Adnl. gain at cell edge (dB)	-25.6	-43.6	-36.6	-51.6	-49.2	-64.2	-47	-62
o	Propagation exponent	4	4	4	4	4	4	4	4
p	**Cell radius (km)**	**0.4**	**1.2**	**0.8**	**1.9**	**1.7**	**4.0**	**1.5**	**3.5**

* Channel bandwidths for 802.11, WCDMA and EDGE are 22 MHz, 3.84 MHz and 200 kHz, respectively.

Let us first examine an 802.11 network's budget. As shown in the first data column of the table, for the 22 MHz channel and an assumed noise factor of 5 dB, the received in-band noise power is –95.6 dBm (the sum of parameters a, b, and c). For DBPSK and the 10.5 dB processing gain for DSSS, the minimum SINR for reliable signal detection is estimated to be 0 dB, prior to dispreading. Combining this with an interference margin of 3 dB, the minimum received signal power is –92.6 dBm (the sum of parameters d, e, and f).

We consider the equivalent isotropic radiated power (EIRP) of 1 W (or 30 dBm). (Note that 1W EIRP

is the maximum allowable transmission power for the ISM band in North America. Also, for practical reasons, currently most 802.11 hand-held devices restrict themselves to transmit power levels of 15-20 dBm with ~0 dBi antenna gain. We consider the power level of 30 dBm to identify the intrinsic limits of the 802.11 specification here.) As a standard practice, each cell in the 802.11 network would likely be divided into three sectors, and we assume a sector antenna gain of 17 dBi for reception at the AP (i.e., uplink transmission). However, for transmission by the AP (i.e., downlink transmission), the ISM band requires that the transmitting antenna gain be subject to a maximum of 6 dB and that transmission power be reduced by one dB for every additional dB gain exceeding the 6 dB limit [11]. So, we consider two cases with only 6 dBi antenna gain at the AP. We also assume a typical value of 8 dB for the shadowing margin and, for indoor reception, 15 dB for building penetration loss. Combining parameters g through k, the allowable path gain (denoted by l) is given by g – (h + i + j + k). Depending on the transmission power and indoor reception requirements, the corresponding allowable path gain is given by the values in the first through fourth columns of the table. We use a propagation model in [12] with a path loss exponent of 4 and a median path gain of –80 dB at 100 m from the access point (AP) antenna. The cell radius is thus computed based on the allowable path gains.

The key differences in the EDGE/W-CDMA link power budgets, as compared with the 802.11 budget, are their channel bandwidths, minimum SINR requirements for reliable reception and allowable antenna gain. Specifically, the channel bandwidths for the W-CDMA and EDGE systems are 3.84 MHz and 200 KHz, respectively. The SINR requirement of –5 dB for the W-CDMA system is based on a processing gain of 10, the required Eb/No of 1 dB, and an inclusion of a fast fading margin of 4 dB. The required SINR of 10 dB in the EDGE system is estimated for the most robust modulation to achieve a block-error rate of about 15% [13]. As mentioned above, the ISM band limits the transmitting antenna gain in the 802.11 network, while the WCDMA and EDGE do not have such a restriction. For the assumed parameters, the cell radii for the W-CDMA and EDGE systems for outdoor reception are 4.0 and 3.5 km, respectively.

Note that the path loss model used in the budget calculation corresponds to a flat terrain with light tree density [12] with the AP antenna mounted on a typical cellular tower of 30 m height. The cell radius for all air-interface standards strongly depends on the terrain categories under consideration. Nevertheless, the link budget reveals that the maximum cell radius in the outdoor 802.11 network is about one-third of those supported in the W-CDMA and EDGE networks. The estimated cell size for 802.11 lies in the range 0.4 to 1.2 km. Since the ISM band does not limit antenna gain for reception, one possible way to improve upon such a range is to employ advanced antenna technology at the terminal receiver. For instance, consider that terminal receiver provides an antenna gain of 11 dBi for reception. Combining this with the maximum, allowable 6 dB gain at the transmitting sector antenna, the total antenna gain at both ends become 17 dBi. In this case, as presented in Table 1, the cell radius can be increased to a range of 0.8 to 1.9 km. We also note that for the cell size of 0.4 to 1.2 km, the signal propagation delay runs between 1.33 to 4 μs. The corresponding rms delay spread is expected to lie between a fraction of a microsecond up to about 1 μs [10].

