

Performance of the Bluetooth System in Fading Dispersive Channels and Interference

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Abstract—A noncoherent limiter-discriminator receiver is often considered for the Bluetooth system because of its simplicity and low cost. While its performance is more than adequate for some channels, the results are significantly degraded in either an interference-limited environment or a frequency selective channel. In this paper, we compare the performance of the traditional limiter-discriminator with integrate and dump filter to a more sophisticated Viterbi receiver. We find that the Bluetooth access code is sufficient to be used for channel estimation in the Viterbi receiver. A comparison is carried out in a Rayleigh fading channel and in the presence of interference either from another Bluetooth piconet or an IEEE 802.11b wireless local area network. Performance metrics include bit error rate, packet loss rate, and residual errors in a packet.

I. INTRODUCTION

Bluetooth works in the 2.4 GHz unlicensed ISM band, which is also shared by other communication systems including 802.11 wireless local area networks (WLANs). The primary range of operation is 10 meters, but it can be extended up to 100 meters. In typical indoor applications where the channel exhibits low delay spread and there is a strong signal path between the transmitter and the receiver, the non-coherent limiter-discriminator with integrate and dump filter (LDI) receiver achieves reasonable performance [1]. However, it would be useful to make the radio system more robust so as to maximize the quality of service in outdoor and large indoor applications.

Some experiments have been conducted [2], [3], [4] to evaluate the power delay profile of indoor channels at 2.4 GHz. The channel is roughly categorized into two major classes: (1.) channels with a line-of-sight (LOS) path and (2.) channels with an obscured path. For a LOS path, Kim *et al.* [2] find that it can be reasonably approximated by a Rician distribution with $K = 5$, where K is the ratio of the power of the dominant path to the power of the scattered paths. For a path with obstructions, the probability density function (pdf) of the amplitude of the fading signal is Rician with $K = 2$, which is close to the Rayleigh distribution. The root-mean-square (rms) average of the delay spread varies between 75 nsec to 90 nsec. Zhang and Hwang [4] report an rms delay spread as large as 217

nsec. Wilkinson [5] studied the channel for the DECT system and considered a worst case rms delay of 200 and 300 nsec for indoor and outdoor channels, respectively. Also in this report, a Rayleigh fading distribution was considered.

Another challenging issue for the Bluetooth system is the coexistence with other Bluetooth piconets and/or with IEEE 802.11 WLANs. The interference emitted by these radios may severely degrade the operation of a Bluetooth radio. The Viterbi receiver may also be a promising substitution for the LDI receiver in this case.

This paper's main contribution is to evaluate the Bluetooth performance in hostile environments. Two scenarios are considered: (1.) a multipath Rayleigh fading channel, and (2.) an interference-limited environment. We show the bit error rate performance in these scenarios as well as system layer performance for Bluetooth voice packets.

II. BLUETOOTH

Bluetooth operates at a channel bit rate of 1 Mbit/sec [6]. The modulation is Gaussian frequency shift keying (GFSK) with a nominal modulation index of $h_f = 0.33$ and a normalized bandwidth of $B_b T = 0.5$, where B_b is the 3 dB Bandwidth of the transmitter's Gaussian low pass filter, and T is the bit period. The Bluetooth radio employs a frequency hopping scheme in order to mitigate the effect of interference and fading. There are a total of 79 hopping channels, each separated by 1 MHz, and the hopping frequency is changed on a packet by packet basis.

