# Analysis of Bluetooth Transmission Delay in Personal Area Networks

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***Abstract*-**Bluetooth is by far the most employed technology to develop practical applications of Wireless Personal Area Networks (WPAN). This paper studies the performance of Bluetooth transmissions that make use of the Bluetooth PAN (Personal Area Network) profile. In particular, the study offers an analytical model that defines the optimal bound for the end-to-end data delay. The proposed 'delay budget' takes into account the overhead and segmentation provoked by the protocols involved in the transmission of user data. The model is empirically validated by comparing its results with those obtained through the measurements of actual Bluetooh connections.

***Index Terms*:** Bluetooth, Wireless Personal Area Networks, transmission delay, BNEP

## I. INTRODUCTION

WPANs (Wireless Personal Area Networks) are short range communication systems (from a few centimetres to about 10 metres) that allow to exchange information among devices organised around an individual person. Nowadays Bluetooth is by far the most widely utilised technology for deploying WPANs. To guarantee the interoperability between devices from different vendors, the Bluetooth (BT) specification defines different profiles [1] describing the protocols and procedures to be implemented in diverse application scenarios. The PAN (Personal Area Network) profile specifies how two or more Bluetooth devices can create an ad-hoc network, and how to access remote networks through access points. The main advantage of the PAN profile is that it enables an IP-based service. Thus Bluetooth nodes can be directly addressed in an independent and transparent manner from any IP network. For this purpose, the PAN profile employs BNEP (Bluetooth Network Encapsulation Protocol), inspired by Ethernet and specifically devised for the transport of IP data over Bluetooth. However, the joint employment of BNEP, IP and the transport protocol related to IP (UDP or TCP) introduces an overhead that can affect the performance of the Bluetooth transmissions.

In the literature, there are significant proposals to optimise the efficiency of Bluetooth connections [2] [3]. Most of these proposals empirically investigate the practical throughput and end-to-end delay that are achieved as a function of the distance between the origin and the destination nodes, the Bit Error Rate or the coexistence with 802.11 networks. However, these studies normally do not consider the effect of the election of a particular BT profile and the data segmentation performed at the upper layers. This letter proposes an analytical model to estimate the lower bound of the delay in transmissions of user data of an arbitrary size when the PAN profile is employed.

## II. AN ANALYTICAL CHARACTERISATION OF THE MINIMUM END-TO-END DELAY WITH PAN PROFILE

In this section the minimum delay for transmitting $N$ user data bytes is estimated assuming ideal conditions, that is, the information flows from the Bluetooth master to the slave with a zero Bit Error Rate (no retransmissions occur) and a negligible storage time in the buffers. In order to incorporate the impact of all the protocols involved in the transmission under the PAN profile, the analysis must take into account the overhead of the headers added by all the layers, as well as the need for fragmentation in the ($i$+1)-th layer to avoid exceeding the $i$-th layer MTU (Maximum Transfer Unit).

The PAN profile allows the transport of TCP/IP or UDP/IP packets over L2CAP (Logical Link Control and Adaptation Protocol) using the BNEP protocol. BNEP replaces the typical Ethernet header of a LAN (Local Area Network) transmission with a specific header. The header size is 15 or 3 bytes depending if a general or a compressed packet format is employed. The compressed format is utilised when both the origin and the destination of a BNEP packet correspond to a master-slave pair in a Bluetooth piconet.

Every BNEP header and its payload are encapsulated in a Bluetooth L2CAP data PDU (Packet Data Unit) or frame. Since the BNEP frames encapsulate IP datagrams, carrying in turn UDP or TCP data, the transmission delay to be calculated will be equal to the transmission delay at the transport layer. If UDP is employed, the time required at the UDP layer ($t_{UDP}$) to transmit $N$-byte user data can be estimated as:

$$t_{UDP}(N) = t_{IP}\,(N + H_{UDP}) \qquad (1)$$

where $H_{UDP}$ is 8 bytes (the size of the UDP header) and $t_{IP}(N)$ is the delay at the IP layer. The computation of this delay, defined in equation (2), must contemplate the fragmentation that occurs at the BNEP layer when the BNEP MTU ($M'_B$) is exceeded:

$$\begin{aligned} t_{IP}(N) = N_{frag}(N)\cdot t_{ACK}(M'_B + H_B + H_{L2CAP}) + \\ + t_{TX}(L_{rem}(N) + H_{IP} + H_B + H_{L2CAP}) \end{aligned} \qquad (2)$$

being:

- $M'_B$: the BNEP MTU (1500 bytes, as the length of the maximum Ethernet payload). Notice that as this value $M'_B$ is lower than the L2CAP MTU for BNEP, which is 1691 bytes, every BNEP packet is encapsulated in a single L2CAP frame.