V. LINK ERROR PERFORMANCE

Our main purpose here is to investigate the error performance of the radio link when the 802.11 standard is used for outdoor cellular networks, wherein the delay spread is higher than that for the indoor WLAN environment. Specifically, we study the link error performance for three kinds of receiver: (1) the *constrained RAKE*, which is limited to 1 μs of multipath channel information; (2) the *full RAKE*, which uses the full multipath channel information; and (3) the ideal equalizer, the performance of which is represented by the *matched filter bound (MFB)* [14].

These three cases are chosen for the following reasons. The key function of a RAKE filter, or channel-matched filter, is to maximize the signal-to-noise ratio (SNR) at its output. In doing so, a RAKE filter also helps mitigate ISI to some extent. The constrained RAKE is considered because the channel information of 1 μs delay span can be readily obtained using the standard technique of correlating the received signal with the 11-bit Barker code. The full RAKE, on the other hand, requires complete channel response information, which could be obtained via the 128-bit SYNC sequence, but with additional processing complexity. The last case, the MFB, is examined to determine the best possible receiver performance, i.e., maximizing the SNR *and* somehow eliminating *all ISI*. Thus, our study of these three receivers provides insights into the tradeoff between link performance and complexity.

A simulation model for these cases is shown in Figure 3. Data symbols are spread by the 11-bit Barker code and the spread signal is transmitted over a noisy, dispersive channel. The received signal is processed by the matched filter (i.e., the full/constrained RAKE; or the MFB computation is applied), and goes through the despreading and detection processes. For simplicity, we study the bit error rate (BER) for *BPSK*, but note that our results can be translated into DBPSK performance by increasing the required SNR by approximately 1 dB for a given BER [15, p.166].

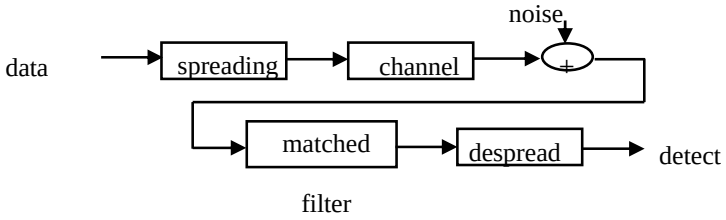

Figure 3. Simulation model for the matched-filter receiver.

We assume a standard model for the multipath channel—quasi-static, frequency-selective, Rayleigh fading [14]. Each realization of the baseband-equivalent channel impulse response comes from a non-stationary, zero-mean complex Gaussian random process, the variance of which is characterized by a discrete exponential delay power profile. (For simplicity, the discrete components are spaced to match the chip period of 90.9 ns.) The delay profile is, in turn, parameterized by the rms delay spread; and the total multipath dispersion span is approximately four times this rms value.

We assume that the channel-matched (RAKE) filter has perfect channel response knowledge of (a) up to 1 μs multipath span for the constrained RAKE and (b) the entire span for the full RAKE. For each channel realization, thousands of bits are transmitted across the simulated link and a BER is determined for each realization (by counting errors). We then determine the *average BER* over many realizations. The number of bits per realization and number of realizations are set to be high enough to ensure a statistically-confident estimate of this average BER. (The required numbers depend on the receiver type and the rms delay spread, which together determine the variation in captured channel energy.) The MFB is computed analytically [14], based on the known channel response.

For rms delay spreads of 250 ns, 1 μs and 3 μs, Figures 4 to 6 show the BER for the three receivers as a function of SNR. For reference purposes, the BER for BPSK in an additive-white-Gaussian-noise (AWGN) *unfaded* channel is also shown. We are particularly interested in the required SNR for a BER of 10^{-5}, which corresponds to a 5–10% packet error rate (we assume retransmission of erroneous packets) for typical packet sizes (thousands of bits).

For a delay spread of 250 ns, which corresponds closely to *frequency-flat* fading, the constrained RAKE captures almost all channel information (i.e., it is contained within 1 μs for this small delay spread), and there is very little residual ISI after receiver processing. Thus, the full and constrained RAKE receivers provide BER performance virtually identical to the MFB, as shown in Figure 4.

