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Exploiting Diversity for Coverage Extension of Bluetooth-Based Mobile Services

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This paper investigates the impact of diversity reception techniques on the performance of Bluetooth (BT) packet transmission in wireless channels with fast fading and shadowing to improve the coverage extension. We firstly derive a tight parametric exponential approximation for the instantaneous bit error probability (BEP) in additive white Gaussian noise with parameters dependent on GFSK modulation format according to the BT standard. Then, from this expression, we derive the mean block error probability (BLEP) for DH packets transmission in Rayleigh fading channel by adopting different diversity reception techniques, such as selection diversity (SD) and maximal ratio combining (MRC). In particular, the joint impact of the diversity order, the combining techniques and the block length on the BLEP, is shown. For both MRC and SD schemes, we also obtain a tight and invertible bound on the BLEP, that enables us to analytically evaluate the quality of service expressed in terms of outage probability in channel affected by fading and shadowing and, as a consequence, the impact of multiple antennas on the system coverage.

1. INTRODUCTION

In the last years, one of the main challenges faced by wireless networks is to offer new services for mobile virtual immersive communication in order to support context-aware applications in heterogeneous environments exchanging information with users (several national projects on immersive systems are under development in the last years. For instance, we are involved in the *virtual immersive communications* (VICOM) project [1]). Immersive and context-aware communication services, offered by islands of wireless nodes in indoor and outdoor environments, are going to play an important role in beyond 3G multimedia mobile communications requiring the development of reliable radio communication technologies, wireless networks, and mobile devices replacing cables and serving real-time processes.

In such a scenario, bluetooth (BT) wireless technology is assuming an increasing importance over the years, supporting a large number of possible applications and services, which may be used in industrial and medical fields, mobile e-commerce, home networking, localization, and so forth.

In fact, the BT system represents the most recent development in the direction of reliable, low cost, and efficient short range radio communications [2–5], allowing users to make effortless, wireless, instantaneous, and low-cost connections between various communication devices within a range of about 10–30 meters. It is important to note that indoor environments are characterized by unpredictable propagation, due to the presence of obstacles, walls, and so forth; in such a scenario, it is important to evaluate and deploy transmission techniques able to cope with the unreliable propagation context, extending the radio coverage of the wireless system adopted, still complying with BT standard.

BT has been mainly designed as a “low-cost” technology aiming at providing communications capability especially to low complexity devices. From a technological point of view, this means that sophisticated specifically designed solutions cannot be adopted. However, BT is very often embedded also in complex devices such as, for instance, laptops and PDAs, where the “low-cost” requirement of the BT transceiver is less critical and this allows the adoption of more sophisticated solutions to improve the communication reliability.

These considerations suggested us to investigate, in this work, the BT performance when multiple antennas are adopted at the receiver and the communication is performed in the presence of additive white Gaussian noise (AWGN), fading and shadowing. Note that the adoption of multiple antennas, placed, for instance, in the back of the laptop screen, does not change the modulation technique nor the spectral occupancy, hence it is fully compliant with the BT specification [2].

Hereafter, the performance improvement that can be achieved by a BT system adopting an N-branches maximal ratio combining (MRC) receiver in Rayleigh fading is firstly accurately investigated. As example results, the impact of the diversity order on the mean block error probability (BLEP) will be shown. The MRC technique requires a number of channel estimators tracking fading evolutions equal to the number of antennas. Then, to meet also the low cost in processing, we obtain the performance when the selection diversity (SD) combining technique is adopted. In fact, this technique is generally less complex than MRC because it only requires the estimation of the strongest signal among the branches.

By passing through and for the sake of completeness, we extend the performance evaluation for MRC technique to the Nakagami-m fading distribution per branch.

In real propagation environment, both small-scale and large-scale effects due to fading and shadowing, respectively, have to be considered for a proper performance evaluation (see, e.g., [6, 7]). Hence, we also take into account a log-normal shadowing channel, extending our description to large-scale channel effects. In fact, real-time applications in mobile networks are a major technical challenge: multiplayer games, group-work, multimedia entertainment, voice-over-IP, and so forth are the most attractive candidates to be used over BT mobile networks even if supporting or provisioning real-time services is quite difficult due to the unpredictable propagation type and to the degree of mobility.

When real-time applications are considered, figures of merit averaged over fading, such as the mean bit error probability (BEP) or the mean packet error probability (PEP), are not sufficient to suitably characterize the system performance, hence the outage probability is also derived in this work as an important index of the system behavior over large-scale effects.

These results, although if not strictly related to BT optimization, are useful when designing other kinds of low-cost communication enabled devices, such as wireless sensors, based on Gaussian frequency shift keying (GFSK) modulation.