-$H_{IP}$: the number of bytes in the standard IP header (20 bytes).

-$N_{frag}$: the number of non-final BNEP fragments, computable as

$$N_{frag}(N) = \left\lceil \frac{N}{M_B^{'} - H_{IP}} \right\rceil - 1 \qquad (3)$$

where the operator $\lceil x \rceil$ indicates the rounding to the lowest integer higher than $x$.

-$H_B$: the number of bytes in the BNEP header (3 bytes for the compressed format).

-$H_{L2CAP}$: the size of he L2CAP protocol header (4 bytes).

-$L_{rem}(N)$: the number of bytes of the last BNEP/L2CAP frame, which is calculated as:

$$L_{rem}(N) = \left((N-1) \bmod (M'_B - H_{IP})\right) + 1 \qquad (4)$$

The formula in (2) also includes the segmentation that Bluetooth (BT) performs when more than one BT baseband packet is required to transport a L2CAP frame. In this sense, the formula considers two components, $t_{ACK}$ and $t_{TX}$, defined as follows:

-The term $t_{ACK}(N)$ describes the time (estimated in terms of BT slots) that is required by Bluetooth to send an intermediate BNEP/L2CAP frame:

$$t_{ACK}(N) = \begin{cases} 2 \cdot T_S & N \le L_1 \\ 4 \cdot T_S & L_1 < N \le L_3 \\ 6 \cdot T_S & L_3 < N \le L_5 \\ 6 \cdot T_S \cdot \left\lfloor \frac{N}{L_5} \right\rfloor + t_{ACK}(N \bmod L_5) & N > L_5 \end{cases} \qquad (5)$$

where $\lfloor x \rfloor$ denotes the highest integer lower than $x$, $T_S$ is the duration of a Bluetooth slot (625µs), and $L_1$, $L_3$ and $L_5$ are the maximum payload sizes for a 1, 3 and 5-slot Bluetooth packet, respectively. These sizes are 27, 183 and 339 bytes for DH (Data High -Rate) packets and 17, 121 and 224 bytes for DM (Data Medium-Rate) packets [1].

As long as a BT packet will not be transmitted until the acknowledgement of the previous one is received, the recursive expression in equation (5) takes into account the time necessary to acknowledge the intermediate BT packets into which the BNEP/L2CAP frames are decomposed. Therefore, for each intermediate BT packet there is a fixed delay of 2, 4 or 6 slots, depending on whether the current segment is transmitted in a 1, 3 or 5-slot packet.

-The term $t_{TX}(N)$ defines the time required for transmitting the final BNEP/ L2CAP frame. In this case, as the transmission will be completed when the last bit of the final fragment is received in the BT slave, neither the final acknowledgement slot nor the complete final slot of the BT packet are computed for the estimation of the delay. Specifically, this time $t_{TX}(N)$ can be calculated as a function of the number of transmitted bits in the following way:

$$t_{TX}(N) = \begin{cases} N_B(N) \cdot T_B & N \le L_5 \\ t_{ACK}(L_5) \cdot \left\lfloor \frac{N}{L_5} \right\rfloor + t_{TX}(N \bmod L_5) & N > L_5 \end{cases} \qquad (6)$$

where $T_B$ is the transmission time for 1 bit (1 µs at the peak data rate of 1 Mbps) and $N_B(N)$ is the size (in bits) of the final BT packet. This size can be computed as:

$$N_B(N) = N_{ov} + N_{pl}(N) \qquad (7)$$

where:

-$N_{ov}$ represents the Bluetooth packet header of 126 bits, obtained by adding the number of bits in the packet header (54 bits) and the access code (72 bits).

-$N_{pl}(N)$ is the number of bits in the Bluetooth payload and body, calculable as:

$$N_{pl}(N) = \begin{cases} \left(N + H_S + H_{CRC}\right) \cdot 8 & DH\ packets \\ \left\lceil \frac{\left(N + H_S + H_{CRC}\right) \cdot 8}{10} \right\rceil \cdot 15 & DM\ packets \end{cases} \qquad (8)$$

where $H_{CRC}$=2 corresponds to the 2 bytes of the CRC (Cyclic Redundancy Check) field while $H_S$ is a header of 1 or 2 bytes depending on the number of slots of the BT packet ($H_S$=1 for 1 slot and $H_s$=2 for 3 and 5 slot-packets, respectively). The previous equation takes into account that for DM packets, which are protected with FEC 2/3 (Forward Error Correction), for every 10 information bits 5 redundancy bits are added. Consequently, if the number of bits is not a multiple of 10, the packet must be filled with extra bits after the CRC.

Finally, note that the equation in (6) also considers that if the final BNEP/L2CAP frame exceeds the size of a 5-slot BT packet, more than one BT packet will be required. Thus, it also computes the time of the acknowledgments of the corresponding intermediate 5-slot BT packets.