At this small delay spread, however, *all receivers* fall short of the link power budget requirements shown in Table 1. At a BER of 10^{-5}, Figure 4 shows that the receivers require an average SNR of about 6 dB, which is 6 dB greater than that specified in the link budget. Fortunately, such small delay spreads tend to occur in line-of-sight (LOS) or near-LOS paths. The shadow fading margin can thus often be relaxed, offsetting the higher SNR requirement. In links where this is not the case—i.e., small delay spreads and significant shadow fading—service will be unreliable.

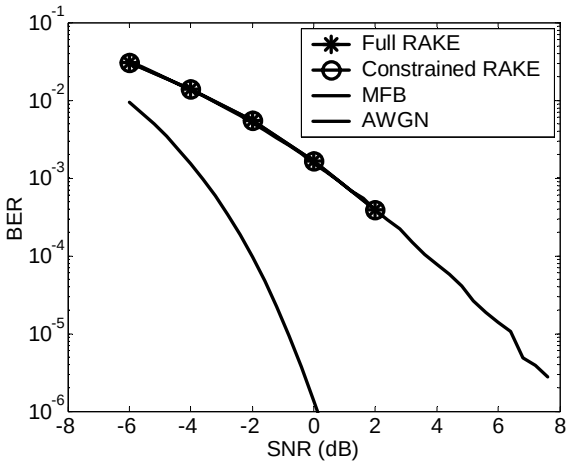

Figure 4. Error performance for 250 ns rms delay spread.

Figure 5 shows performance for an rms delay spread of 1 μs. At this value, all receivers benefit from *multipath diversity*. That is, there are more resolvable multipath components, and there is thus less overall signal fading. Provided the receiver can suppress the ISI introduced from the multipath dispersion, performance will approach that of the *unfaded* channel. The MFB result, which eliminates *all* ISI, best illustrates this phenomenon, but all receivers show a performance improvement compared with the results in Figure 4.

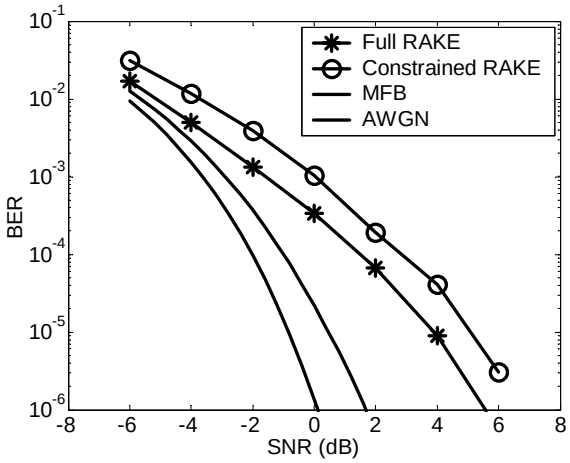

Figure 5. Error performance for 1 μs rms delay spread.

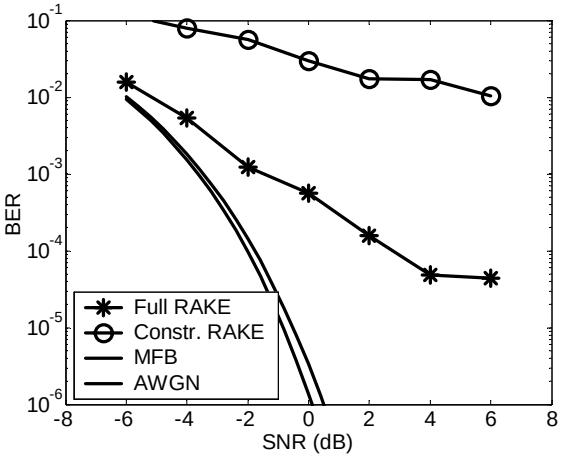

Figure 6. Error performance for 3 μs rms delay spread.

As one would expect, the BER performances for three receivers diverge for increasing delay spread. At an rms delay spread of 1 μs, the MFB roughly meets the link budget's 0 dB SNR requirement (for BER=10^{-5}), but the full and constrained RAKE receivers fall short by about 4 dB and 5 dB, respectively.

The results in Figure 5 are of special relevance because a 1 μs rms delay spread is typical in urban-area cells that have a radius in the range estimated by our link power budget (see Section IV). With a modest relaxation in reliability requirements or perhaps a small reduction of cell sizes in cluttered environments (which bring about large delay spreads), we expect that the constrained/full RAKE receiver may well be adequate. As evidenced by the results, however, an improved equalizer would be beneficial in improving service reliability or in accommodating somewhat larger cells. An important area for future study is to devise advanced equalization techniques to realize such potential improvements.

