

# Techniques for Bluetooth Performance Improvement

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**Abstract**— This paper examines the application of some techniques in Bluetooth communications expected to improve system's performance under certain environmental conditions. The transmitter diversity Alamouti scheme [1] and receiver diversity have been evaluated and compared to the standard single antenna transmitter and receiver system by means of the achievable BER. Some analytical considerations about multiple correlated channels according to the Gilbert-Elliot (GE) model are provided besides the simulation results for the case of flat-fading.

## I. INTRODUCTION

Bluetooth short-range systems enable transmissions between consumer devices as well as industrial applications. In such indoor environment the received signal is made up of numerous attenuated, reflected, diffracted and transmitted versions of the original signal. The multipath propagation and interferences from another equipment in the industrial scientific and medical (ISM) band result in a received signal with significantly variable amplitude depending on the location. In order to mitigate these factors, a Bluetooth system is designed to use frequency hopping and transmit power control. However, the performance of frequency hopping systems depends strongly on the environmental conditions and the distance between a transmitter and receiver.

For short-range indoor Bluetooth communication the coherence bandwidth of 7.4 MHz is much wider than channel bandwidth of 1 MHz occupied during a hop and the appropriate model is known as flat-fading [3]. Thus, the frequency hopping being alone applied will combat the interference. On the other side the transmit power control is theoretically the most effective approach mitigating multipath fading [1]. A transmit power control is mandatory for the first power class Bluetooth radios with transmit power of 20 dBm and it is carried out by means of the receive signal strength indicator (RSSI). It is reported back to transmitter and the link manager protocol (LMP) decides if the transmit power should be increased or decreased [4]. Although, for third power class radios with transmit power of 0 dBm it is an optional approach. If being applied alone, it has a positive effect on the interference problem. However the receiver's feed back about the channel state adds complexity to both receiver and transmitter resulting in reduced data throughput. Therefore some diversity techniques are investigated in order to cope with multipath fading and to improve both the reliability and data transmission rate of a Bluetooth system.

The spatial diversity offers designers a way to improve signal reliability by minimizing signal loss and mitigating the effects of multipath fading obtained by placing mul-

tipole antennas either at the transmitter or at the receiver only, alternatively at both receiver and transmitter. Although the use of multiple antennas is not a new idea and most cellular base stations and mobile phones employ antenna diversity techniques, it may be difficult to implement more than one antenna at portable Bluetooth units due to the size limitations and the low-power used. On the other hand, many signal processing techniques used for reliable communication and effective spectral utilization demand significant processing power, retarding the use of low power devices. Continuous advances in very large scale integrated (VLSI) and application specific integrated circuit (ASIC) technology for low power application and demanded small antenna size provide a partial solution of this problem [2].

If the antennas are situated sufficiently far apart, the channel gains between the antenna pairs are relative different. Also such separation depends on the local scattering environment as well as on the carrier frequency. For Bluetooth links organized near the ground with many scatterers around, the channel decelerates over shorter spatial distances, and typical antenna separation of half to one carrier wavelength is sufficient [3]. Moreover in diversity model the performance of the Bluetooth antenna will be degraded by the effects of inter antenna coupling and envelope cross-correlation.

The implementation of multiple antennas at the receiver (referred as receiver diversity) results in multiple copies of transmitted stream which can be efficiently combined using the appropriate matched filter, i.e. maximal ratio combining (MRC) is applied. The greater the number of antennas is, the smaller is the outage probability. Then the effective channel approaches an additive Gaussian noise channel, which simplifies the communications. In contrast, transmitter diversity is less straightforward exploited, particularly when bandwidth expansion is not feasible and when no feedback about the channel's parameters is provided to the transmitter.

The purpose of this paper is to evaluate the performance of Bluetooth system with transmitter diversity applied according to the Alamouti scheme [1] and to compare it to the receiver diversity by means of BER achieved. Then multiple correlated channels should be considered and the GE model is chosen because of its simplicity. However, for the simulation model multiple independent quasi-static fading channels are assumed due to the greatest efficiency of the spatial diversity over such channels.

