

# Outdoor IEEE 802.11 Cellular Networks: Radio Link Performance

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**Abstract** — In this paper, we explore the feasibility of designing an outdoor cellular network based on the IEEE 802.11 standard, which was developed originally for wireless local area networks. For channel typical in cellular networks, we study the radio link power budget and, via simulation, the bit error performance of three kinds of receiver: (1) the *constrained RAKE*, which is limited to a  $1 \mu\text{s}$  multipath span; (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*.

Our link budget reveals that the maximum cell radius in an outdoor 802.11 network ranges from 0.7 to 3 km, about half that supported by W-CDMA and EDGE networks. For an rms delay spread of  $1 \mu\text{s}$ , typical for urban area cells of this size, our simulation results show that the conventional constrained RAKE receiver may yield satisfactory performance. The improved receivers, however, yield 1–3 dB gain over the constrained implementation. Combining these results with those in a companion paper on the MAC protocol, we conclude that an 802.11-based cellular network with a cell radius of a few km is feasible.

**Index Terms** — Cellular networks, dispersive channel, equalization, IEEE 802.11, radio link budget, radio link performance, RAKE receiver, wireless local area networks.

## 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 [I97, I99b, VAM99], and (b) its operation in unlicensed spectrum (the 2.4 GHz ISM band). In contrast, the cost per user of a 3G network is higher than that of an 802.11 WLAN because of high equipment costs and operation in expensive licensed spectrum. The 802.11 networks, moreover, can provide data rates up to 11 Mbps, far exceeding the maximum data rate to be offered by EDGE (Enhanced

Data Rates for GSM Evolution) and W-CDMA (Wideband Code Division Multiple Access) 3G networks [SAE98, CQW99, HT00]. Due to popular demand, the 802.11 b card 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 b 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 b air interface standard not only for WLANs, but also for outdoor, cellular data networks. First, much of the low-cost advantage of 802.11 b WLANs would translate to an 802.11 b cellular network. Second, 802.11 b 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.

If possible, such 802.11 b cellular networks should have cell radii of several 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 802.11 b network, compared with its WLAN counterpart. For example, the data rate might be lower, some 802.11 b features might be unsupported, and additional signal processing and control algorithms might be required.

In this research effort, we explore whether such an 802.11 b network is feasible. The focus of our paper is on the impact of increased path loss and multipath dispersion on the performance of the 802.11 b *radiodesign*. The impact of increased propagation delay (also associated with increased range) on the 802.11 b *medium access control (MAC) protocol* is examined in a companion paper [LMCW01]. We note that there are many other important issues and challenges, not addressed in either of these papers, with deploying an outdoor 802.11 b network. For instance, the use of unlicensed spectrum in 802.11 b 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 in Section II. In Section III, 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 IV studies the link performance in terms of bit error rate for various receivers operating in multipath dispersive channel typical in outdoor environments. Finally, our conclusion and future work on the subject are discussed in Section V.

## II. IEEE 802.11B RADIO DESIGN

IEEE 802.11 [19] 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 (QPSK), 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, which operates in the 2.4 GHz band (commonly known as the ISM band). 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).

We emphasize that it is 802.11b networks that have been widely used and incorporated into personal computers recently. In addition, radio propagation in the 2.4 GHz band is more favorable than in the 5 GHz band. 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:

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

As a result, the chip rate is 11 Mchips/s. Each station in the 802.11 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 simpler 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 preamble of each packet could be used to estimate channel responses with greater spans.

In typical urban environments (outdoor), root-mean-squared (rms) delay spread can be several microseconds [GEYC97], compared with just fractions of a microsecond in typical indoor WLAN environments. As a result, ISI can sometimes span several data symbols. In the following, we first examine the link power budget and then investigate how the 802.11 radio design performs in multipath dispersive radio channels, parameterized by a range of delay spread values.

## III. RADIO LINK POWER BUDGET FOR OUTDOOR 802.11 NETWORKS

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

Table I. Radio link power budgets.