At an rms delay spread of 3 μs, which is high in even the harshest of multipath environments (perhaps with the exception of some mountainous areas), Figure 6 shows a major divergence in the performances of the three receivers. First, the MFB performance is very close to the AWGN curve because such high dispersion offers a high order of multipath diversity. The full RAKE benefits from the same multipath diversity, but it cannot cope with the high ISI as well as the MFB can and it yields an irreducible BER of about $4\text{x}10^{-5}$ (i.e., with infinite SNR). And finally, the constrained RAKE is subjected to high ISI *and* captures only a small fraction of the total multipath energy in its 1 μs window. Thus, its performance is very poor, even at high SNR values.

Figure 7 summarizes the SNR degradation, with respect to the AWGN channel, as a function of the ratio of rms delay spread to symbol period (e.g., a value of 1 would correspond to 1 μs rms delay spread for the 1 Mbps data rate). In particular, we see how robust the full RAKE is compared with the constrained RAKE for rms delay spreads greater than 1 μs. The constrained RAKE becomes *unable* to achieve the target BER, at any SNR, when the delay spread goes beyond 1.25 μs. Note that the results in Figure 7 are for a target BER of 10^{-4}. We set this higher BER target to get higher numerical precision in the simulation results, but the trends are similar for other BER thresholds (e.g., the SNR would be further degraded by about 1-2 dB for the more practical BER target of 10^{-5}).

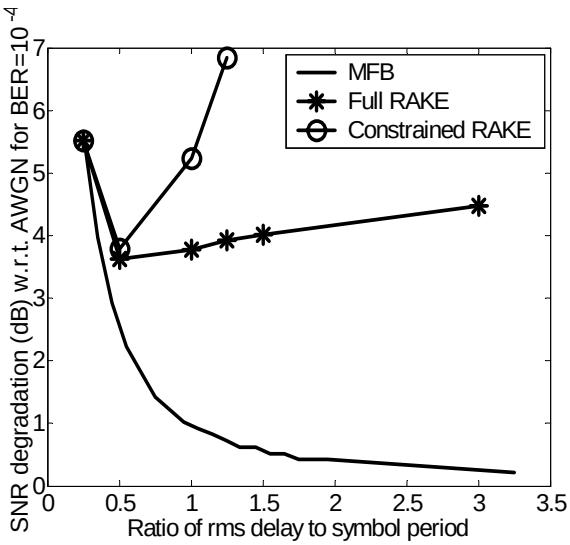

Figure 7. Performance degradation vs. rms delay spread.

VI. FEASIBILITY OF DCF PROTOCOL IN OUTDOOR NETWORKS

As noted above, the PCF protocol has not been implemented and only the DCF protocol is widely used in commercial products. So, we focus on the feasibility of the DCF protocol in outdoor environments here.

A. Applicability of the DCF Protocol

It is worth noting that as far as the DCF protocol is concerned, the major difference between the 802.11 outdoor networks and their WLAN counterparts is an increased signal propagation delay. As shown in Figure 2, the major constraint for the applicability of the DCF in the outdoor networks is that the ACK is expected to be receive within a SIFS interval (10 μs) after a packet transmission. That is, the 10 μs includes the round-trip signal propagation and processing at the receiver. However, in order to be useful, we aim at having the cell size of the outdoor networks on the order of several km. Thus, the one-way signal propagation delay can be close to or more than 10 μs, while neglecting the return propagation and processing time. Evidently, such would not be practical without violating the protocol specification. Our solution is based on the following key observation: Typically, there can be no consequence if the ACK receives later than the SIFS interval. This is so because after a station transmits a packet, it starts an ACK_timeout period, which is not specified in the IEEE standards and usually chosen to be a value much larger than 10 μs by equipment manufactures. As a result, as long as the ACK is received prior to the timeout expiration, the MAC protocol can respond accordingly.