A. The GFSK signal

The GFSK signal can be represented by [7]

$$s(t, \mathbf{a}) = A \cos(2\pi f_c t + \phi(t, \mathbf{a})), \quad (1)$$

where $A = \sqrt{\frac{2E_b}{T}}$, E_b is the energy per data bit, f_c is the carrier frequency, and \mathbf{a} is the random input stream, comprised of the data bits α_i ; $\phi(t, \mathbf{a})$ is the output phase deviation, given by [7]

$$\phi(t, \mathbf{a}) = 2\pi h_f \sum_{i=n-L+1}^n \alpha_i q(t - iT) + \pi h_f \sum_{i=-\infty}^{n-L} \alpha_i. \quad (2)$$

The second sum is the accumulated phase of all previous symbols, and it is called the phase state. $q(t) = \int_{-\infty}^t g(\tau) d\tau$, where $g(t)$ is the impulse response of a Gaussian filter, and L is the length of $g(t)$ in bit periods. For Bluetooth with $B_b T = 0.5$, we have $L = 2$.

B. LDI Receiver

This receiver consists of a pre-detection bandpass filter, a limiter-discriminator, and an integrate and dump filter as shown in Fig. 1. Details on the design of the receiver, including parameter choices, are given in [1].

The bandpass filter has a Gaussian shape with impulse response $h_r(t) = \sqrt{\frac{2\pi}{\ln 2}} B_r e^{-(\frac{2\pi^2}{\ln 2})(B_r t)^2}$. In an AWGN channel, the optimum value for $B_{IF} = 2B_r$ is chosen as 1.1 MHz [8], where B_r is the 3 dB bandwidth. The integrate and dump filter has a rectangular impulse response with a length of T . The appropriate sampling time is chosen at the maximum eye opening.

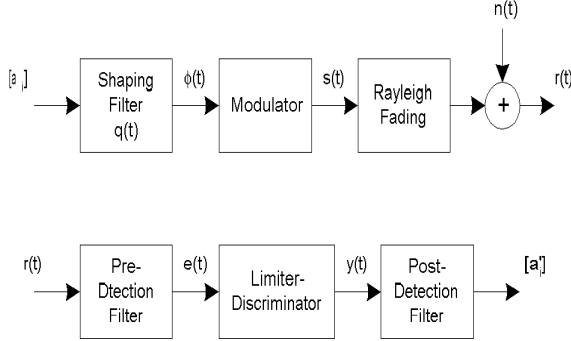


Fig. 1. Limiter-Discriminator

C. Viterbi Receiver With Equalizer

The Viterbi receiver takes advantage of the phase trellis created by the transmitter. For GFSK with modulation index $h_f = \frac{2k}{p}$, $p2^{L-1}$ states are required for the Viterbi receiver [7]. Given $h_f = 1/3$ and $L = 2$, the total number of phase states is $p = 6$, which includes $\{0, \frac{\pi}{3}, \frac{2\pi}{3}, \pi, \frac{4\pi}{3}, \frac{5\pi}{3}\}$. Consequently, the total number of states for the Bluetooth Viterbi receiver is $6 \times 2 = 12$. This receiver may be too complex for low cost implementations since it requires a lot of signal processing hardware. One way to simplify the receiver is to remove the effect of the additional phase states in the decoding trellis. This action can be done by not only passing the cumulative metrics from a node to all its successor nodes, but also by passing the information about the phase state. In this way, after selecting the metric with minimum value, the phase state of that metric is also recorded at the new trellis node. This architecture change requires adding a little complexity to branch metric calcu-

lations, but it reduces the total number of trellis states from 12 to 2. We do not add any additional states to account for channel multipath delay.

Because no equalization is intended in Bluetooth, no training sequence is explicitly defined in the standard. We found that the 64 bits access codes, which are sent in every packet, show good correlation properties, and so can be used for the estimation of the channel. This estimation is then used to compensate for the effect of fading and phase rotation in the received signal. Also, the correlation function can be used for the purpose of synchronization. In order to have a fair comparison with the LDI receiver, the Viterbi receiver front end contains the same Gaussian filter to reject out of band interference and noise. Results for this receiver appear in Section IV.