		802.11b	WCDMA	EDGE
a	Thermal noise (dBm/Hz)	-174	-174	-174
b	Channel BW* (dBm)	73	66	53
c	Noise factor (dBm)	5	5	5
d	Noise power (dBm)	-96	-103	-116
e	Interference margin (dB)	3	3	3
f	Minimum SINR (dB)	0	-5	10
g	Min. RX sig. power (dBm)	-93	-105	-103
h	Terminal EIRP** (dBm)	24 24 30 30	30	30
i	Sector gain (dBi)	10 10 10 10	10	10
j	Shadowing margin (dB)	-8 -8 -8 -8	-8	-8
k	Building penetration (dB)	-15 0 -15 0	-15	-15
l	Allowable path gain (dB)	-104 -119 -110 -125	-122	-120
m	Med. path gn. @ 100m (dB)	-73 -73 -73 -73	-73	-73
n	Adnl. gain at cell edge (dB)	-31 -46 -37 -52	-49	-47
o	Propagation exponent	3.5 3.5 3.5 3.5	3.5	3.5
p	Cell radius (km)	0.7 2 1.1 3	2.5	2.2

\*Bandwidths 22 MHz, 3.84 MHz, 200 kHz, respectively.

\*\*0.25 W and 1 W.

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 -96 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 despreading. Combining this with an interference margin of 3 dB, the minimum received signal power is -93 dBm (the sum of parameters d, e, and f).

We consider the equivalent isotropic radiated power (EIRP) of 250 mW and 1 W (24 and 30 dBm, respectively). (Note that 1 W EIRP is the maximum allowable transmission power for the ISM band in North America. Also, for practical reasons, currently most 802.11 devices restrict themselves to transmit power levels of 15–20 dBm with ~0 dB antenna gain.) 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 10 dBi. 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  $l = -(h+i+j+k)$ . 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. With a typical path gain model, a path loss exponent of 3.5, and a median path gain of -73 dB at 100 m from the access point (AP) antenna, the cell radius is computed based on these allowable path gains.

The key differences in the EDGE/W-CDMA link power budgets, as compared with the 802.11 budget, are the channel bandwidths and minimum SINR requirements for reliable reception. 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  $E_b/N_0$  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 1% [LDCQ01]. For the assumed parameters, the cell radii for the W-CDMA and EDGE systems are 2.5 and 2.2 km, respectively.

In summary, the link budget reveals that the maximum cell radius in the outdoor 802.11 network is about half of those supported in the W-CDMA and EDGE networks. The estimated cell size lies in the range 0.7 to 3 km. We note that for such a range, the signal propagation delay runs between 2.3 to 10  $\mu$ s. The corresponding rms delays spread is expected to lie between a fraction of a microsecond up to about 1  $\mu$ s [GEYC97].

#### IV. LINK ERROR PERFORMANCE

Our main purpose here is to investigate the error performance of the radiolink when the 802.11 standard is used for outdoor cellular networks, where 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  $\mu$ s 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)* [CGKS92].

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  $\mu$ s delays 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 latter 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 1. Data symbols are spread by the 11-bit Barker code and the spread signal is transmitted over an 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 [p. 166, SKL88].

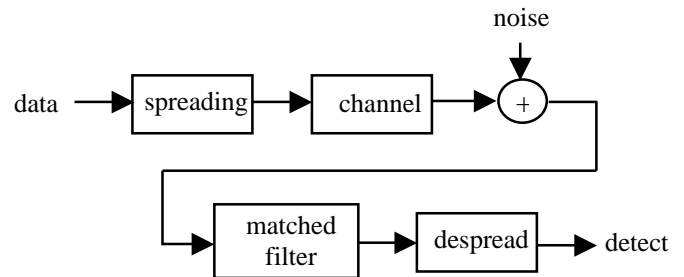


Figure 1. Simulation model for the matched filter receiver.