The paper is organized as follows: in Section 2, the mean BLEP and a tight bound are derived as a function of block length, diversity order, antenna combining technique, and the modulation parameters, following the parametric expression for the instantaneous BEP here introduced. In Section 3, the outage probability is evaluated in fading and shadowing channels together with the impact of the diversity reception on the communication range extension. In Section 4, numerical results are presented and our conclusions are given in Section 5.

2. PACKET ERROR PROBABILITY EVALUATION

A complete investigation on BT performance requires, in general, the adoption of an integrated approach jointly taking aspects related to different protocol layers into account. In almost cases, the only practicable way to perform such an investigation is the realization of system or network simulators whose elaborations are, usually, time consuming. The availability of analytical models describing the overall performance up to a given protocol level, would alleviate the complete system investigation (see, e.g., [8]).

As far as the model of the physical level behavior is concerned, in this paper we derive an analytical expression of the mean BLEP for DH[1] packets transmission in BT links affected by fading and with diversity reception. This is obtained starting from a parametric tight approximation of the instantaneous BEP. Parameters values depend on the normalized maximum frequency deviation, f_dT (f_d being the maximum frequency deviation and T being the bit duration), of the BT GFSK modulation. In particular, we approximate the instantaneous BEP with the following exponential parametric expression [9]:

$$P_b(\gamma) \simeq a \cdot e^{-b\cdot\gamma}, \tag{1}$$

where γ is the instantaneous signal-to-noise ratio (SNR), and parameters a and b have to be properly chosen depending on the normalized maximum frequency deviation f_dT.

For instance, in the case $f_dT = 0.165$, which is within the interval $[0.14, 0.175]$ permitted by BT specification [2], we found that a tight approximation can be obtained when $a = 0.47$ and $b = 0.52$, as shown in Figure 1 referred to a coherent demodulation.[2] In Figure 1 the analytical model (1) with proper parameters (a, b) is compared with simulation results. A good agreement can be noticed between the parametric model and simulation results (see, e.g., [10]).

For different modulation formats, that is, for different f_dT values, it is possible to find out different couples (a, b) representing the best approximation of the instantaneous BEP also outside the BT admitted range. As an example, for noncoherent demodulation, we obtained the following values (a, b) for various f_dT [9]: $(0.08, 0.22)$, $(0.22, 0.52)$, $(0.24, 0.66)$ for $f_dT = 0.21, 0.3, 0.4$, respectively. Thus, it can be observed that the proposed approach is also valid for noncoherent demodulation, by simply changing the parameters a and b. Obviously, in this case, only SD can be performed.

In the following, we will consider the case of coherent detection.

Taking advantage of the knowledge of the empirical parameters of (1) for different f_dT values, through the proposed methodology, it is straightforward to obtain the mean BLEP in fading channels also for a generic GFSK system (being the GFSK modulation so common among short range

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[1] DH stands for data-high rate and represents unprotected data packets for an ACL (asynchronous connection less) link [2].

[2] The parameters a and b have been empirically found by fitting simulative results with the minimum mean square error technique.

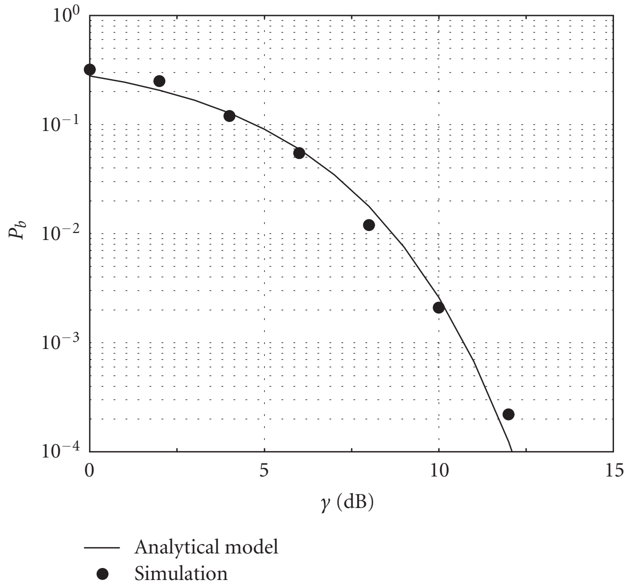

FIGURE 1: Bit error probability versus the instantaneous SNR in AWGN channel when $f_dT = 0.165$: simulation and analytical results.

radio systems or radio mobile systems) with diversity reception.

The relevance of (1) is that it allows the derivation of overall performance figures (such as the packet error probability or the throughput) without performing time consuming bit level simulations [8].

