Throughput and Energy Efficiency of Bluetooth v2 + EDR in Fading Channels

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Abstract—In this paper, we present a mathematical framework that permits an accurate performance analysis, both in terms of average throughput and energy efficiency, of Bluetooth link performance in fading channels. Conversely to most part of the literature concerning Bluetooth performance, this analysis takes into consideration the microscopic level power-saving mechanisms introduced in Bluetooth specifications to reduce the energy consumption during active mode. The analysis makes use of a two-state Markov chain to distinguish the transmission of useful and duplicate packets by the master. Then, the average energy spent, the amount of data exchanged and the time elapsed for each transition of the Markov chain, are derived. Hence, we apply the renewal reward theory to derive the average throughput and energy efficiency of the data link for different data packet formats and transmission rates, both in AWGN and fading channels. A proof of concept is provided by applying the mathematical framework to a Bluetooth v2.0 with Enhanced Data Rate data link. The analysis permits to appreciate the advantage, in terms of throughput and energy efficiency, of the enhanced data rate packet formats over the basic rate.

I. INTRODUCTION

Although the penetration of Bluetooth in the market has been slower than what expected, the technology has now reached a maturity level that is fostering its integration in thousands of portable electronic devices. Furthermore, the SIG [1] is promoting the enhanced data rate version of the standard, Bluetooth v2.0 + EDR (Enhanced Data Rate), that will permit higher bit rates (up to 3 Mbps) and faster node connections [2]. These upgrades promote Bluetooth to the rank of high-speed radio technologies and open the way to its use in pervasive networking scenarios, which include different types of applications such as opportunistic data exchange, bulk data transfer, distributed and cooperative computing and storage and so on [3].

The success of Bluetooth in these competitive areas, however, depends on the actual performance, in terms of throughput, delay and energy efficiency, that the technology can provide in realistic propagation environments. This topic has been partially addressed by previous work. In [4], the authors investigate some techniques to improve Bluetooth EDR data throughput by using forward error correction and interleaving schemes. However, the study does not present any delay and energy efficiency analysis. In [5]–[7] point-to-point Bluetooth throughput is derived under different channel conditions. Segmentation–and–Reassembly (SAR) policies are investigated in [8], [9], where throughput was still considered as target performance metric. Some discussions on the energy efficiency aspects of the Bluetooth system can be found in [10] and references therein. Such works are mainly focused on the definition of dynamic power management policies, which reduce the energy consumption by using the low power modes provided by the standard. Hence, the energetic model considered is very simple and does not take into consideration the effect of the radio channel and the details of the actual reception mechanism provided by the standard.

In this paper, we propose a mathematical framework for the performance analysis of an EDR Bluetooth data link, both in terms of average throughput and energy efficiency. We model the link state by means of a very simple Markov chain with only two states: Normal and Duplicate. The transitions between these states are driven by the possible reception events that may occur during a master–slave data packet exchange. Then, we associate suitable reward functions to each transition of the Markov chain, and we resort to the renewal reward analysis to compute the average throughput and energy performance achieved by the system in active mode.

As a case study, we apply the mathematical model by considering the energy figure provided in [11] and we derive the average throughput and energy efficiency of the different EDR packet formats in both AWGN and Rician fading radio channel, for different values of the signal to noise ratio. We wish to remark that, although the results presented in this paper have been obtained for specific bit error rate and energy consumption profiles, the framework is applicable to any system for which it is possible to determine the average power consumed during transmission and reception processes and the bit error rate performance for the different transmission rates.

The contribution provided by this work, hence, is twofold: first, a complete performance model for Bluetooth data link is given; second, the throughput and energy efficiency figures for EDR packet formats are derived.

The remainder of this paper is organized as follows. Sec. II provides an overview of the Bluetooth radio system. In Sec. III, we derive the mathematical model used to describe the system dynamic. Sec. IV presents a detailed performance analysis, based on the provided mathematical model. Finally, Sec. V provides concluding remarks.
II. BLUETOOTH V2.0 + ENHANCED DATA RATE

This section shortly overviews the features of the Bluetooth v2.0+EDR standard that are related to the topic dealt in the paper. An extensive description of the standard may be found, for instance, in [2], [12].