III. CHANNEL AND INTERFERENCE

Our channel model is a simple Rayleigh fading two ray model, with variable delay between the two equal average power paths. If the time delay between the paths is equal to τ_1 , the rms of the delay spread is, $\sigma = 0.5\tau_1$. This model is a good approximation for indoor channels, especially for low rms delay spreads $\sigma \leq 100$ nsec, but the results for higher delay spreads $\sigma \geq 200$ nsec are optimistic in comparison to more accurate models [5]. The fading is assumed to be static for the duration of the packet length and the channel coefficients are sampled at the packet rate. This is a weak assumption, since the coherence bandwidth of the indoor channels is usually greater than the frequency separation of the hops [2], [9], and the fading statistics may not vary for several consecutive packets.

For the second scenario, we consider the performance of Bluetooth in the presence of interference. The channel is AWGN in this case, and the interference may be another Bluetooth piconet or an 802.11b system. The 802.11b WLAN can use either direct sequence spread spectrum (DSSS) at 1 or 2 Mbits/sec, or it can use complementary code keying (CCK) [10] at 5.5 or 11 Mbits/sec. Here, we consider 1 Mbit/sec DSSS and 11 Mbits/s CCK. In the former, data bits are spread by a Barker code with 11 chips per bit, which leads to a rate of 11 Mchips/sec. The modulation is differential BPSK (DBPSK). The CCK modulation can be considered as a block code over the complex field, also with a symbol rate of 11×10^6 per second. In either case, a pulse shaping filter may be employed to reduce the out of band emissions, thereby giving an interference bandwidth of 22 MHz.

Either a Bluetooth or an 802.11b type interference signal can be represented as

$$S_I(t, \mathbf{b}) = B \cos(2\pi(f_c + f_d)t + \phi_2(t, \mathbf{b})), \quad (3)$$

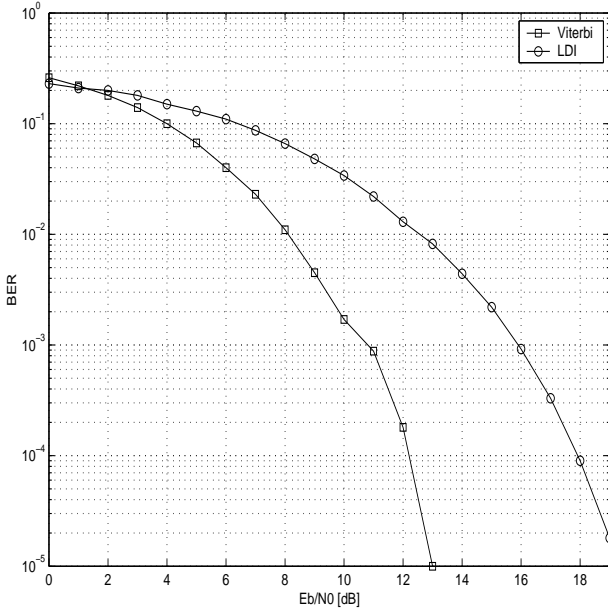


Fig. 2. Performance in the AWGN channel.

where \mathbf{b} is the random input data which is independent of \mathbf{a} , and ϕ_2 depends on the type of the interferer. f_d is the frequency difference between the desired signal and the interference. The Bluetooth radio channels are 1 MHz apart, so f_d can take values of 0, 1, 2 \dots MHz. The bandwidth of the 802.11b system is 22 MHz, so we carried out simulations for $f_d \leq 11$ MHz. There are $N_s = 44$ samples/bit, which equals 4 samples/chip for the 802.11b system. This sampling rate is appropriate for f_d up to 22 MHz. A uniform random delay $t_d \in [0, T)$ and a random phase $\phi_d \in [0, 2\pi)$ are applied to the interferer signal for each packet.