Assuming independent errors on a block of $N_{\rm BL}$ bits and by means of (1), the instantaneous BLEP, that is, the probability to have at least an error in a block of bits, can be written as

$$\begin{aligned} P_{\rm BL}(\gamma) &= 1 - (1 - P_b(\gamma))^{N_{\rm BL}} \\ &= 1 - \sum_{k=0}^{N_{\rm BL}} \binom{N_{\rm BL}}{k} (-a)^k e^{-kb\gamma} \\ &= \sum_{k=1}^{N_{\rm BL}} \binom{N_{\rm BL}}{k} (-1)^{k+1} (a)^k e^{-kb\gamma}. \end{aligned} \quad (2)$$

We assume the fading to be constant over a block but statistically independent among branches with identical distribution on mean value $\overline{\gamma}$ [11].

By averaging the instantaneous BLEP over fading statistic, we obtain the following expression for the mean BLEP:

$$\begin{aligned} P_{\rm BL}(\overline{\gamma}) &= \mathbb{E}_\gamma \left\{ 1 - (1 - P_b(\gamma))^{N_{\rm BL}} \right\} \\ &= \sum_{k=1}^{N_{\rm BL}} \binom{N_{\rm BL}}{k} (-1)^{k+1} a^k \mathbb{E}_\gamma \{ e^{-bk\gamma} \}. \end{aligned} \quad (3)$$

Recalling the definition of the moment generating function (MGF) [11–15] of γ, that is, $\Phi_\gamma(s) \triangleq \mathbb{E}_\gamma\{e^{s\gamma}\}$, (3) becomes

$$P_{\rm BL}(\overline{\gamma}) = \sum_{k=1}^{N_{\rm BL}} \binom{N_{\rm BL}}{k} (-1)^{k+1} a^k \Phi_\gamma(-bk). \quad (4)$$

The general form for (4) enables us to consider different fading statistics and diversity techniques. It has to be specialized to particular fading characteristics and diversity techniques by adopting the appropriate MGF.

For N-branches MRC and Rayleigh independent identically distributed (i.i.d.) fading channels, the MGF is given by (see, e.g., [9, 13])

$$\Phi_\gamma(s) = (1 - s\overline{\gamma})^{-N}, \quad (5)$$

hence, (4) results in

$$P_{\rm BL}(\overline{\gamma}) = \sum_{k=1}^{N_{\rm BL}} \binom{N_{\rm BL}}{k} (-1)^{k+1} a^k (1 + kb\overline{\gamma})^{-N}. \quad (6)$$

Since in a BT data packet the payload is the longest and the least protected field, the mean packet error probability (PEP) almost coincides with the mean payload error probability, $PE_{\rm pa}$ [8]. In particular, for DH packets the payload has no error protection [2] and having fixed $N_{\rm BL}$ equal to the payload length, we can state that the PEP of DH packets can be approximated as

$$\text{PEP}(\overline{\gamma}) \simeq PE_{\rm pa}(\overline{\gamma}) = P_{\rm BL}(\overline{\gamma}). \quad (7)$$

It follows that (6) can be conveniently used for evaluating the mean PEP of DH packet types. Similar derivation are proposed in [8] also for BT data-medium rate (DM) packets, where the payload foresees a code-error protection.

In many applications, figures of merit such as the BLEP-based outage probability are necessary and the inversion of (6) is required to analytically derive the SNR for a given BLEP target [16]. This problem is not analytically tractable and, in this case, we substitute the BLEP with a tight invertible bound. By observing that in the last factor of (6) the term 1 can be neglected with respect to the term $kb\overline{\gamma}$ for large values of the mean SNR, we obtain the asymptotical behavior of the mean BLEP, that is also an upper bound, as given by the following invertible expression:

$$P_{{\rm BL},U} = \min\left\{1, \frac{C_{\rm MRC}}{\overline{\gamma}^N}\right\}, \quad (8)$$

where

$$C_{\rm MRC} = \sum_{k=1}^{N_{\rm BL}} \binom{N_{\rm BL}}{k} (-1)^{k+1} a^k (kb)^{-N}. \quad (9)$$

As will be shown in Section 4, the asymptotical BLEP in (8) represents a simple invertible and accurate upper-bound of the mean BLEP for diversity orders, block lengths, and mean BLEPs of interest (i.e., $P_{\rm BL} \le 10^{-1}$). The fact that (8) is invertible allows us to analytically evaluate the system outage probability [16]. In Table 1 some values of interest for $C_{\rm MRC}$ with different $N_{\rm BL}$ and N are reported for $f_dT = 0.165$, that is a case of particular interest for BT standard.

Regarding the diversity combining techniques, it is well known that MRC provides the best performance but requires a number of channel estimators equal to the diversity order.

Table 1: Values of C_{MRC} and C_{SD} in (9) and (14) for different N_{BL} and N in Rayleigh fading.