The paper is organized as follows: section II a short Bluetooth overview is represented and in section III a mathematical system model for transmitter diversity and receiver diversity is provided, where the Alamouti scheme is

reviewed for the Bluetooth case. Section IV presents some theoretical considerations about the extended Gilbert-Elliot (GE) model for the case of multiple correlated channels. In section V some simulation results are provided in order to demonstrate the performance of antenna diversity techniques over Bluetooth. Finally, in section VI conclusions and comments are given.

## II. BLUETOOTH OVERVIEW

Bluetooth replaces all types of cables with a point-to-point or point-to-multipoint wireless connection on peer-to-peer principle between fixed and portable wireless devices. Due to their low power transmitters of 1 mW or optional with amplifier to 100 mW, such connections are possible only in the short range of 10 meters or in the best case of 100 meters [4].

Because of the chosen unlicensed 2.4 GHz ISM band, the number of devices sharing this range is already impressive. In this context should be mentioned microwave ovens, WLANs according to IEEE 802.11b Standard, industrial, security and medical applications. In order to mitigate the interferences Bluetooth devices transmit data packets or voice using seventy-nine 1 MHz hopping frequencies with a maximal rate of 1600 hops per second. Additionally, the advanced frequency hopping scheme (AFH) enhances the Bluetooth performance in WLAN environment avoiding already occupied frequencies. Although majority of publications examined the coexistence issue between these devices, several techniques can be outlined here, namely power control, dynamic MAC scheduling [5], [12] and traffic control [9].

The Bluetooth Standard provides two types of links: synchronous connection-oriented (SCO) for voice exchange and asynchronous connectionless (ACL) links for packets of 1, 3 or 5 slots long. All types of packets except AUX1 are protected by cyclic redundancy check (CRC) and automatic repeat request (ARQ) scheme for error control. Moreover, in order to mitigate the fading effects and other packet loss sources, three times repetition for forward error correction (FEC) is applied in the header and the payload of the data medium rate (DM) packets is protected by shortened Hamming code for FEC with rate of 2/3. However, no such coding is applied by data high rate (DH) packets and the error probabilities of transmitted data are higher. Then it will be worth comparing system's performance when DM and DH packets are exchanged.

## III. SYSTEM MODEL

The Bluetooth channel is assumed to be flat-fading (frequency-nonselective), constant over one packet and independent from packet to packet transition. Then, a quasi-static fading is an appropriate channel model because the duration of a single packet is relative short compared to the coherence time of the channel and frequency hops from packet to packet [11]. During the quasi-static fading signal's envelope associated with the entire packet is multiplied by the same channel gain which is typically Rayleigh

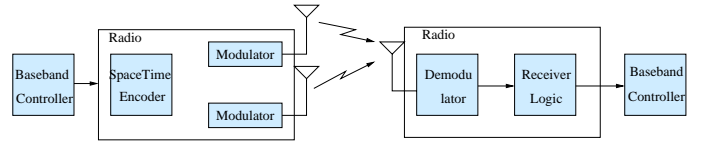


Fig. 1. Transmitter diversity model

distributed, since the channel gains vary independently from packet to packet. The independent channel gain from each pair of transmitter and receiver antennas is modeled as independent Gaussian random variables with variance 0.5. Then the quasi-static assumption is an effective approximation to many typical operating environments and admits tight analytical predictions of the performance of isolated piconet. However, due to the asynchronous nature of Bluetooth piconets, the quasi-static assumption might not be appropriate when there is a second piconet located in close proximity to the considered piconet. Each frequency could only be used for a time slot of  $625\mu s$  for master-to-slave transmission or slave-to-master transmissions. As modulation type BGFSK (Binary Gaussian Frequency Shift Keying) was chosen because of its robustness but BPSK (Binary Phase Shift Keying) modulated signal can be used because of similarity to GFSK modulation and easy simulation [6],[7].