We assume a standard model for the multipath channel — quasi-static, frequency-selective, Rayleigh fading [CGKS92]. 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. (The discrete components are spaced to match the chip period of 90.9 ns.) The delay profile is, in turn, parameterized by the rms delays 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  $\mu$ s multipath span for the constrained RAKE and (b) the entire span for the full RAKE. For each channel realization, thousands of bits are retransmitted 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

delayspread, which together determine the variation in captured channel energy.) The MFB is computed analytically [CGKS92], based on the known channel response.

For rms delayspreads of 250 ns, 1  $\mu$ s and 3  $\mu$ s, Figures 2 to 4 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  $10^{-4}$ , which corresponds to a 5% 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  $\mu$ s 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.

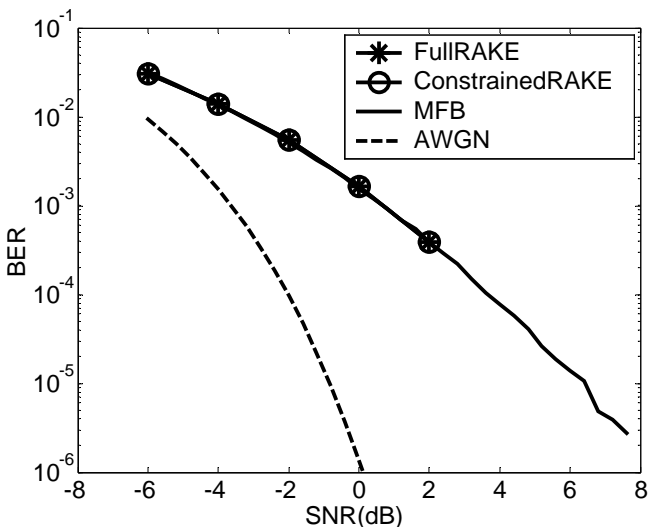


Figure 2. Error performance for 250 ns rms delay spread.

At this small delay spread, however, all receivers fall short of the link power budget requirements shown in Table 1. At a BER of  $10^{-4}$ , the receivers require an average SNR of about 4 dB, which is 4 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 3 shows performance for an rms delay spread of 1  $\mu$ s. 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

performance improvement compared with the result in Figure 2.

As one would expect, the BER performances for three receivers diverge for increasing delay spread. At an rms delay spread of 1  $\mu$ s, the MFB meets the link budget's 0 dB SNR requirement (for BER =  $10^{-4}$ ), but the full and constrained RAKE receivers fall short by about 3 dB and 4 dB, respectively.

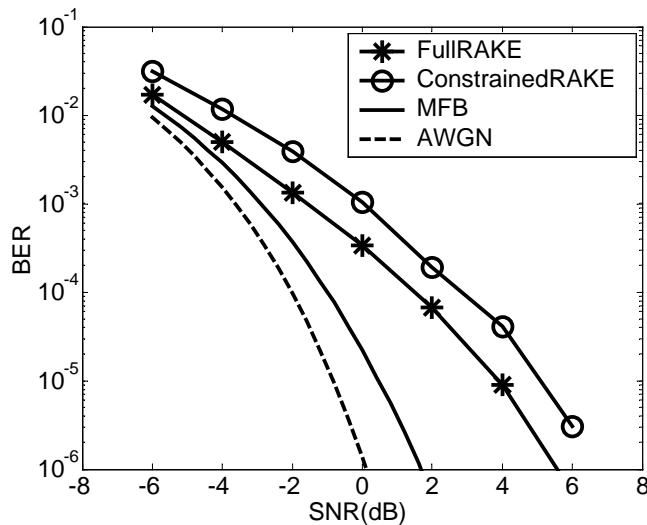


Figure 3. Error performance for 1  $\mu$ s rms delay spread.