$N_{\mathrm{BL}} \backslash N$	1		2	
	C_{MRC}	C_{SD}	C_{MRC}	C_{SD}
20	5.47	5.47	17.89	35.79
40	6.78	6.78	25.95	51.91
80	8.10	8.10	35.80	71.60
110	7.62	7.62	41.24	81.94
$N_{\mathrm{BL}} \backslash N$	3		4	
	C_{MRC}	C_{SD}	C_{MRC}	C_{SD}
20	46.21	277.27	104.94	2518.48
40	75.00	450.01	184.11	4418.66
80	115.77	694.61	309.38	7425.21
110	139.17	834.97	387.11	9290.69

Since, in some cases, the reduction of devices complexity represents an important issue for BT, we also investigate the BT performance for an N-branches SD receiver scheme that only requires the estimation of the strongest path by choosing the branch with the highest SNR.[3]

The MGF for an N-branches SD receiver in Rayleigh channels is given by [13, 15]

$$\Phi_{\gamma}(s) = \sum_{h=0}^{N-1} \frac{(-1)^h N \binom{N-1}{h}}{1+h-s\overline{\gamma}}, \tag{10}$$

hence, (4) for an SD receiver becomes

$$P_{\mathrm{BL}}(\overline{\gamma}) = \sum_{k=1}^{N_{\mathrm{BL}}} \binom{N_{\mathrm{BL}}}{k} (-1)^{k+1} a^k \sum_{h=0}^{N-1} \frac{(-1)^h N \binom{N-1}{h}}{1+h+kb\overline{\gamma}}. \tag{11}$$

In summary, (6) and (11) provide the BLEP for BT in Rayleigh fading with N-branches MRC and SD, respectively, that can approximate the PEP following (7).

Aiming at evaluating the outage probability also for an SD scheme, we need the inversion of (11). As for the previous MRC case, this problem is not analytically tractable, but a tight upper bound, $P_{\mathrm{BL},U}$, can be represented by the following expression which can be derived from (11) for high values of $\overline{\gamma}$:

$$P_{\mathrm{BL},U} = \min\left\{1, \frac{C_{\mathrm{SD}}}{\overline{\gamma}^N}\right\}, \tag{12}$$

where C_{SD} has been derived by expanding (11) for N of interest ($N = 1, 2, 3, 4$) and then obtaining asymptotical expressions. In fact, let us focus, for instance, the attention on (11) when $N = 1$ for high value of mean SNR, we obtain

$$\begin{aligned} P_{\mathrm{BL}}(\overline{\gamma}) &= \sum_{k=1}^{N_{\mathrm{BL}}} \binom{N_{\mathrm{BL}}}{k} (-1)^{k+1} a^k \frac{1}{1+kb\overline{\gamma}} \\ &\leq \sum_{k=1}^{N_{\mathrm{BL}}} \binom{N_{\mathrm{BL}}}{k} (-1)^{k+1} \frac{a^k}{kb} \frac{1}{\overline{\gamma}}. \end{aligned} \tag{13}$$

Proceeding for all the values of N of interest, the parameter C_{SD} results in

$$C_{\mathrm{SD}} = \sum_{k=1}^{N_{\mathrm{BL}}} \binom{N_{\mathrm{BL}}}{k} \frac{(-1)^{k+1} N! a^k}{(kb)^N}. \tag{14}$$

Equation (12) allows us to analytically evaluate the outage probability of the system when an SD receiver is adopted as will be shown later. In Table 1, some values of interest of C_{SD} are reported for $f_d T = 0.165$ and different values of N_{BL} and N.

By passing through, we easily extend the results for MRC reception to the case of Nakagami-m distributed fading channel ($m \geq 1/2$).[4] For this kind of fading distribution, the MGF is given by [11, 17]

$$\Phi_{\gamma}(s) = \left(1 - \frac{s\overline{\gamma}}{m}\right)^{-mN}. \tag{15}$$

Hence, the mean BLEP (4) becomes

$$P_{\mathrm{BL}}(\overline{\gamma}) = \sum_{k=1}^{N_{\mathrm{BL}}} \binom{N_{\mathrm{BL}}}{k} (-1)^{k+1} a^k \left(1 + \frac{kb\overline{\gamma}}{m}\right)^{-mN}. \tag{16}$$

As far as the asymptotical behavior (i.e., an upper bound) is concerned, we obtain

$$P_{\mathrm{BL},U} = P_{\mathrm{BL}_\infty}(\overline{\gamma}) = \min\left\{1, C_{\mathrm{MRC}} \overline{\gamma}^{-mN}\right\}, \tag{17}$$

where

$$C_{\mathrm{MRC}} = \sum_{k=1}^{N_{\mathrm{BL}}} \binom{N_{\mathrm{BL}}}{k} (-1)^{k+1} a^k \left(\frac{kb}{m}\right)^{-mN}. \tag{18}$$

Note that for $m = 1$, that is Rayleigh fading, (16), (17), and (18) result in (6), (8), and (9).

