

# 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 and packet loss rate.

## I. INTRODUCTION

Bluetooth (BT) 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 noncoherent 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 an 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 substitute 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  $\alpha_i$ ;  $\phi(t, \mathbf{a})$  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].

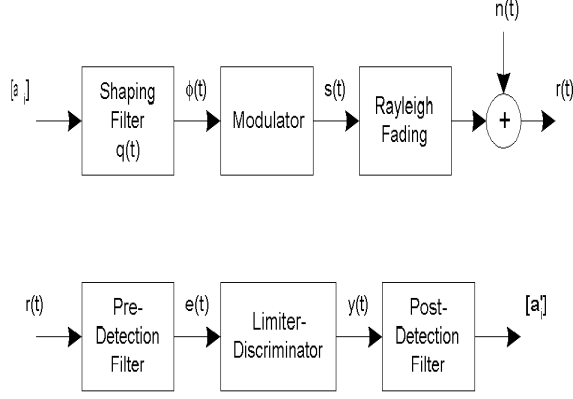


Fig. 1. Simulation model for the LDI receiver.

The bandpass filter has a Gaussian shape with impulse response

$$h_r(t) = \sqrt{\frac{2\pi}{\ln 2}} B_r e^{-(\frac{2\pi^2}{\ln 2})(B_r t)^2}. \quad (3)$$

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.

### 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 calculations, 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. However, if more signal processing is permitted in the receiver design, the memory of the channel could

also be considered as additional states.

Because no equalization is intended in Bluetooth, no training sequence is explicitly defined in the standard. We found that the 64 bit 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  $\tau_1$ , 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. At this bit rate, 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), which facilitates noncoherent detection. 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

$$S_I(t, \mathbf{b}) = B \cos(2\pi(f_c + f_d)t + \phi_2(t, \mathbf{b})), \quad (4)$$

where  $\mathbf{b}$  is the random input data that is independent of  $\mathbf{a}$ , and  $\phi_2$  depends on the type of the interferer.  $f_d$  is the frequency difference between the desired signal and the interference. We assume that the interference signal is always on and exists for the entire length of the Bluetooth packet. Also, for a pure physical layer simulation, there is no error correction and retransmission in the channel. 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

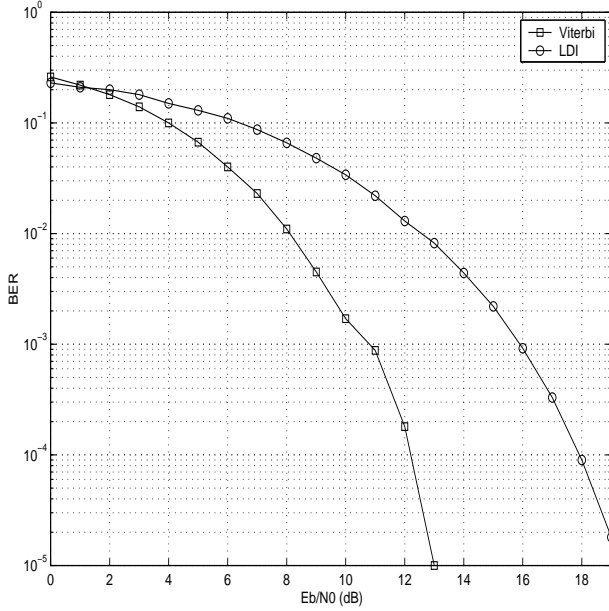


Fig. 2. Performance in the AWGN channel.

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 very high. 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  $E_b/N_o$  level of 30 dB is required to achieve a BER close to  $10^{-3}$ . This performance is not maintained as  $\sigma$  gets higher, and for  $\sigma \geq 100$  nsec, even for high values of  $E_b/N_o$ , the 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,  $f_d$  is the absolute frequency offset between the Bluetooth signal and the interference. The carrier-to-interference ratio (CIR) is defined as the ratio of the received signal power to the received interference power, and it is mea-