A. Physical layer: basic and enhanced rates

The Bluetooth v2.0 with Enhanced Data Rate specifications encompass three transmission rates, namely [2]: the basic rate at $R_1 = 1$ Mbps, the enhanced data rates at $R_2 = 2$ Mbps (EDR2) and the enhanced data rate at $R_3 = 3$ Mbps (EDR3). The Basic Rate makes use of a binary Gaussian-shape Frequency Shift Keying scheme (GFSK), while EDR2 and EDR3 are obtained by using Differential encoded Phase Shift Keying (DPSK) modulations, with a constellation of four symbols ($\pi/4$-DQPSK) and eight symbols (8DPSK), respectively. In all the cases, the symbol period remains equal to $T_s = 1 \mu s$, so that the frequency band of the signal is not significantly modified by the introduction of the EDR schemes.

The expressions of the bit error rate (BER) for the three modulations can be found, for instance, in [13]–[15], while the curves are reported in Fig. 1. As it can be observed, GFSK and $\pi/4$-DQPSK have comparable BER, so that the last modulation is always preferable yielding a transmission rate that is twice the basic one.

B. Data packet formats

The protocol encompasses two types of links: Synchronous Connection Oriented (SCO) and Asynchronous Connection-Less (ACL). SCO links are aimed at the transport of real-time services (mainly voice) and are based upon a periodical reservation scheme. ACL links are intended for the transport of asynchronous traffic, typically generated by elastic services such as web browsing, file transfer and so on. Since this paper is focused on data traffic, only ACL links will be considered.

Bluetooth v1.0 defined six different data packet types, all composed by three fields, namely Access Code (AC), Packet Header (HEAD) and Payload (PAYL).

The AC field is used for synchronization, DC offset compensation and piconet identification. AC is followed by the packet header field (HEAD), which contains link control information, including packet type, destination address, sequence number, acknowledgment flag (ARQN). An Header Checksum field (HEC) is used to verify the integrity of the decoded HEAD field. The HEAD field is immediately followed by the PAYL field, which can extend over one, three or five consecutive slots. The PAYL field contains a header of 1 or 2 bytes and a 2-byte cyclic redundancy code (CRC) that is used to check the integrity of the field after decoding. Furthermore, the PAYL field can be optionally protected by a 2/3 forward error correction code. Unprotected data formats are denoted by $DH_n$, while $EDR_n$ denotes the packet length in number of slots. Similarly, $DMn$ is used for protected formats. All these packets are transmitted at the basic rate.

Bluetooth v2+EDR adds other six packet formats to the original ones. To maintain backward compatibility with Bluetooth v1.0, EDR packets start with the same AC and HEAD described above, which are still transmitted at the basic rate. However, the HEAD is now followed by a guard time of approx $5 \mu s$, which is used to switch the transceiver circuitry to the appropriate DPSK modulation scheme. The guard time is followed by a synchronization field (SYNC) consisting of 10 DPSK modulated symbols, which is used for signal acquisition at the receiver. The SYN is followed by a variable length payload field, which includes a 2-byte header and a 2-byte CRC. Finally, an Enhanced Data Rate Trailer field of 2 symbols close the packet. SYNC, PAYL and trailer fields are transmitted at the selected EDR rate, by using the associated DPSK modulation scheme. Nevertheless, the slot occupancy of EDR packets is still limited to 1, 3 or 5 consecutive slots. The notation used to distinguish the six EDR packet formats is $jDH_n$, where $j = 2, 3$ is the transmission rate (in Mbps), while $n = 1, 3, 5$ is the slot occupancy. A summary of the characteristics of the different ACL packet formats provided by Bluetooth v2.0+EDR is reported in Tab. I.