As in typical implementations, we assume that the ACK_timeout period is longer than the DIFS interval of 50 μs. Then, we argue that as long as the ACK arrives at the sending station within the DIFS interval following a packet transmission, the DCF operates properly in the outdoor network environment where the link distance can reach as much as several km. The reasoning is as follows. First, as the ACK is received within the DIFS interval, the ACK_timeout has not expired so that the protocol can respond upon receipt of the ACK as if it were received within the SIFS interval, as originally specified in the protocol standards. Second, since the DCF protocol requires any station to sense the channel being idle for at least the DIFS interval before transmitting, the return of ACK within the DIFS interval following the previous packet transmission by the sending station precludes any stations other than the receiving one to gain access to the channel. Consequently, the channel is implicitly "reserved" for the receiving station to send the ACK. In addition, the pairing of a packet transmission and its ACK transmitted in sequence in time for any pair of sending and receiving stations remains intact, as required by the specification.

It is noteworthy that extending the arrival delay of the ACK from the SIFS to the DIFS interval does come with a penalty. That is, the computation of the NAV for the virtual channel sensing is based on the assumption of ACK return within the SIFS interval. So, the delay extension causes erroneous determination of the NAV value, thus incorrect virtual sensing. Nevertheless, since the protocol operations are based on both the physical and virtual channel sensing, as long as the former works properly, the malfunctioning of the virtual sensing due to incorrect NAV value will cause no apparent, negative impacts. More specifically, the incorrect virtual sensing may allow a ready station to transmit despite an on-going transmission from another station. However, as the physical sensing works properly, it will prohibit the new transmission by the former station.

Actually, the extension of the ACK arrival delay from the SIFS interval to the DIFS interval can also apply to the RTS and CTS handshake for resolving the hidden terminal problem. More specifically, a sending station starts a CTS_timeout period after sending an RTS. The MAC protocol specifies that the CTS, if any, is supposed to arrive from the receiving station within the SIFS interval (10 μs). However, similar to the ACK_timeout, the CTS_timeout period is typically chosen to be much longer than 10 μs by equipment manufacturers. Therefore, by the same arguments discussed above, the arrival delay for the CTS can be extended to the DIFS interval.

B. Maximum Cell Size for the DCF Protocol

With the arrival delay for the ACK and CTS extended to the DIFS interval, let us consider its limit on the maximum cell size (i.e., link distance) in the outdoor 802.11 networks.

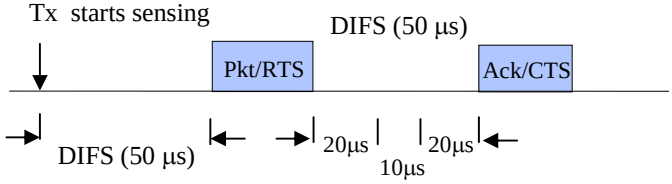

Figure 8. Allocation of ACK/CTS delay

Recall that the ACK and CTS arrival delay consists of a round-trip signal propagation delay and the signal processing time. One reasonable allocation of the 50 μs DIFS delay is: the one-way signal propagation delay of 20 μs and the processing time of 10 μs at the receiving station. The latter should not cause significant processing burden for the receiver because the original delay of the SIFS interval is 10 μs. For the 20 μs propagation delay, the maximum cell size is about 6 km, by assuming that signal propagates at the speed of light. In other words, with the cell size of 6 km or less (and an assumption of correct signal reception at the physical layer in this paper), the DCF protocol is expected to operate properly in the 802.11 cellular networks.

In fact, as far as the DCF is concerned, the cell size for the 802.11 outdoor networks can be further increased beyond 6 km radius by faster signal processing at the receiver. Furthermore, as long as the ACK_timeout and CTS_timeout periods are sufficiently large, the arrival delay for the ACK and CTS can be increased to a value larger than the DIFS interval of 50 μs. In this case, depending on the traffic load condition, the MAC efficiency will degrade as stations other than the sending and receiving station pairs can gain access to the channel, thus interrupting the pairing sequence of a packet transmission and its ACK (or the RTS/CTS handshake) and causing unnecessary retransmission. Nevertheless, for practical consideration, we view that a maximum cell size of 6 km is reasonable and feasible to maintain the correct operations of the DCF protocol in the 802.11 outdoor networks.

VII. DCF PERFORMANCE IN OUTDOOR NETWORKS

As the signal propagation delay for the 6 km cell radius is higher than that on the WLAN, the DCF throughput performance is expected to degrade in the outdoor networks when compared with the WLAN counterparts. Instead of providing detailed analyses as in [16] and [17], as an initial attempt to quantity the performance degradation, we present in the following an approximate analysis of the DCF throughput for the outdoor networks and WLAN.