## III. EMPIRICAL VALIDATION

To evaluate the validity of the previous theoretical expressions, numerous experiments were carried out on real Bluetooth connections between a master and slave employing the PAN profile. Both the BT master and the slave were installed in the same equipment (a PC with two USB Bluetooth dongles) to avoid synchronization problems in the measurement of the delay. The testbed and the connections between the master and the slave were programmed in C using the BlueZ protocol stack [4]. Each experiment consisted in the transmission through a UDP socket of a user data block of a pre-determined size. 150 different packet sizes (ranging from 1 to 1500 bytes) were considered. The delay for each data block was computed as the time elapsed from the start of the data transmission to the reception of the last data bit in the slave. The delay introduced by the Operating System and USB interfaces was removed from the empirical results. To optimise the transmission conditions and minimise any possible interference, both BT modules were located in a small metal box.

Figure 1 compares the results of the analytical model and the measurements on the actual connections when the two types of BT packets (DH and DM) are employed. For the real BT transmissions, each point represents the mean value of 1000 different transmissions executed with the same data size.

The empirical estimations clearly confirm the ability of the analytical model to characterise the end-to-end delay. In the figure The equally spaced ‘steps’ of the graphs coincide with the filling of 5-slot BT packets and the need of waiting for a new acknowledgment slot to receive the final BNEP/L2CAP frame. With the PAN profile and DH packets, these steps appear for sizes of 304 (=339-35) bytes and their multiples, due to the 35-byte overhead introduced by UDP, IP, BNEP and L2CAP (8, 20, 3 and 4 bytes, respectively). This overhead reduces the maximum capacity (339 bytes) of a 5-slot DM packet.

The figure also shows that, for user data sizes greater than 1472 bytes, the delay increases, since the 1500-byte BNEP MTU is exceeded (1472 data bytes plus 28 bytes of the UDP and IP headers) and consequently data fragmentation is necessary at the BNEP layer.

## IV. CONCLUSIONS

This work has studied the performance of the PAN profile in Bluetooth transmissions. In contrast with other empirical analysis, normally performed at the lower layers of Bluetooth, this paper proposes an analytical model to define the minimum end-to-end delay introduced by the PAN profile. The model considers the whole protocol stack, computing both the overhead and the fragmentation provoked by the different protocols up to the transport layer. The validity of the proposed formulation has been confirmed by a wide set of empirical measurements in an actual BT network.

## ACKNOWLEDGEMENTS

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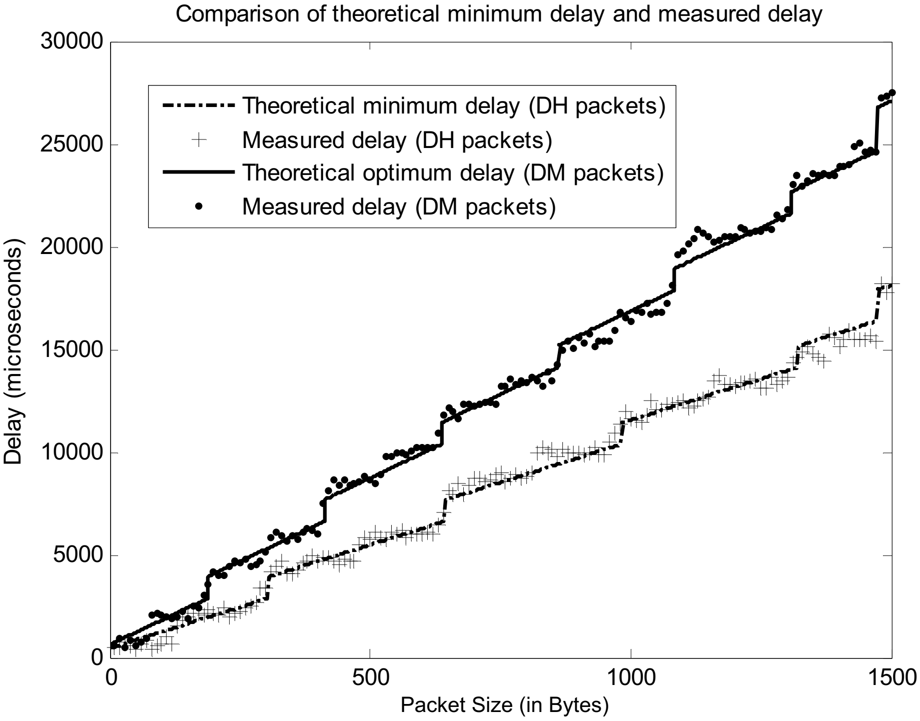

Fig. 1. Comparison of the theoretical minimum (optimal) delay computed with the analytical model and the measured delay in the actual BT transmissions