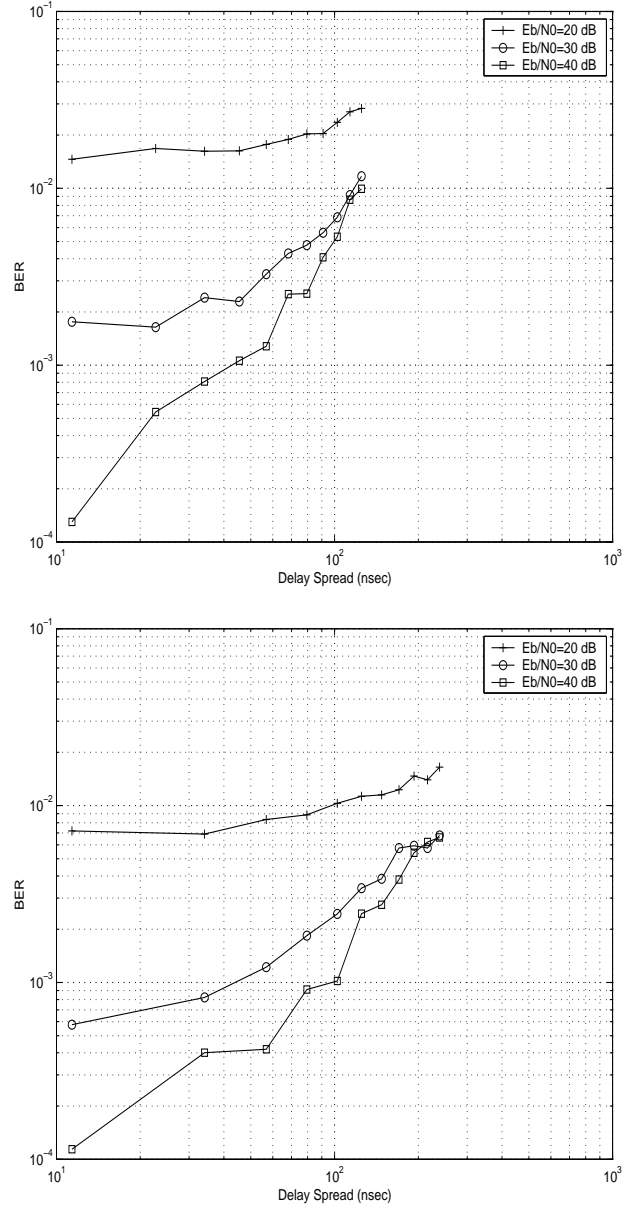


Fig. 3. (a) LDI receiver. (b) Viterbi receiver. Rayleigh two path channel.

sured at the input to the bandpass filter. Fig. 4 contains the results for both Viterbi and LDI receivers experiencing Bluetooth interference. For the Viterbi receiver, there is a 2 dB improvement for co-channel interference, and about 3 dB improvement for the adjacent channel. The figure also shows that the Viterbi receiver produces more errors than the LDI receiver in the presence of a strong interferer (low CIR). The main reason is that the interference reduces the effectiveness of the channel estimator used in the Viterbi receiver. However as the CIR increases, the channel estimator performs better and the overall BER improves. Other narrowband interference signals with  $f_d \geq 2$  MHz are strongly attenuated by the bandpass filter, and

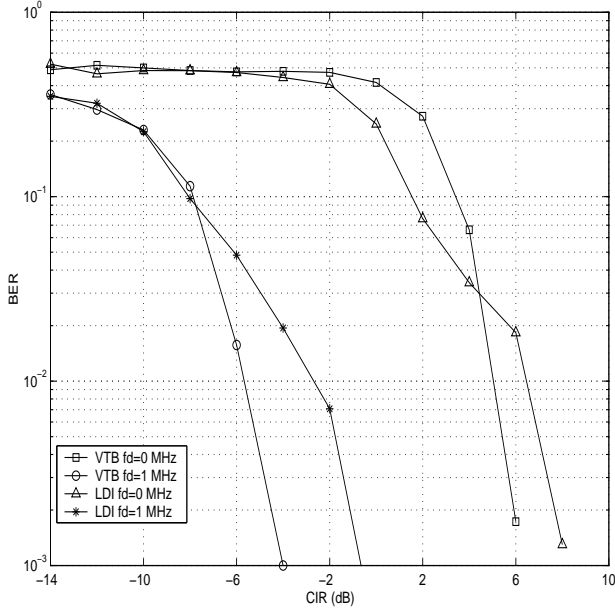


Fig. 4. Performance with Bluetooth interference.

they do not produce errors for this range of CIR.

For the 802.11b interference, Figs. 5(a) and (b) show 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.

The LDI receiver needs at least  $CIR = 4$  dB in order to get  $BER \leq 10^{-2}$  for all frequencies. The degradation for  $f_d \leq 4$  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  $E_b/N_0 = 8$  dB for  $BER = 10^{-2}$ . The bandpass filter has about 12 dB out-of-band rejection. So, the maximum tolerable CIR at the input of the receiver is about -4 dB.