As shown in Figure 8, if a station with a packet for transmission senses the channel idle for the DIFS interval (denoted by d in μs in the following), it starts to transmit. Following the packet transmission, the channel remains idle for the DIFS interval and then the ACK is transmitted by the receiver. If the sending station senses the channel busy, it goes through the backoff mechanism discussed above. For simplicity, we however do not consider the details of the backoff algorithm. Instead, it is assumed that the aggregated traffic, which includes the new packets and transmission reattempts, from all stations forms a Poisson with process with intensity of G packets/μs. It has been shown that this traffic assumption for analysis of MAC protocols is reasonable, if the backoff period is sufficiently long so that the new transmission and reattempts become independent sources. This is especially true for systems with a large number of stations.

A key performance parameter for the CSMA protocol is the vulnerable period (denoted by a), which includes the signal propagation delay, busy-detection time and the receiver-transmitter (RX-TX) switchover time. A new packet transmission just started by one station will not be sensed and responded to by other stations during the vulnerable period. As a result, the latter under the CSMA protocol can possibly start their transmissions and cause collision. For simplicity, we assume that the vulnerable period a in μs is identical between any pair of sending and receiving stations. Each station senses the channel idle for d μs (DIFS interval) before transmitting. The packet transmission time is assumed to be constant and denoted by L in μs.

Consider the channel activity for a successful packet transmission. The channel is idle for d μs and followed with the packet transmission of L μs. As shown in Figure 8, the transmitter waits for d μs (DIFS interval) for the ACK. Let the transmission time for an ACK is c μs. The channel can be sensed as being idle by all stations a μs after the ACK transmission. Figure 9 shows a typical busy period with collided transmissions due to the vulnerable period for the CSMA protocol, where Y denotes the time span between the first and the last packet transmission in the busy period.

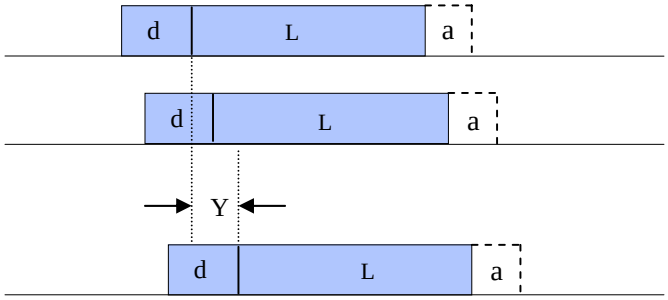

Figure 9. Busy period with Collides Transmissions

Note that Y must be less than a because every station in the WLAN senses the channel busy after the vulnerable period. Using the existing result in [18], the average duration of Y is given by

$$\overline{Y} = a - \frac{1-e^{-aG}}{G}. \qquad (1)$$

The average length of a busy period (which contains a successful transmission or collisions) is given by

$$\overline{B} = d + \overline{Y} + L + a + (d+c)e^{-aG} \qquad (2)$$

where the last term is to account for the waiting and transmission time of the ACK in case of successful transmission with probability e^{-aG}, based on the Poisson assumption of aggregated traffic. By the same assumption, the average cycle time, which consists of a busy period and the following idle period, is given by

$$\overline{T} = d + \overline{Y} + L + a + (d+c)e^{-aG} + \frac{1}{G}. \qquad (3)$$

The channel throughput (denoted by S) is defined as the fraction of time during which data is successfully transmitted. Thus, we have

$$S = \frac{Le^{-aG}}{\overline{T}} \qquad (4)$$

where the numerator is the average amount of time at which data is transmitted without collision and $\overline{T}$ has

been obtained in (3). In addition, let us define the *effective channel utilization* (denoted by *U*) as the fraction of time at which stations will prohibit themselves from transmission as the channel is sensed to be "busy." Then, we get

$$U=\frac{\bar{B}}{\bar{T}}=\frac{\bar{B}}{\bar{B}+1/G} \qquad (5)$$

Where $\bar{B}$ is given by (2).