3. OUTAGE PROBABILITY EVALUATION

For home and office devices, channel variations due to shadowing (losses due to the presence of obstacles between transmitter and receiver) have a significant impact on the performance perceived by the user. In fact, shadowing causes a signal fluctuation which occurs over larger area and time scales with respect to fading. In such environments, in fact, we have a fast process superimposed on a slow process, hence, the

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[3] Since BT adopts an FH technique by hopping among 79 channels, the antenna selection at the current hop can be based on the last measurements taken on that hop (or adjacent ones).

[4] At the authors' knowledge, the closed form for the MGF, when an SD receiver in Nakagami-m fading is considered, is not known.

mean BLEP (or PEP) alone is not sufficient to describe the system performance and the link quality.

As an example, for a mobile terminal the coherence time of the fast fading is inversely proportional to the maximum Doppler frequency [18]: with a carrier frequency of 2.4 GHz, the coherence time is about 27 milliseconds for a mobile speed of 3 Km/h. On the other hand, the coherence time of the shadowing is proportional to the coherence distance (e.g., some tens of meters in urban area [19]). Assuming a coherence distance of 10 m, this results in a coherence time of about 12 seconds at 3 Km/h. Note that the coherence time of the fast fading can be an order of magnitude smaller than the coherence time of the shadowing. In such a scenario, a significant figure of merit related to the slow variations of the channel and useful to evaluate the system performance also in term of maximum distance coverage, is represented by the packet error outage (PEO).

Note that PEO represents a form of quality of service (QoS)-based outage probability when the QoS of interest is the PEP instead of the BEP usually considered for digital wireless communications [7].

Hence, the outage probability adopted here is an appropriate figure of merit to describe the performance of a digital mobile radio system, where $\overline{\gamma}$ also varies, due to shadowing, at a rate much slower than fading.

We aim at evaluating the impact of the adoption of multiple antennas at the receiver side on the BT useful range of coverage, taking into account a more complete channel model which considers also the possible presence of obstacles (e.g., walls, in the reported example).

The PEO, defined as the probability that the mean PEP exceeds a maximum tolerable level $\text{PEP}^\star$, is given by

$$P_o = \mathbb{P}\{\text{PEP} > \text{PEP}^\star\}. \qquad (19)$$

Hence, by considering the asymptotical behavior of the PEP in Rayleigh channel, that is a tight upper bound for the PEP of interest, we obtain an upper bound for the PEO as given by

$$P_o \le P_{o,U} = \mathbb{P}\{C\overline{\gamma}^{-N} > \text{PEP}^\star\} = \mathbb{P}\left\{\overline{\gamma}^{N} < \frac{C}{\text{PEP}^\star}\right\}, \qquad (20)$$

being $P_{o,U}$ the upper bound of PEO derived by (8) or by (12) and C corresponds to C_{MRC} or to C_{SD} in case of an MRC or an SD receiver, respectively.[5]

We consider the case of a shadowing environment in which $\overline{\gamma}$ is log-normal distributed with parameters μ_{dB} and σ^2_{dB} (i.e., $\overline{\gamma}_{\text{dB}} = 10\log_{10}\overline{\gamma}$ is a Gaussian random variable with mean value μ_{dB} and variance σ^2_{dB}) [20]. This is, for instance, the scenario of an indoor environment when a transmission occurs from a room to another (and the shadowing is caused by the walls) or the channel in a motorway when two vehicles communicates during a queue or the attenuated propagation due to people moving. Hence, the upper bound of the PEO results in

$$P_o \le \mathbb{P}\left\{\overline{\gamma}_{\text{dB}} < \frac{10}{N}\log_{10}\frac{C}{\text{PEP}^\star}\right\}. \qquad (21)$$

Defining $\overline{\gamma}^\star_{\text{dB}} = (10/N)\log_{10}(C/\text{PEP}^\star)$, as the SNR giving the PEP equal to $\text{PEP}^\star$, we obtain the following upper bound for the PEO:

$$P_o \le P_{o,U} = \frac{1}{2}\operatorname{erfc}\left(\frac{\mu_{\text{dB}} - \overline{\gamma}^\star_{\text{dB}}}{\sqrt{2}\sigma_{\text{dB}}}\right), \qquad (22)$$

where erfc is the complementary error function.

In addition, for a fixed requirement on the PEO we can obtain from (22) the required value of μ_{dB} corresponding to the median value of the SNR on each branch which plays an important role in the link-budget evaluation for system design, as will be shown later.