### 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 BT system, (2) the error detection and correction in the BT medium access control 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

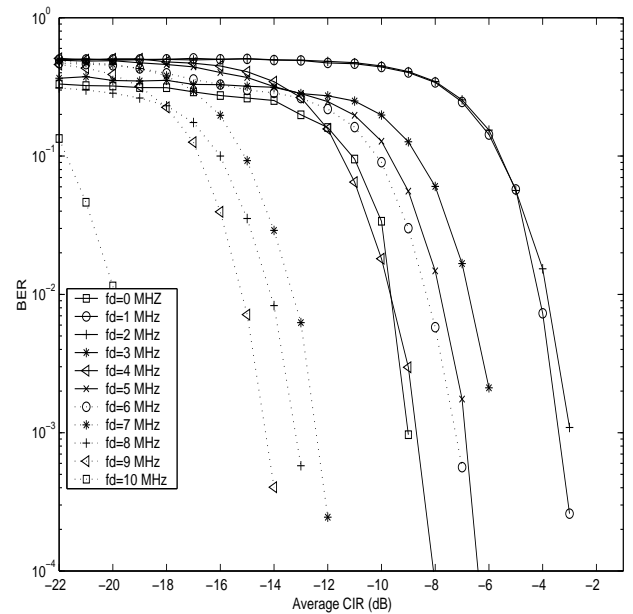
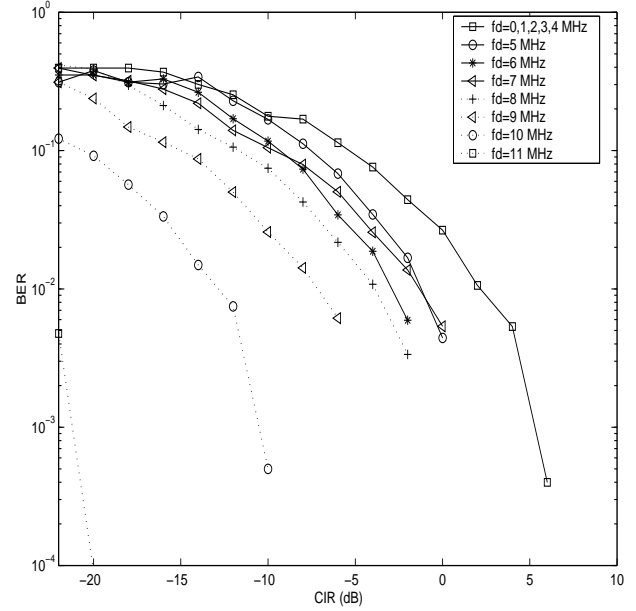


Fig. 5.  $\frac{(a)}{(b)}$  Performance with 802.11b interference. (a) LDI receiver. (b) Viterbi receiver.

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.

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 words have large Hamming distances between each pair, 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

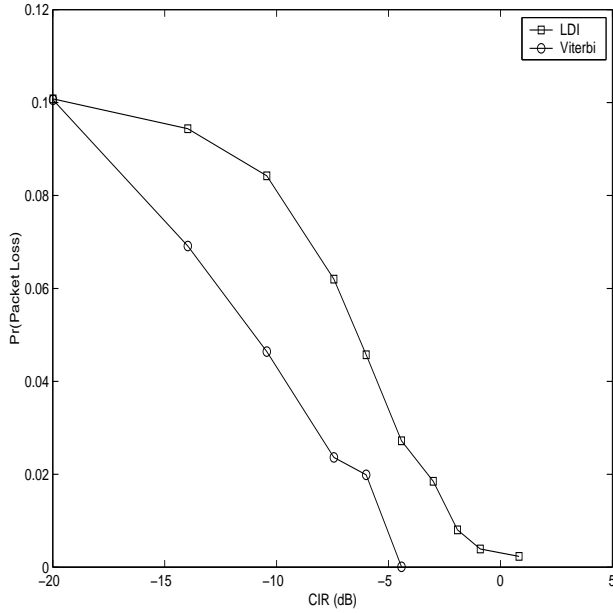


Fig. 6. Bluetooth voice packet loss with 802.11b interference.

either the access code or the header leads to the packet being dropped.

Fig. 6 shows the probability of packet loss versus CIR for both the LDI and the Viterbi receivers. For the LDI receiver, a  $CIR = 0$  dB is necessary to get low packet loss. However, this value decreases to  $CIR = -5$  dB for the Viterbi receiver. In both cases, we use exponentially distributed packet inter-arrival times for the WLAN, with an offered load of 50%. The packet length for the WLAN interference is fixed and equal to 8,000 bits.

## V. CONCLUSIONS

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 in an interference-limited environment. Even though the frequency hopping and error correction help both receivers, thereby reducing the differences in performance due to the physical layer, the Viterbi receiver still provides a substantial improvement.

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  $\pm 0.01$ . 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.

## ACKNOWLEDGMENTS

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