Three common packet sizes of 60 bytes (e.g., TCP ACK packet), 576 bytes (typical size for web browsing applications) and 1500 bytes (the maximum size for Ethernet) plus a 34 bytes 802.11 MAC header are considered. For an 802.11 network with 1 Mbps data rate, the corresponding transmission time *L* is 0.75, 4.88 and 12.27 msec, respectively. The sensing idle time of the DIFS interval is 50 μs and the transmission time *c* for the 112-bit ACK is 0.112 μs. It is assumed that the combined busy-detection and RX-TX switchover time is 5 μs. Based on our discussion above, the link distance in the cellular network is assumed to be 6 km and thus the one-way propagation delay and the corresponding vulnerable period are 20 and 25 μs, respectively. For comparison, we also consider a WLAN with a service radius of 600 m and its respective signal propagation delay and vulnerable period are 2 and 7 μs. In this WLAN, after a packet transmission, a station waits for the SIFS interval of 10 μs as specified in the standards in Figure 2, instead of the DIFS interval as shown in Figure 8, for the arrival of the associated ACK. Substituting these parameters into (1) to (4), we obtain in Figure 10 the MAC throughput as a function of the aggregated traffic load for the selected packet lengths. As expected, when the link distance is increased from 600 m to 6 km for a fixed packet length, the maximum throughput decreases because of the increase of signal propagation delay and thus the vulnerable period. Specifically, for the 576-byte packet size, the maximum throughput drops from 89.8% to 83.6% as shown in the figure, when the link distance increases from 600 m to 6 km. Nevertheless, since 576-byte size is typical for the popular web applications, the throughput of 83.6% is still satisfactory. For the packet size of 1500 bytes, the channel throughput for the 6 km cell can reach the maximum of 89.9%. Even for the typical short TCP ACK packets of 60 bytes long, the channel throughput is about 58.1%, which is still satisfactory despite the increase of cell size.

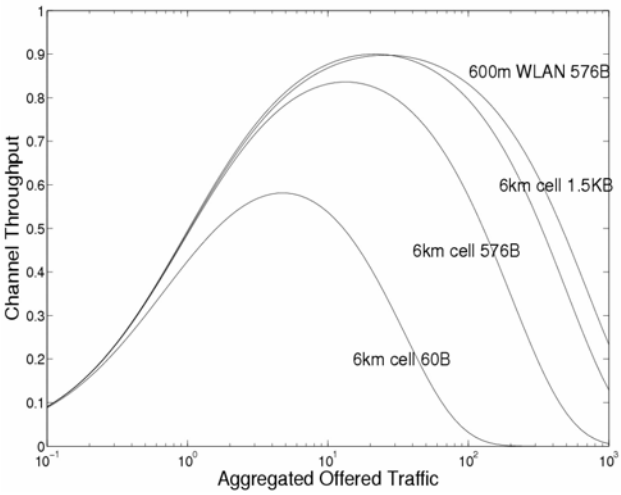

Figure 10. MAC Throughput Comparison

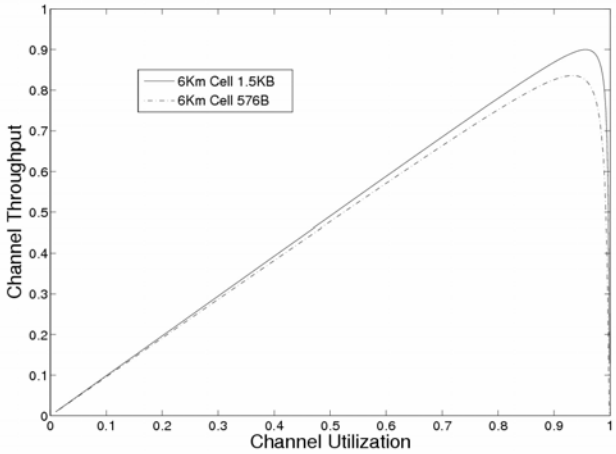

Figure 11. Throughput Vs. Utilization for 6 km Cell

Figure 11 depicts the relationship between the channel throughput and utilization. Note that the decrease of throughput at very high utilization is due to excessive traffic, which results into very high probability of transmission collision. For both packet lengths of 576 and 1500 bytes in the 6 km cell, these results reveal that unless the channel utilization goes beyond 90%, the channel still maintains satisfactory throughput. This verifies the robustness of the 802.11 MAC protocol.