<table>
<thead>
<tr>
<th>Type</th>
<th>Slots</th>
<th>Rate [Mbps]</th>
<th>PAYLOAD [bytes]</th>
<th>FEC rate</th>
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<tr>
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<td>1</td>
<td>1</td>
<td>17</td>
</tr>
<tr>
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<td>1</td>
<td>1</td>
<td>27</td>
</tr>
<tr>
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<td>1</td>
<td>2</td>
<td>2</td>
<td>54</td>
</tr>
<tr>
<td>3-DH1</td>
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<td>3</td>
<td>2</td>
<td>83</td>
</tr>
<tr>
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<td>2</td>
<td>121</td>
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<tr>
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<td>2</td>
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<td>3-DH5</td>
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<td>1021</td>
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</table>

Table I

MAIN CHARACTERISTICS OF ACL DATA PACKETS

Figure 1. BER vs SNR curves for GFSK ($\times$), $\pi/4$-DQPSK ($\cdot$) and 8DPSK modulations ($\circ$).
C. Baseband

The basic Bluetooth network configuration is the so-called piconet, a cluster of no more than eight devices sharing a common frequency—hopping radio channel. The access to the shared medium is regulated by one unit, called master, which polls the other devices, named slaves. Transmissions can directly occur between master and slaves only. Duplex communication is obtained by a slot-based Time Division Duplex scheme: time is divided into consecutive slots of $T_{\text{slot}} = 625 \mu s$ that are used for downlink (master-to-slave) and uplink (slave-to-master) transmissions, alternatively. The carrier frequency is changed at each frame transmission. Channel access is controlled by the master through a polling scheme: only the slave addressed by a downlink (DL) packet is allowed (and required) to transmit a packet to the master in the following uplink (UL) slot. The master can poll the slave implicitly, by using a useful data packet, or explicitly, with a short control packet (POLL) that does not contain the payload field. The recipient slave is required to reply immediately to the master by transmitting a data packet or a special control packet (NULL) with no payload. Bluetooth provides an Automatic Retransmission Query (ARQ) mechanism at the baseband layer: each data frame is transmitted and retransmitted until successfully acknowledged by the receiver. The acknowledgment is piggybacked in the HEAD field of the return packet. Since negative acknowledgment is assumed by default, retransmissions of successfully delivered packet may occur because the related ACK is not received. In this case, the master will keep transmitting duplicate packets (DUPCKs), which all carry the same sequence number. To save energy, a slave that recognize a DUPCK can skip the reception of the payload field, remaining in a low—power mode till the end of the transmission. Note that slaves never transmit DUPCKs. Indeed, a slave is allowed to transmit an uplink packet only upon reception of a valid downlink packet that also carries the ACK for the previous slave transmission. Thus, slave retransmissions occur only when needed, i.e., in case of reception of a negative ACK from the master.

III. MATHEMATICAL MODEL

In this section, we define a mathematical model for a Bluetooth v2.0+EDR ACL connection. We first introduce some hypothesis and notations. Then, we define the Markov model used to describe the system evolution and we briefly outline the basis of the renewal reward theory. Finally, we define the reward functions in each state of the Markov Chain and derive the performance indexes.

A. Hypotheses

For the sake of simplicity, we limit the study to the case of a piconet with only two units: one master and one slave. (The extension of the analysis to the multi—slave case requires a more cumbersome notation and exposition, without adding any relevant concept.) We consider a heavy traffic scenario, where master and slave have always packets to transmit. We assume infinite retransmission timeout: packets are retransmitted over and over again until the sender receives a positive acknowledgment. In order to determine the performance achieved by the different packet formats, we consider a static Segmentation and Reassembly (SAR) policy, so that a single packet type per connection is used. For the radio channel, we assume the classical WSSUS (Wide—Sense Stationary Uncorrelated Scattering) slow flat Rician fading model [16], so that, by virtue of the frequency hopping mechanism, packets are subject to statistically independent flat fading. Finally, we assume nodes are capable of determining the end of an ongoing transmission by measuring the Received Signal Strength (RSS) at the antenna, in case the packet is not recognized because of unrecoverable errors in the AC or HEAD fields. Although this carrier sensing mechanism is not explicitly required by the Bluetooth specifications, it is now provided by the last generation Bluetooth chipsets [17]. In any case, the mathematical framework we provide may be very easily extended to include the case in which carrier—sensing is not supported, as done in [18].

B. Notations

Let $A$, $H$ and $D$ denote the access code acquisition, packet header recognition and payload data reception phases, respectively. The success or failure of any of these phases will be denoted by adding the subscripts $s$ or $f$, respectively, to the related symbol. For instance, $A_s$ denotes a successful AC acquisition. Note that, the reception of each field is subordinated to the good recognition of the preceding fields. Consequently, an $H_f$ event occurs when the AC of the incoming packet is successfully received, while the HEAD field contains unrecoverable errors.