IV. PERFORMANCE RESULTS

A. Physical Layer Performance

As a baseline for the performance comparisons of the two receivers, we first consider the AWGN channel. Fig. 2 shows that the Viterbi receiver has a gain of 4 dB over the LDI receiver at a BER of 10^{-2} . The gain increases to about 5 dB at 10^{-3} and nearly 6 dB at 10^{-5} . Because of the short ranges involved, even for a transmit power of 1 mW, the received E_b/N_o is typically over 30 dB. Consequently, if one considers only this channel, there is no need for the more complex Viterbi receiver.

Simulation results for the LDI receiver in the two ray channel are presented in Fig. 3(a). For very low delay spreads where the channel exhibits flat fading, an average E_b/N_0 level of 30 dB is required to achieve a BER close to 10^{-3} . This performance is not maintained as σ gets higher, and for $\sigma \geq 100$ nsec, even for high values of E_b/N_0 , the

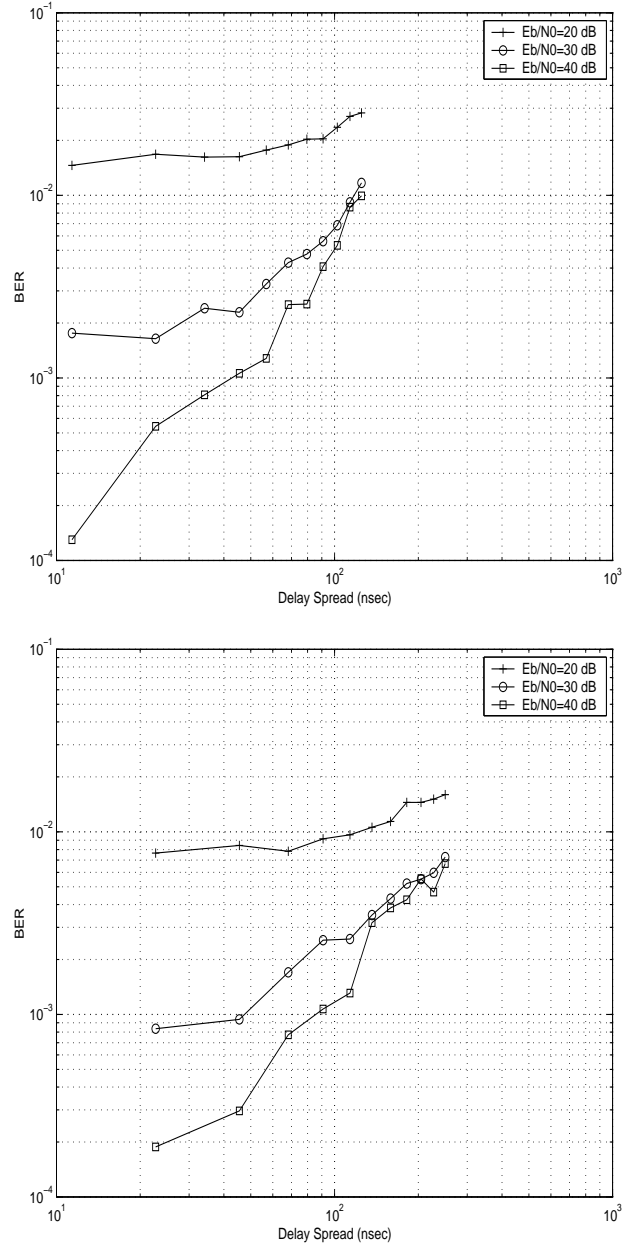


Fig. 3. $\frac{(a)}{(b)}$ Performance as a function of channel delay spread.

(a) LDI Receiver. (b) Viterbi Receiver. Rayleigh two path channel.

performance is poor. The Viterbi receiver performance in Fig. 3(b) indicates that this receiver can tolerate more delay spread, and it achieves $BER = 10^{-2}$ for $\sigma \simeq 300$ nsec. Also, this receiver is insensitive to the sampling time of the signal.