### A. Transmitter Diversity

A basic system model that employs space time coding consists of a transmitter equipped with  $n$  antennas and the receiver is equipped  $m$  antennas is described. At each time  $t$ , signals  $x_i^t$ ,  $i = 1, 2, 3, \dots, n$  are transmitted simultaneously from  $n$  transmit antennas. Arriving at different receive antennas the signals will undergo independent fading. Therefore the independent path gain from transmit antenna  $i$  to receive antenna  $j$  is denoted by  $h_{i,j}$ . Two separated cases can be considered, if the channel gain is known at the transmitter or not. In the first case the system performance is very similar to receiver diversity. In contrast, without knowledge of this gain a combination of space and time diversity is applied, known as Alamouti scheme [8]. In fig.1 is represented such transmitter diversity scheme [1], where an alphabet of two symbols  $x_1$  and  $x_2$  is transmitted simultaneously from the first and second antenna at certain symbol period. During the next one the symbols are exchanged and complex conjugate operation over them is performed. Thus the transmitted symbols from the first and second antenna are  $-x_2^*$  and  $x_1^*$  respectively. If a receiver with one antenna is used,  $h_1(t)$  and  $h_2(t)$  represent the equivalent complex channel gain between the transmit antennas and the receive antenna during the first symbol period. Alternatively, during the second period they are denoted as  $h_1(t+T)$  and  $h_2(t+T)$ , where  $T$  is the symbol duration. In case the fading is constant over one packet transmission or one hop, then the  $h_1(t)$  is equal to  $h_1(t+T)$  and  $h_2(t)$  is equal to  $h_2(t+T)$ . It is assumed that  $Es$  is the total energy transmitted (by all antennas) per input symbol. Therefore, the

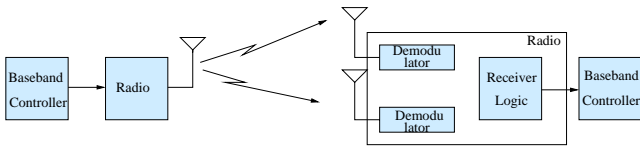


Fig. 2. Receiver diversity model

energy per input symbol transmitted by each antenna is  $E_s/n$ . Alternatively, the received signal  $y_t^j$  at antenna  $j$  is a noisy superposition of faded versions of the transmitted signal and it is given at certain time  $t$  by the expression

$$y_t^j = \sqrt{\frac{E_s}{n}} \sum_{i=1}^n h_{i,j} x_t^i + \eta_t^j, j = 1, 2, \dots, m \quad (1)$$

where the noise samples  $\eta_t^j$  are independent and identically distributed zero mean Gaussian with variance  $\sigma^2 = \frac{1}{2SNR}$ . Completing in this way a space-time block encoding, the data is split into two streams which are simultaneously transmitted from two antennas. Thus the received signal versions can be given by

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} h_1 & h_2 \end{pmatrix} \begin{pmatrix} x_1 & -x_2^* \\ x_2 & x_1^* \end{pmatrix} + \begin{pmatrix} \eta_1 & \eta_2 \end{pmatrix} \quad (2)$$

After rewriting the equation for the received signals  $y_1$  and  $y_2$  at time  $t$  and  $(t + T)$

$$\begin{pmatrix} y_1 \\ y_2^* \end{pmatrix} = \begin{pmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{pmatrix} \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} \eta_1 \\ \eta_2^* \end{pmatrix} \quad (3)$$

### B. Receiver Diversity

One transmit antenna and two receive antennas are considered in the receiver diversity model shown in fig.2. At a time  $t$  the transmit signal  $x_t$  is received by two antennas simultaneously as signal versions  $y_1$  and  $y_2$ . The independent channel gain  $h_1$  is represented between the transmit antenna and receive antenna 1, alternatively  $h_2$  is between the transmit antenna and receive antenna 2.