When necessary, we use the superscript $(M)$ and $(S)$ to distinguish between master and slave units. For example, $A^*(M)$ denotes an AC error events occurred at the master side, i.e., an unsuccessful uplink packet reception.

C. Markovian Model

Under the considered hypotheses, the system dynamic can be captured by means of a Two—State Markov Chain (MC) with event space $E = \{N, D\}$. In Normal state $(N)$, the master transmits new downlink packets or retransmit packets that have never been correctly received by the slave. Duplicate state $(D)$ is entered whenever the master does not recognize an uplink packet carrying a positive acknowledgment. In state $D$, the master keeps retransmitting duplicate packets, i.e., packets correctly received by the slave unit but not yet acknowledged because of unrecoverable errors in the AC or HEAD fields of the return packets. State $D$ is left when the master finally gets a positive acknowledgment from the slave. Hence, state transitions occur in discrete steps, each corresponding to a downlink—uplink transmission phase.

Tab. II gives a schematic summary of all the possible events that may occur during the reception of a downlink packet by the slave ($((S)$ column) and the corresponding uplink packet by the master ($((M)$ column). We identify 10 disjoint reception events that are indexed from $\phi_0$ to $\phi_9$ (Event column). The state of the MC entered after each reception event is indicated
on the right–most column of the table (X means that the new state is either D or N, as it was at the previous step).

Transitions from state N to D are determined by the occurrence of events g2 or g3. Transitions from state D to N, instead, occur with events {g0 ∪ g4} or {g1 ∪ g5}, where the symbol ∪ denotes the union operator. We consider these compounded events because, in state D, the slave disregards the PAYL field of the incoming packets, since they are DUPCKs. Hence, denoting by \( p_i \) the probability of the generic event \( g_i \), the transition probabilities from state D to N, \( P_{DN} \), and back, \( P_{ND} \), can be expressed as

\[
P_{DN} = (p_0 + p_4) + (p_1 + p_5) \quad ; \quad P_{ND} = p_2 + p_3 .
\]

The steady state probabilities \( \pi_N \) and \( \pi_D \) of the MC being in states N and D, respectively, are then given by

\[
\pi_N = \frac{P_{DN}}{P_{ND} + P_{DN}} \quad ; \quad \pi_D = \frac{P_{ND}}{P_{ND} + P_{DN}} .
\]

Note that, for the frequency hopping mechanism, successive packets have mutually independent error probabilities. Furthermore, the probabilities from \( p_0 \) to \( p_7 \), which refer to events involving the reception of the PAYL field of downlink or uplink packet, clearly depend on the packet formats used by master and slave units. Conversely, \( p_8 \) and \( p_9 \) probabilities are the same for all the packet types. (For space constraints, we do not report the expressions of such probabilities, which can be found in [19].)

### D. Renewal Theory & Reward functions

Following the approach suggested in [20], Bluetooth performance can be investigated by resorting to the classical theory of renewal reward processes [21]. Consider two generic reward functions, \( R^{(1)} \) and \( R^{(2)} \), such that \( R_j^{(1)} \) and \( R_j^{(2)} \) are the average reward earned each time the Markov chain enters in state \( j \in E \). Furthermore, let \( R^{(1)}(\tau) \) and \( R^{(2)}(\tau) \) be the total reward earned through the system evolution in the interval \([0, \tau]\). Then, from renewal theory [21], we have:

\[
\lim_{\tau \to \infty} \frac{R^{(1)}(\tau)}{R^{(2)}(\tau)} = \frac{\sum_{j \in E} \pi_j R_j^{(1)}}{\sum_{j \in E} \pi_j R_j^{(2)}} = \frac{\bar{R}^{(1)}}{\bar{R}^{(2)}} ;
\]

where \( \pi_j \) is the steady state probability of the chain being in state \( j \), while \( \bar{R}^{(1)} \) and \( \bar{R}^{(2)} \) are the expected rewards per state transition.

A proper choice of the reward functions will allow us to derive a number of performance indexes. In particular, we consider the following functions:

- state transition time \( T \);
- average number of successfully delivered data bits, \( \bar{D} \);
- amount of consumed energy, \( \bar{W} \).