BER measurements for an interference-limited environment are presented in Figs. 4 and 5; in all cases, the carrier-to-noise ratio, $CNR = 30$ dB. In these figures, df is the absolute frequency offset between the carrier of the Bluetooth signal and the carrier of the interference. The carrier-to-interference ratio, (CIR), is measured before the band-

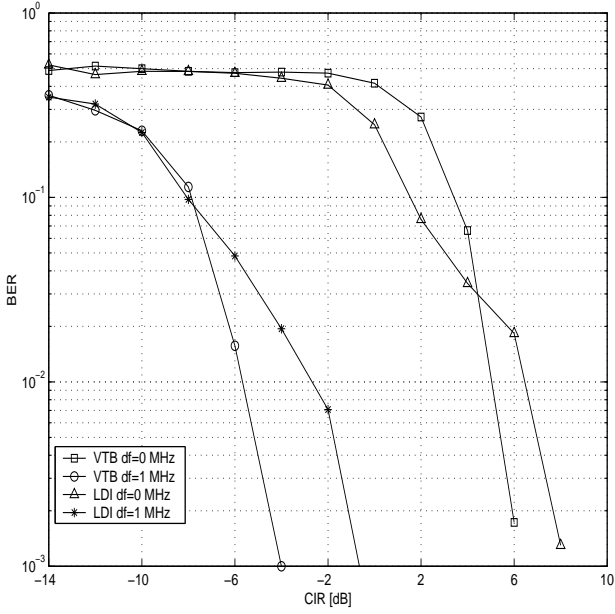


Fig. 4. Performance with Bluetooth interference.

pass filter. Fig. 4 contains the results for both Viterbi and LDI receivers experiencing Bluetooth interference. There is a 2 dB improvement for co-channel interference, and for the adjacent channel the improvement is about 3 dB for the Viterbi receiver. Other narrowband interference signals with $df \geq 2$ MHz are strongly attenuated by the bandpass filter, and they do not produce errors for this range of CIR.

For the 802.11b interference, it is appreciated from Figs. 5(a) and (b) that for frequency offsets up to 10 MHz, the system is still interference-limited. This result stems from the fact that the two-sided bandwidth of the 802.11b WLAN is 22 MHz, which is much wider than that of Bluetooth. In these figures, the 1 Mbit/sec DSSS system is used as the interferer; however, the 11 Mbits/sec CCK interferer provides almost the same results.

The LDI receiver needs at least $CIR = 5$ dB in order to get $BER \leq 10^{-2}$ for all frequencies. The degradation for $df \leq 4$ MHz is the same, since the 802.11b spectrum is flat at these offsets. In Fig. 5(b), we observe a dramatic enhancement in performance for the Viterbi receiver over the LDI receiver. The minimum required CIR is about -4 dB in this case. Since the 802.11b interferer is more like uncorrelated noise at the input of this receiver, this level for CIR can also be concluded by looking at the performance of the Viterbi receiver in the AWGN channel (Fig. 2). This receiver requires $E_b/N_0 = 10$ dB for $BER = 10^{-3}$. The bandpass filter has about 12 dB out-of-band rejection. So, the maximum tolerable CIR at the input of the receiver is about -2 dB.