The equation for the model is expressed below

$$\begin{pmatrix} y_1 \\ y_2 \end{pmatrix} = \begin{pmatrix} h_1 \\ h_2 \end{pmatrix} x_1 + \begin{pmatrix} \eta_1 \\ \eta_2 \end{pmatrix} \quad (4)$$

In receiver diversity, independent fading paths are realized without an increase in transmit signal power and bandwidth. Also, coherent combining of the diversity signals leads to an increase in SNR at the receiver over the SNR that would be obtained with just a single receive antenna. Conversely, to obtain independent paths through transmitter diversity, the transmit power must be divided among multiple antennas. Thus, with coherent combining of the transmit signals the received SNR is the same as if there were just a single transmit antenna.

### C. Receiver Logic Design

A channel estimator is used in each receiver in order to estimate both  $h_1$  and  $h_2$  for transmitter and receiver diversity case. It is assumed that both channel estimations

are perfect and there is no difference between the channel and estimation used. In [1] came up that this transmit diversity scheme provides the same diversity order to well known receiver diversity scheme with most optimal combining techniques as maximal-ratio receiver combining (MRRC). Thus, both cases MRRC and maximum likelihood detection are applied.

The combining scheme for receiver diversity is expressed via the equation

$$\begin{aligned} \tilde{x}_1 &= h_1^* y_1 + h_2^* y_2 = \\ &(\alpha_1^2 + \alpha_2^2) x_1 + h_1^* \eta_1 + h_2^* \eta_2 \end{aligned} \quad (5)$$

where  $\alpha_1$  and  $\alpha_2$  are the channel attenuations. Alternatively, for the transmitter diversity is given the expression

$$\begin{pmatrix} \tilde{x}_1 \\ \tilde{x}_2 \end{pmatrix} = \begin{pmatrix} h_1^* & h_1 \\ h_2^* & -h_2 \end{pmatrix} \begin{pmatrix} y_1 \\ y_2^* \end{pmatrix} \quad (6)$$

From the equations for the combined signals is seen that they are equivalent to the receiver diversity scheme:

$$\begin{aligned} \tilde{x}_1 &= (\alpha_1^2 + \alpha_2^2) x_1 + h_1^* \eta_1 + h_2^* \eta_2 \\ \tilde{x}_2 &= (\alpha_1^2 + \alpha_2^2) x_2 - h_1^* \eta_1 + h_2^* \eta_1 \end{aligned} \quad (7)$$

Both diversity schemes apply a simple maximum likelihood (ML) detector, which uses Euclidean distance to give the proximity symbol to each constellation point. The point with the least Euclidean distance from the estimated symbol is detected as original symbol transmitted.

The combining signal  $\tilde{x}_1$  for receive diversity and signals  $\tilde{x}_1$  and  $\tilde{x}_2$  for transmit diversity are passed to the maximum likelihood detector for decision. The ML decision rule at the receiver for two received signals is to choose signal  $x_i$  if and only if:

$$\begin{aligned} d^2(y_1, h_1 x_i) + d^2(y_2, h_2 x_i) &\leq d^2(y_1, h_1 x_k) + \\ &d^2(y_2, h_2 x_k), \forall i \neq k \end{aligned} \quad (8)$$

For BPSK signals the above equation can be rewritten as:

$$d^2(\tilde{x}_1, x_i) \leq d^2(\tilde{x}_1, x_k), \forall i \neq k \quad (9)$$

When describing fading wireless channels the so called Diskrete Time Markov Chain (DTMC) channel model (often referred as Gilbert-Elliot (GE) model) is used. Thus, a description of multiple correlated channels based on this model is represented in next section.