4. NUMERICAL RESULTS

In this section, we present the results related to a BT system, hence with parameters a and b related to $f_dT = 0.165$ (permitted by the specification [2]). These results are in terms of the mean BLEP for N-branches MRC and SD in Rayleigh fading ($m = 1$), when varying the block length N_{BL} and the diversity order N. However, it is possible to investigate different values of f_dT, even outside the BT specifications, considering a general GFSK system with parameters (a, b) proposed in Section 2.

4.1. *Block error probability (BLEP) and packet error outage (PEO)*

In Figure 2, the mean BLEP is reported as a function of the mean branch-SNR in the case of MRC with 1 and 2 branches ($N = 1, 2$) and $f_dT = 0.165$. Different values of the block length, N_{BL}, are considered, such as $N_{\text{BL}} = 20, 40, 80, 120$. As an example, the case $N_{\text{BL}} = 120$ meets the BT specifications for the fully loaded DH1 packets. As can be observed the performance is more affected by the diversity order than by the block length (i.e., the payload length).

Figure 3 shows the BLEP (continuous line) for MRC with different diversity orders N as a function of $\overline{\gamma}$ with $N_{\text{BL}} = 120$ and $f_dT = 0.165$. The asymptotical behavior (8) is also reported (dashed line) showing a good agreement for BLEP of interest.

For actual BT equipped laptops, where several integrated antennas could be placed in the back of the laptop screen, at least an extended communication range is expected by increasing N. On the other hand, a great number of branches could be expensive and complex for an MRC receiver (because of the number of channel estimators). Having this in mind, the case of N-branches SD receiver is investigated in Figure 4, where the BLEP as a function of the mean branch-SNR for $f_dT = 0.165$, $N_{\text{BL}} = 120$, and different number of branches N is shown. We can observe that also with an SD receiver the gain obtained in terms of SNR with respect to BT without diversity is still significant even obtained with a simpler receiver structure. The difference in the performance

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[5] For an MRC receiver, the results can be extended to a Nakagami-m channel considering the upper-bound given by (17); $P_o \le P_{o,U} = \mathbb{P}\{C\overline{\gamma}^{-mN} > \text{PEP}^\star\} = \mathbb{P}\{\overline{\gamma}^{mN} < C/\text{PEP}^\star\}$.

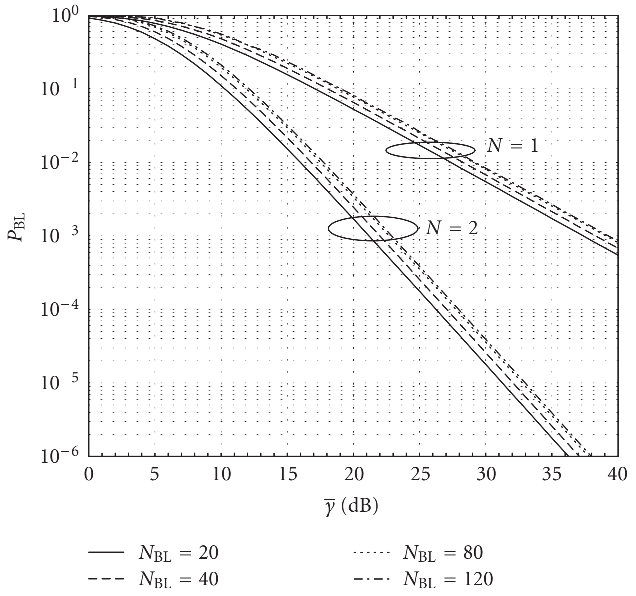

Figure 2: Mean block error probability versus $\overline{\gamma}$ when an MRC receiver is considered, for $f_dT = 0.165$ in cases of one branch and two branches for different values of N_{BL}.

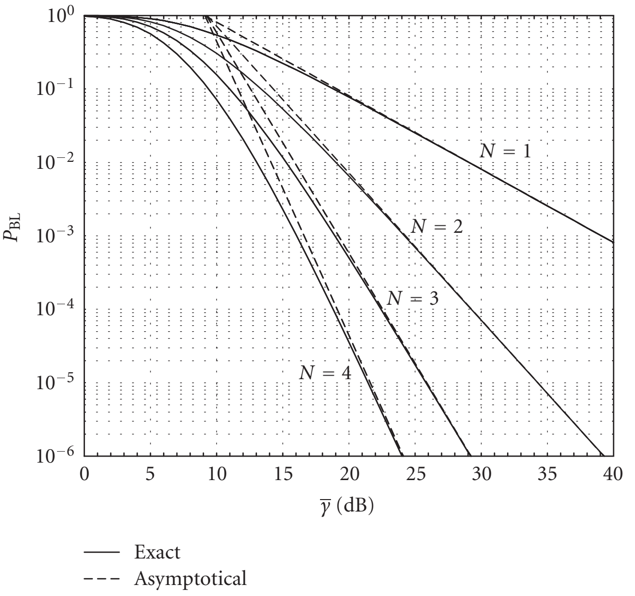

Figure 4: Mean block error probability and its asymptotical behavior versus $\overline{\gamma}$ for an SD receiver when $f_dT = 0.165$ varying the number of branches N.