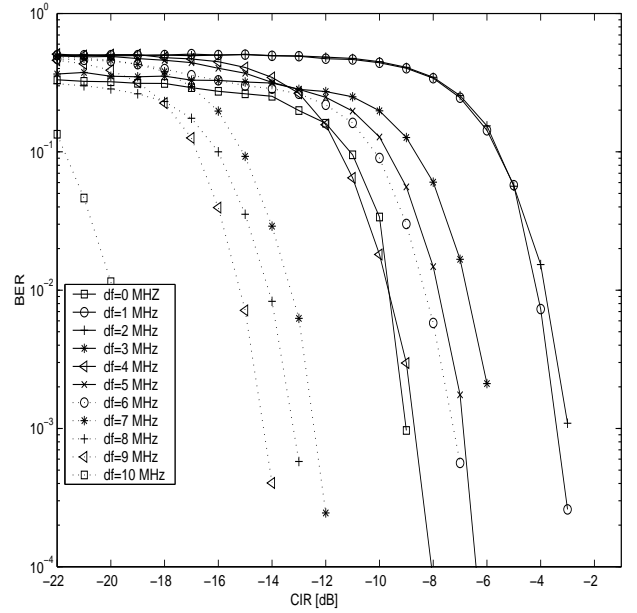
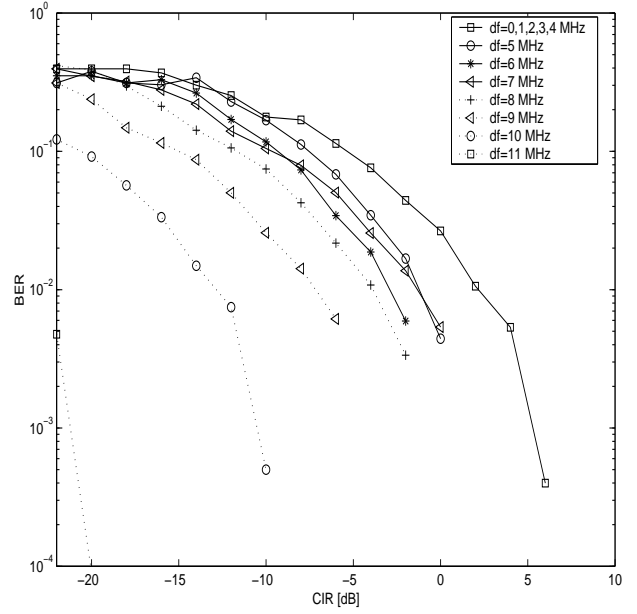


Fig. 5. (a) LDI receiver. (b) Viterbi receiver.

B. System Layer Performance

While the results of the previous section strongly suggest that the Viterbi receiver provides substantially better physical layer performance, the main question is how does this advantage translate into better system level performance. Four factors affect this mapping: (1.) the frequency hopping pattern of the Bluetooth (BT) system, (2.) the error detection and correction in the BT medium access control (MAC) layer, (3.) the BT traffic pattern, and (4.) the traffic pattern of the interferer. These issues are discussed in much greater detail in [11], where performance results are provided for a number of scenarios, all using

the LDI receiver.

The frequency hopping implies that the probability a BT packet falls within the interference bandwidth is approximately 22/79. Even then, the BER will depend on the frequency offset between the two received signals and whether the interferer is actually transmitting. To quantify the system performance, we note that the CIR is the ratio of the received signal power to the received interference power before the receiver's bandpass filter; the values used in the plots below correspond to when the interferer is transmitting.

We consider a two-way communication between a Bluetooth master and slave, where each is sending 64 Kbits/sec of HV1 voice packets. These packets contain the BT access code, the packet header, and the payload. The access code is protected by a $d = 14$ Hamming code, while both the header and payload are protected by 1/3 rate repetition codes. The overall packet length is 366 bits. An uncorrected error in either the access code or the header leads to the packet being dropped.

Fig. 6(a) shows the probability of packet loss versus CIR for both 1 Mbit/sec and 11 Mbits/sec 802.11b interference using the LDI receiver. Note that both curves follow the same pattern, and lead to very little packet loss as the CIR approaches 0 dB. The main reason for the differences between the two curves is that the traffic distributions are different for the 1 and 11 Mbits/s WLANs. In both cases, we use exponentially distributed packet inter-arrival times with an offered load of 30% of the channel capacity [11]. Because the 11 Mbits/sec packets are shorter, there is less overlap in time between the BT packets and the WLAN packets, leading to a slightly lower loss rate. Fig. 6(b) shows the residual errors after the FEC decoding. A CIR of about -5 dB is required for good performance. The reason that this number is lower than those in Fig. 5(a) is due to the system level benefits discussed above.