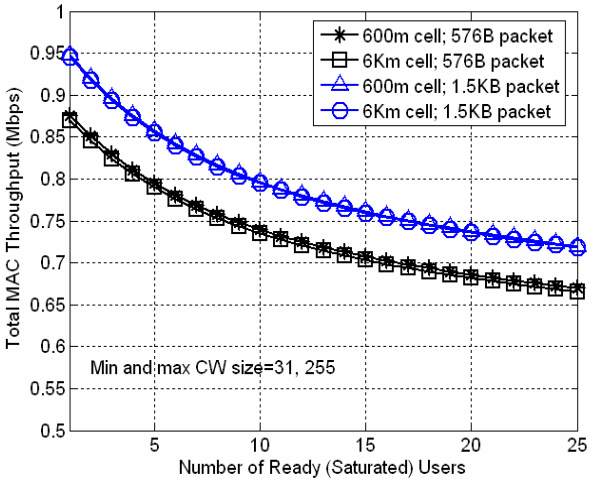

Figure 12. MAC Throughput for Stations with Saturated Traffic

To complement the above throughput analysis, we also apply the model in [19] to study the MAC throughput as a function of stations (users) with saturated traffic. That is, each of these users constantly has packets pending for transmission. Using the same system parameters above, Figure 12 reveals that as the number of saturated users increases, the total throughput decreases due to increased contention. As expected, the throughput increases as packet length is increased, while all other parameters remain unchanged. More importantly, for the packet lengths of 576 bytes and 1500 bytes, the throughput difference between the 600 m WLAN and the 6 km cell (with their vulnerable periods of 7 and 25 μs, respectively) is very small. In fact, for 1500-byte packets, their difference is almost invisible.

Based on results of the throughput analysis and the saturated throughput study, one can conclude that the MAC throughput is expected to reduce slightly due to increased signal propagation delay when the 802.11 standard is extended from the WLAN to the outdoor cellular environments.

VIII. Interference Issue

We note that besides the link budget, channel dispersion and increased signal propagation delay, another important issue for the outdoor 802.11 networks is interference. This is particularly so when access points are densely deployed in a given area. The issue is challenging also because the ISM band at 2.4 GHz is unlicensed and available for any use as long as certain restrictions (e.g., transmission power, antenna gain, use of spread spectrum techniques) are observed. While the issue lies beyond the scope of this paper, let us highlight two solution approaches for the issue here. First, as discussed above, the 802.11 network uses the CSMA protocol to control channel access. When a sufficient amount of interference exists, the channel is sensed busy and a ready station simply defers its packet transmission. As a result, the MAC protocol automatically reduces interference impacts on link error performance at the expense of reduced network throughput as mutually interfering stations do not transmit simultaneously. Furthermore, channel allocation algorithms for 802.11 networks represent an active area of research (see e.g., [20-21]) and it is expected that these efficient algorithms can reduce interference and enhance network capacity. The second approach is by use of smart antennas and signal processing techniques to suppress interference. For example, consider an adaptive-array antenna. Signal received by the multiple antenna elements is combined with appropriate weighing factors. Thus, the antenna can be used to track interference and determines the appropriate weighing factors so that the impacts of interference on the desired signal can be minimized. Use of smart antenna in WLANs is also an active area of research (see e.g., [22-24]). Smart antennas not only improve error performance and link distance, but also enable more stations to transmit concurrently, leading to an increase in network capacity.

IX. Conclusion and Future Work

In this paper, we have demonstrated the extent to which the IEEE 802.11b standard is applicable to outdoor cellular environments. We have focused on the 1 Mb/s DSSS operating mode because it both lends itself to maximizing wireless range and may be adequate for many wide-area applications.

It has been found that the 802.11 MAC protocol can support a cell radius up to 6 km without violating the standard. While some enhancements may be needed—e.g., improved equalization for some multipath environments—we estimate that sectorized-cell radii in the range 0.4–1.2 km are feasible in outdoor 802.11b networks. This range is about *one-third* that supported in EDGE and WCDMA systems. However, this smaller-cell disadvantage could well be outweighed by the strong incentives for using 802.11b as a wide-area wireless technology, i.e., low-cost AP and terminal equipment, operation in unlicensed radio spectrum, end-to-end IP support, and compatibility with increasingly popular WLANs. In urban areas where a high cell density may be *necessary* to meet capacity requirements, the case for 802.11 cellular networks is particularly strong.

In future work, we plan to investigate how well smart antennas can extend the cell radius and suppress interference in these networks. In addition, we plan to devise methods for estimating channel information and to study the performance improvement of advanced equalization techniques in outdoor 802.11 networks. At the system level, we also plan to enhance new algorithms for efficient allocation of a limited number of available frequencies to various access points.

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