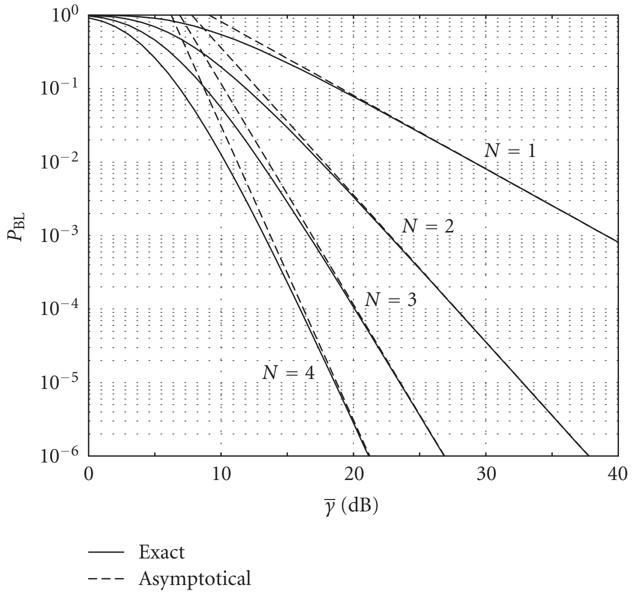

Figure 3: Mean block error probability and its asymptotical behavior versus $\overline{\gamma}$ with an MRC receiver, for $f_dT = 0.165$ varying the number of branches N.

with respect to the adoption of MRC can be investigated by comparing Figures 3 and 4.

Figures 5 and 6 show the upper bound of the PEO as a function of the median SNR μ_{dB} in the case of MRC and SD receivers, respectively. The results are presented for different diversity orders N having fixed $\text{PEP}^\star = 10^{-2}$, $f_dT = 0.165$ and for two different payload lengths (20, dotted line, and 120, continuous line) with $\sigma_{dB} = 3$ (a typical shadowing parameter value for an indoor environment [21]). Here, the performance improvement due to the adoption of MRC technique can be observed. In addition, the figures show that now the impact of the block length on the PEO is more significant than on the BLEP.

Focusing, for instance, the attention on Figure 5 (the same conclusions can be derived, however, from Figure 6), it is possible to obtain the relation between the number of branches and the required median SNR having fixed a target PEO: the adoption of two branches instead of one allows a reduction of about 11 dB in the link-budget having fixed 1% of outage and $N_{BL} = 120$.[6]

4.2. Impact of multiple antennas on the system coverage

Let us consider the following free path loss dependence on the distance d at 2.4 GHz according to [22]:

$$\text{FPL}(d)[\text{dB}] = 40 + 35\log_{10} d. \tag{23}$$

Considering also the presence of walls, the propagation loss between the transmitter and the receiver becomes

$$\text{PL}(d)[\text{dB}] = \text{FPL}(d) + nA_{\text{wall}}, \tag{24}$$

where A_{wall} is the signal attenuation in dB due to the presence of a wall and n is the number of walls encountered by the signal.

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[6] Note that when $N = 3$ and $N_{BL} = 20$ bit, the performance in terms of $P_{o,U}$ coincides with the case $N = 4$ and $N_{BL} = 120$.

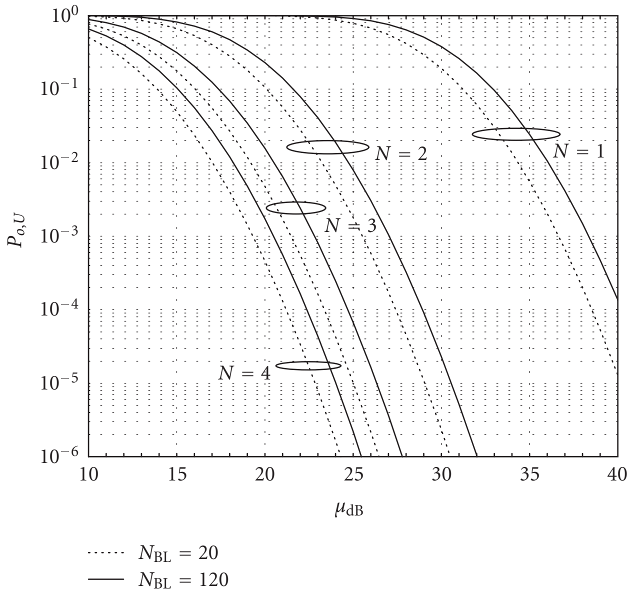

Figure 5: Upper bound on the packet error outage versus μ_{dB} with an MRC receiver for $f_d T = 0.165$ varying the number of branches N and the block length giving $\text{PEP}^\star = 10^{-2}$.