In order to derive the expected values of these reward functions, we need to introduce some further notations. Let \( w_{RX}(X) \), \( w_{RX}(X) \) and \( w_{SS}(X) \) be the amount of energy consumed by a unit for transmitting, receiving and sensing, respectively, the generic packet field \( X \). Moreover, let \( \mathbb{D}(Z) \) be the number of data bits carried by the PAYL of packet type \( Z \). Finally, let \( rDxn \) and \( sDym \) be the packet types used in downlink and uplink transmission, respectively, with \( r, s \in \{1, 2, 3\} \) denoting the transmission rate [Mbps], \( n, m \in \{1, 3, 5\} \) is the slot occupancy, and \( x, y \in \{H, M\} \) is the payload format (EDR formats do not encompass any protection over the payload field, so that they are only of type \( H \)).

#### State Transition Time

The transmission of a \( rDxn \) downlink packet takes \( n \) time slots. If the slave recognizes the AC and HEAD of the downlink packet, it replies with a \( sDym \) packet that lasts for \( m \) time slots. On the contrary case, the slave is not allowed to transmit and, hence, the uplink phase takes only one slot. Note that, the length of the incoming packet is written in the packet header. If an \( Hf \) event occurs, however, the receiving unit can determine that the packet transmission is over by sensing the radio channel. Consequently, reception events from \( g_0 \) to \( g_7 \) take \( n+m \) time slots, while events \( g_8 \) and \( g_9 \), take \( n+1 \) slots. The average reward earned per MC transition is, then, given by

\[
T = (n + m)(1 - p_8 - p_9) + (n + 1)(p_8 + p_9) .
\]

#### Delivered Data

In state \( N \), the master transmits useful packets that have never been correctly received by the slave. In state \( D \), the master transmits DUPCKs that do not carry useful information. Thus, the average number of data bits successfully delivered by the master and slave units, respectively, is given by

\[
\bar{D}^{(MS)} = \pi_N \mathbb{D}(rDxn)(p_0 + p_1 + p_2 + p_3) ;
\]

\[
\bar{D}^{(SS)} = \mathbb{D}(sDym)(p_0 + p_4) .
\]

#### Consumed Energy

The computation of the energy spent by the master and slave units for each transition step of the MC, though cumbersome, is not complicate. We first focus on the master unit. At each step, the master spends \( w_{RX}(rDxn) \) energy units by transmitting the \( rDxn \) downlink packet. The energy spent in reception depends on the reception status of the uplink packet fields. In case of events \( g_0, g_2, g_4, g_5 \), the master receives the entire uplink packet, consuming \( w_{RX}(sDym) \) energy units. In case of events \( g_0 \) and \( g_9 \), the slave does not return any uplink packet and, thus, the master turns off its receiver immediately after the failed reception of the AC, spending only \( w_{RX}(AC) \).
energy units. In the remaining cases, the master stops receiving after the first erroneous field, but keeps sensing the radio channel for the remaining of the uplink packet. Therefore, the average amount of energy spent by the master is given by

\[
W^{(M)} = w_{TX}(rDxn) + w_{RX}(sDym)(p_0 + p_1 + p_4 + p_5) + w_{RX}(AC)(p_5) + (p_5 + p_2 + p_6 + p_3 + p_7) + (w_{RX}(HEAD) + w_{SS}(PAYL_{sym}))(p_2 + p_6) + (w_{SS}(HEAD) + w_{SS}(PAYL_{sym}))(p_3 + p_7).
\]

Notice that, for easy of notation, we assume that the PAYL field of EDR packet formats also includes the symbols of the SYN field.