The results in Figure 3 are of special relevance because a 1  $\mu$ s rms delay spread is typical in urban-area cells that have a radius in the range estimated by our link power budget (see Section III). 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  $\mu$ s, which is high even in the harshest of multipath environments (perhaps with the exception of some mountainous areas), Figure 4 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. (Note, however, that the SNR required by the full RAKE at BER =  $10^{-4}$  is not much different from that for a delay spread of 1  $\mu$ s.) And finally, the constrained RAKE is subjected to high ISI and captures only a small fraction of the total multipath energy in its 1  $\mu$ s window. Thus, its performance is very poor, even at high SNR values.

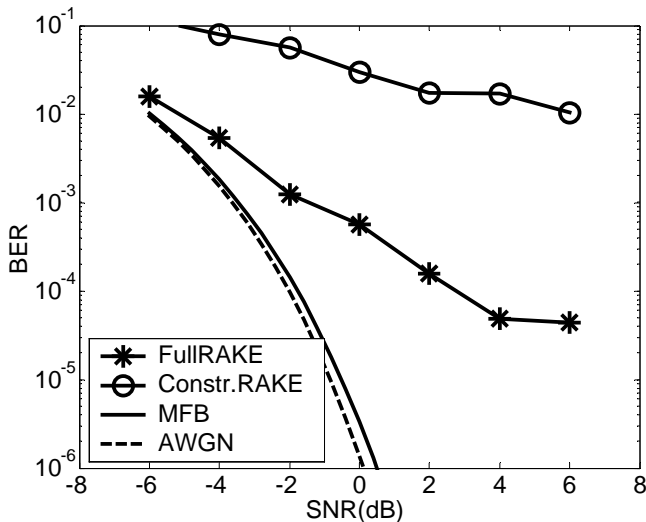


Figure 4. Error performance for 3  $\mu$ s rms delay spread.

Figure 5 summarizes the SNR degradation, with respect to the AWGN channel, to achieve the target BER of  $10^{-4}$ . We show the degradation as a function of the ratio of rms delay spread to symbol period (e.g., a value of 1 would correspond to 1  $\mu$ s 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  $\mu$ s. The constrained RAKE becomes unable to achieve the target BER, at any SNR, when the delay spread goes beyond 1.25  $\mu$ s.

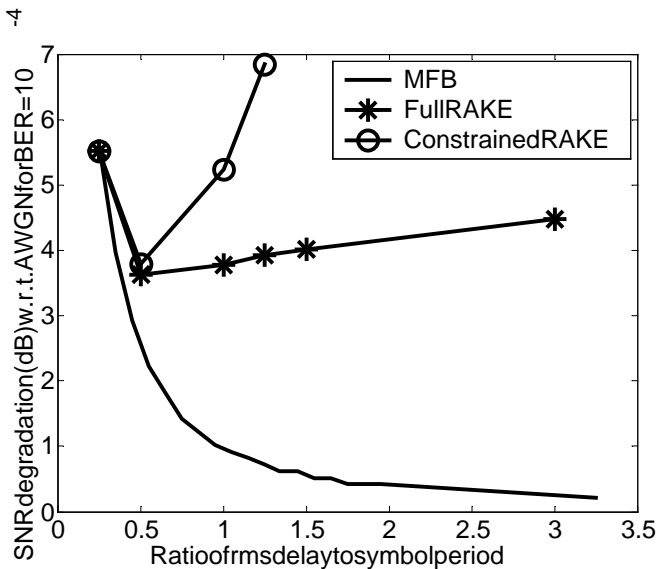


Figure 5. Performance degradation vs. rms delay spread.

## V. CONCLUSION AND FUTURE WORK

In conjunction with results from a companion paper [LMCW01], we have demonstrated the extent to which the IEEE 802.11b air interface 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.

While some enhancements may be needed — e.g., improved equalization for some multipath environments — we estimate that sectorized-cell radii in the range 0.7–3 km are feasible in outdoor 802.11b networks. This range is about half 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 devise methods for estimating channel information and to study the performance improvement of advanced equalization techniques in outdoor 802.11 networks. In addition, we plan to investigate how well smart antennas can extend the service range and suppress interference in these networks.

## ACKNOWLEDGMENTS

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