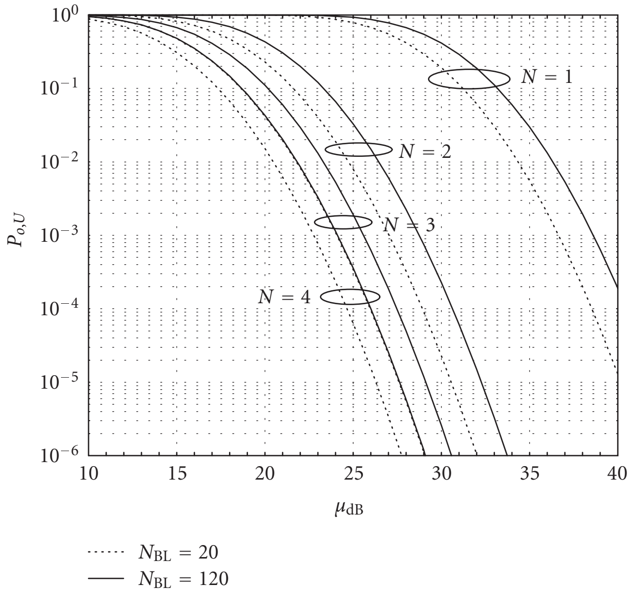

Figure 6: Upper bound on the packet error outage versus μ_{dB} with an SD receiver for $f_d T = 0.165$ varying the number of branches N and the block length giving $\text{PEP}^\star = 10^{-2}$.

Let us assume that both the transmitting and receiving antennas gains are 3 dB (e.g., a patch antenna gain) and that the antenna connections cause an attenuation of 1 dB each; thus, for a receiver noise figure of 3 dB, it is possible to derive the maximum distance between transmitter and receiver for a given value of μ_{dB}, that is for a given outage value and for a given transmitted power.

Table 2: MRC and SD reception: maximum distance [meters] between transmitter and receiver versus the number of branches for two values of outage $(10^{-1}, 10^{-2})$ giving $\text{PEP}^\star = 10^{-2}$ with transmitted power $P_e = 0\,\text{dBm}$.

N	No walls	
	$P_o = 10^{-1}$	$P_o = 10^{-2}$
1	16	13
2, MRC	33	27
2, SD	30	24
3, MRC	44	36
3, SD	37	29
4, MRC	51	42
4, SD	44	33
N	1 wall	
	$P_o = 10^{-1}$	$P_o = 10^{-2}$
1	11	8
2, MRC	22	18
2, SD	20	16
3, MRC	29	24
3, SD	25	20
4, MRC	35	28
4, SD	29	22
	2 walls	
	$P_o = 10^{-1}$	$P_o = 10^{-2}$
1	7	6
2, MRC	15	12
2, SD	13	11
3, MRC	20	16
3, SD	17	13
4, MRC	23	19
4, SD	20	15

Table 2 shows the maximum distance between transmitter and receiver as a function of the number of branches when 0, 1, and 2 walls are present introducing an attenuation $A_{\text{wall}} = 6\,\text{dB}$ [23]. The results refer to two different values of outage (i.e., 10^{-1} and 10^{-2}) for a given $\text{PEP}^\star = 10^{-2}$ when BT transmits with a power of 0 dBm, that is the minimum nominal power allowed by specification [2].

As can be noted, the presence of walls in general drastically reduces the coverage. However, 2–3 receiving antennas with simple SD reception are sufficient to extend the maximum distance to values close to those achievable in absence of walls using 1 receiving antenna. Hence, the range extension allowed by diversity techniques is quite remarkable.

5. CONCLUSIONS

In this paper, we addressed the performance evaluation of bluetooth packet transmission, in terms of mean block error probability (BLEP) and outage probability, when diversity reception is adopted in fading and shadowing channels. We firstly derived a tight parametric exponential approximation for the bit error probability in additive white Gaussian noise depending on GFSK modulation parameters within BT standard. Then, starting from this expression we derived the mean BLEP when DH data packets are transmitted in fading channels and different diversity reception techniques are adopted, such as selection diversity (SD) and maximal ratio combining (MRC). In particular, the impact of the diversity order and combining techniques on the BLEP has been shown. Then, we derived a tight bound on the BLEP for MRC and SD useful to derive the packet error outage, a significative figure of merit in the presence of slow variations of the channel due to shadowing. Our results allow the evaluation of performance and coverage increasing due to the adoption of diversity techniques.

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