V. CONCLUSIONS AND PRESENT WORK

We have investigated the performance of the Bluetooth radio by employing two different types of receivers: (1.) a low cost LDI and (2.) a more sophisticated Viterbi receiver. From the physical layer simulation results, we conclude that the Viterbi receiver is superior in both the multipath Rayleigh fading channel and in interference. This superiority is particularly considerable in the latter case, especially when the interference comes from an 802.11b WLAN. We have also shown system level performance for Bluetooth voice packets using the LDI receiver in an interference-limited environment. In the final paper, similar results for the Viterbi receiver will be presented, further quantifying its performance advantage.

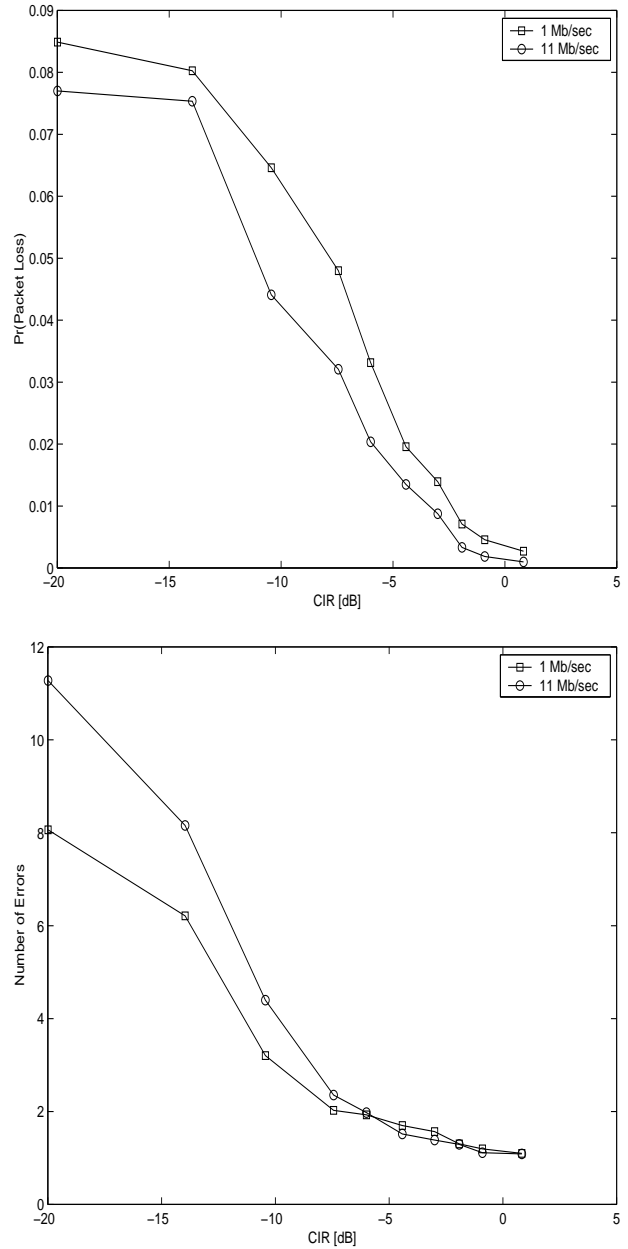


Fig. 6. $\frac{(a)}{(b)}$ Bluetooth voice packets with 802.11b interference. (a) Probability of packet loss. (b) Residual errors. LDI receiver.

One issue of present concern is the large allowed deviation in a Bluetooth transmitter's modulation index. While the nominal value is 0.33, the range is 0.28 to 0.35. For a Viterbi receiver designed to use this nominal value, we find that it is robust to variations of about ± 0.01 . Although there are methods that allow one to estimate the modulation index [12], the receiver architecture, including the number of states, would have to be changed. Therefore, we suggest that the deviation allowed in the standard be reduced.

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