## IV. EXTENDED GILBERT-ELLIOT (GE) MODEL

A GE channel could be considered as variation of the Binary Symmetric Channel (BSC) model at different time moments, where only two channel states are defined: good and bad according to the actual value of the error probability  $P_e$ , i.e. for  $P_e > 10^{-3}$ , the Bluetooth channel quality is considered as *good*, otherwise it is qualified as *bad*. The probability for staying in a *bad* state due to burst errors is represented via  $p_{BB}$  and the opposite probability is  $p_{GG}$ . The transition probability from a *good* state to a *bad* state

is  $p_{GB} = 1 - p_{GG}$  and the alternative probability is  $p_{BG} = 1 - p_{BB}$ . Therefore, the channel transition matrix  $\mathbf{P}$  could be given by the expression

$$\mathbf{P} = \begin{pmatrix} p_{GG} & 1 - p_{GG} \\ 1 - p_{BB} & p_{BB} \end{pmatrix} \quad (10)$$

When the channel is in a *good* state the bit errors occur with error probability  $e_G$  according to a BSC model, but usually it is assumed to be zero. In the opposite case the bit error probability  $e_B$  is defined according to another BSC model and it is significant ( $e_B \gg e_G$ ).

The modified GE Model for a Bluetooth system, where a communication between a master and slave take place, is represented by the equation [10]:

$$\mathbf{P} = Q + d(I - Q)Q = \begin{pmatrix} (1 - p_B) & p_B \\ (1 - p_B) & p_B \end{pmatrix} \quad (11)$$

where  $d$  is a correlation parameter,  $I$  is an identity matrix (4x4) and  $Q$  is given by the expression

$$Q = \begin{pmatrix} p_{G_1 G_2} & p_{G_1 G_2} & p_{G_1 G_2} & p_{G_1 G_2} \\ p_{G_1 B_2} & p_{G_1 B_2} & p_{G_1 B_2} & p_{G_1 B_2} \\ p_{B_1 G_2} & p_{B_1 G_2} & p_{B_1 G_2} & p_{B_1 G_2} \\ p_{B_1 B_2} & p_{B_1 B_2} & p_{B_1 B_2} & p_{B_1 B_2} \end{pmatrix} \quad (12)$$

The  $p_B$  is different for the various types of packets, thus a constant value  $h_B$  should be implemented:

$$h_B = (P_{max} - P_e)/P_{max} \quad (13)$$

The error probability is  $P_e$  unequal to zero for the various types of packets in a bad channel state. It is assumed a maximal error rate equal to 5 timeslots but such equations can be applied if no FEC is applied [10], i.e. only for transmission of DH packets.

For a system with parallel channels between a master and two slaves should be applied a complex Matrix of two GE channels. The probability of good channel quality at the first slave is  $p_{G_1}$ , alternatively for the second slave  $p_{G_2}$ . The transition probabilities are calculated according to the equations:

$$p_{G_1 G_2} = \gamma p_{G_1}^2 + (1 - \gamma)p_{G_1}p_{G_1 B_2} = \gamma p_{G_1}(1 - p_{G_1}) \quad (14)$$

$$p_{B_1 G_2} = \delta p_{G_1}(1 - p_{G_1})p_{B_1 B_2} = \delta(1 - p_{G_1})^2(1 - \delta) + (1 - p_{G_1}) \quad (15)$$

If an equal distance between the slaves the master is assumed, then the states probabilities  $p_{G_1}$  and  $p_{G_2}$  are equal. Thus the space correlation parameters  $\gamma$  and  $\delta$  are equal too. In similar way the transition matrix  $\mathbf{P}$  is calculated by

$$\mathbf{P} = (1 - d)Q + dI \quad (16)$$

The spatial correlation between two channels is expressed by  $\alpha$  according to

$$\frac{p_{(G_1, B_2)}}{p_{G_1}p_{B_2}} = \frac{p_{(B_1, G_2)}}{p_{B_1}p_{G_2}} = \frac{\gamma p_G(1 - p_G)}{p_G(1 - p_G)} = \gamma \quad (17)$$