The energy spent by the slave unit depends also on the state of the system. Indeed, as explained in Sec. II-B, the slave does not listen for the PAYL field of DUPCKs. Hence, if the system is in state \( D \) and the slave does recognize the HEAD field of the downlink packet, it enters sleep mode till the end of the incoming packet, saving energy. However, if the AC or HEAD fields are not recognized, the slave has to sense the channel to recognize the end of the downlink transmission. On the basis of the rationale discussed for the master case, it is easy to realize that the average amount of energy spent by the slave unit can be expressed, after some algebra, as follows

\[
W^{(S)} = (1 - p_8 - p_9)w_{TX}(sDym) + w_{RX}(AC)(p_8 + p_9) + w_{RX}(HEAD)p_8 + w_{SS}(HEAD)p_9 + w_{SS}(PAYL_{xn}')(p_8 + p_9) + (1 - p_8 - p_9)(w_{RX}(rDxn) - w_{RX}(PAYL_{xn}')(\bar{p}_D)).
\]

IV. PERFORMANCE ANALYSIS

In this section we analyze the performance achieved by various Bluetooth packet formats, in different cases, by using the bit error rate (BER) statistics and the reception event probabilities given in [19]. We assume that the average Signal to Noise Ratio (SNR) value is the same for the master and slave units. We also assume that the energy consumed by performing a basic operation, such as transmission, reception and channel sensing, is given by the product of the overall power absorbed by the device during that operation and the time taken to complete the task. This model has been confirmed by some experimental studies carried out for Bluetooth v1.0 [11], from which we also take the power values used in our case study. For simplicity, we assume that handling EDR packet formats has the same energetic cost of Basic rate formats. For convenience, we also normalize to 1 the amount of energy required for transmitting a bit at the basic rate, so that we assume the energy consumed in performing transmission, reception and channel sensing over a time interval \( T_s = 1\mu s \) is equal to \( \bar{P}_{TX} \times T_s = 1, \bar{P}_{RX} \times T_s = 0.8 \) and \( \bar{P}_{SS} \times T_s = 0.1 \), respectively.

System performance is evaluated in terms of the goodput \( G \) and energy efficiency \( \xi \), which are defined as the average amount of successful delivered data bit per unit of time and per unit of energy [22], respectively. Therefore, the overall system goodput can be obtained as:

\[
G = \frac{D^{(M)} + D^{(S)}}{T};
\]

while overall energy efficiency is defined by

\[
\xi = \frac{D^{(M)} + D^{(S)}}{W^{(M)} + W^{(S)}}.
\]

A. AWGN channel

Fig. 2 and Fig. 3 show the average system goodput and energy efficiency, respectively, versus SNR, for a master-to-slave connection in an AWGN channel. The curves have been obtained by changing the packet type used by the master unit, while the slave unit always used NULL packets. A first evidence that arises from the figures is that for SNR values lower than \( \sim 12 \text{ dB} \), the system goodput is practically zero for any packet type. For \( \text{SNR} > 20 \text{ dB} \), best performance, both in terms of goodput and energy efficiency, is achieved by 3 Mbps EDR packet types, namely 3DH5 and 3DH3. EDR packet formats at 2 Mbps appear more suitable for SNR values lower than 18 dB. Finally, we can see that basic rate packet types achieve lower performance than EDR formats basically for all the SNR values of interest.
B. Fading channel

Curves shown in Fig. 4 give the average system goodput vs SNR for a master–to–slave asymmetric connection in a Rayleigh–fading scenario. The energy efficiency curves, related to the same scenario, are plotted in Fig. 5. As expected, system performance worsens significantly in a Rayleigh channel, though the tradeoff among the different packet formats remains, in general, as for AWGN channel.

V. CONCLUDING REMARKS

In this paper, a detailed mathematical framework for the performance analysis of Bluetooth links was presented. The model is based on an accurate analysis of the microscopic energy-saving mechanisms provided by Bluetooth standard, which have a non marginal impact on the overall performance figure of the system.

A case study, we applied the model to an asymmetric data connection using both EDR and Basic rate packet formats, in AWGN and Rayleigh fading channel. The study has revealed, as expected, that 3DH$H_3$ packet formats yields better performance, both in terms of goodput and energy efficiency, for high SNR (\(> 20\)), while 2DH$H_3$ packet types perform better in the low SNR region. Basic packet formats show poor performance in all the situations considered and, therefore, their use shall be deprecated in Bluetooth v2.0+EDR systems.

We wish to remark that, although the results have been obtained for a specific case, the analytical framework here proposed can be applied to other cases as well, thus representing a useful tool for a detailed performance analysis of Bluetooth v2.0+EDR systems both in terms of data exchange and energy efficiency.

REFERENCES