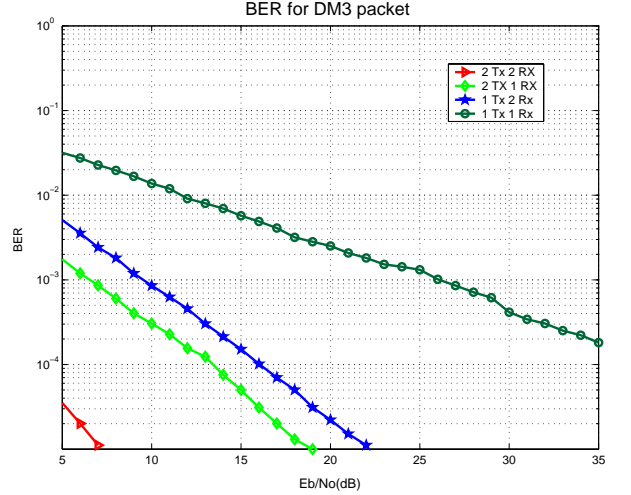


Fig. 3. DM3 packet transmission in different antenna diversity systems

In case  $\gamma = 1$  the channels are independent on each other

$$p_{(G_1|B_2)} = \frac{p_{(G_1, B_2)}}{p_{B_2}} = p_{G_1} \quad (18)$$

When the distance between the devices vary, the correlation index will be variable too. In case of  $\alpha = 0$  completely dependent channels are observed

$$p_{(G_1, B_2)} = p_{(B_1, G_2)} = 0 \quad (19)$$

On similar way equations for more than two channels could be derived. Although only completely independent channels are considered further.

## V. SIMULATION RESULTS

The modeled system consists of multiple Bluetooth flat-fading independent channels applying antenna diversity and it is evaluated by means of MATLAB. In order to achieve an effective comparison, models for the cases of standard single antenna system (1x1), transmitter diversity system (2x1), receiver diversity (1x2), and MIMO (2x2) antenna systems have been used. By the standard single antenna system and the receiver diversity scheme no space time block coding is applied but at the receiver maximum likelihood detection is used. In contrast, the systems with 2x1 and 2x2 antennas such space time coding and at the receiver a MMSE scheme for both cases are considered.

During the simulations was assumed that the amplitudes of the fading between transmitter and receiver are mutually uncorrelated Rayleigh distributed. Also same average power at each transmit and receive antenna are assumed in order to be able to compare the systems when 3-slot packets are transmitted. As shown in fig.3 and fig.4, the performance of transmitter diversity is about 17 dB better than the ordinary 1x1 single antenna system at a BER of  $10^{-3}$ . As mentioned above, for the case of medium

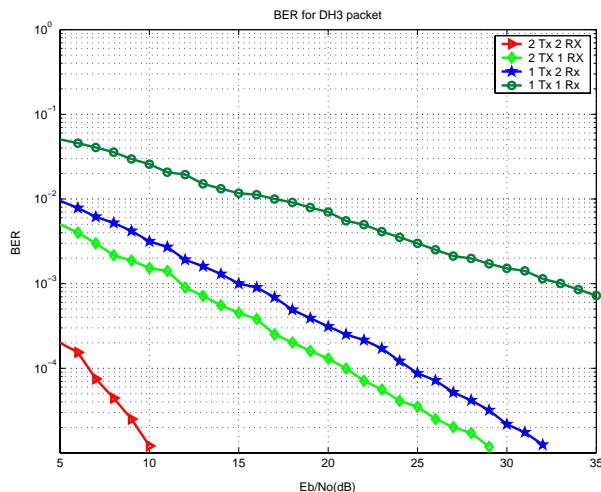


Fig. 4. DH3 packet transmission in different antenna diversity systems

data rate (DM3) packets FEC is applied in contrast to high data rate (DH3) packets. However, the transmitter diversity for both types of packets is 3 dB worse than receiver diversity, which was expected according to [1].

## VI. CONCLUSIONS

The transmitter diversity was examined when only the receiver has perfect knowledge about channel, where as a parameter with high significance for the availability and reliability of a Bluetooth link the BER has been determined. It was shown that antenna diversity is a powerful approach for improvement of Bluetooth links quality. The performance of receiver diversity was found to be significantly better than that of transmitter diversity. Although, this methodology was applied only to independent channels, it can be extended for variable spatial correlation coefficient under different environmental conditions. Also transmitter diversity with perfect knowledge at both transmitter and receiver could be examined. In this case it is expected the same performance as receiver diversity.

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