# Modelling the Bluetooth Logical Link Control and Adaptation Layer

Pi Huang, A.C.Boucouvalas and P.Chatzimisios
Multimedia Communications Research Group, School of Design, Engineering and Computing
Bournemouth University, Fern Barrow, Poole, BH12 5BB, U.K. Email: {phuang, tboucouv, pchatzimisios}@bmth.ac.uk

**Key words to describe the work:** Bluetooth, L2CAP, Baseband, mathematical modelling, throughput analysis

**Key Results:** derivation of the throughput equation as a function of packet rate, Baseband packet types, L2CAP packet length

**How does the work advance the state-of-the-art?:** throughput analysis for Bluetooth at the L2CAP layer will allow a better understanding of the interaction between high and low layers, as well as the derivation of a suitable design guideline for Bluetooth devices to improvement the system performance.

**Motivation (problems addressed):** In contrast to the studies focused on the Bluetooth Physical and Baseband layer, there have not been enough studies to examine the important interaction between the lower layer (Baseband) and the higher layer (L2CAP). Thus, a mathematical model of L2CAP is needed.

## Introduction

Bluetooth is one of the major indoor wireless technologies and was designed for both voice and data communications. After years of development and popularization, the Bluetooth data applications have been gradually accepted and used. The Bluetooth data applications use the Asynchronous Connection-Less (ACL) transport provided by the Bluetooth Baseband layer. To improve the Bluetooth ACL performance, many studies have been carried out to address different issues at the Radio and Baseband layer. However, there have not been enough studies to examine the important interaction between the lower layer and the higher layer. The Logical Link Control and Adaptation Layer Protocol (L2CAP) is layered over the Baseband [1]. L2CAP bridges the data applications and the Baseband by providing many important services. This paper focuses a detailed study of the L2CAP performance and examines the interaction between Baseband and L2CAP. In this paper, data communications are considered exclusively and Bluetooth throughput at the L2CAP level is investigated.

## Baseband and L2CAP Probabilities

**Baseband:** Bluetooth uses an ad-hoc, piconet structure with a single master and up to seven slaves. Within a piconet, time is divided into $625\mu s$ slots. All transmissions are synchronized to this slot grid and are completely controlled by the piconet master. Among all the packet types defined in Baseband, DH1, DH3, DH5, DM1, DM3 and DM5 are commonly used for the ACL transport. A rate of 2/3 FEC coding is applied to the payload of DM packets, while the payload of DH packets is not protected by any error correction scheme. DM1/DH1, DM3/DH3 and DM5/DH5 packets have a maximum duration of one, three and five time slots respectively. Each data packet is acknowledged by a fast (one slot) acknowledgement (ack). The Baseband packet is to be retransmitted if a negative or no ack is received. For each Baseband packet, a Flush Timeout ($t_{TO}$) [1] is used to limit the retransmission. $t_{TO}$ is the maximum period after which all segments of the L2CAP PDU are flushed from the buffer. Although $t_{TO}$ can be disabled, it is often implemented in practice. The $t_{TO}$ is negotiated at the connection state and its value is from $625\mu s$ to $1.28s$ [1].

**L2CAP:** L2CAP is layered above the Baseband. It supports channel multiplexing and conveys the quality of service information [1]. L2CAP also provides optional error retransmission, segmentation and reassembly, and flow control. All the Bluetooth data applications use L2CAP to communicate with the Baseband. L2CAP supports 3 different operation modes. In this paper, we consider L2CAP operates in the 'retransmission' mode. This mode is widely implemented since it provides reliable and error-free communication link for the data applications. In this mode, L2CAP implements error checks and any necessary packet retransmissions. The error checking protects L2CAP PDU against failures of CRC checks. The retransmission mechanism protects against loss of L2CAP PDU due to the Baseband flushing.

## Mathematical Modelling

In the analysis, we consider the challenge of transmitting a large L2CAP PDU. Thus, a L2CAP PDU is to be fragmented and transmitted in many Baseband packets. The overall Bluetooth throughput is equal to the summation of all slaves' data communication throughput. To simplify the analysis, one active slave is considered during the transmission of one L2CAP PDU.

As shown in Fig.1, the average time to transmit one Baseband packet should consider all the possible retransmissions. For any given packet error rate (*p*), by including a one slot ack, the average time to transmit one Baseband packet is given in (1):

$$T_{BS} = a\delta + a\delta\sum_{i=1}^{N}(ip^{i}) = a\delta\left(1+\frac{p(1-(N+1)p^{N}+Np^{N+1})}{(1-p)^{2}}\right) \quad (1)$$

where $a$=2 for DH1&DM1, $a$=4 for DH3&DM3 and $a$=6 for DH5&DM5, $\delta$ is one time slot ( $\delta = 0.625ms$ ), $N$ is the number of retransmissions before reaching the Flush Timeout ($t_{TO}$), thus $N$ has the value of $N = \left\lfloor {t_{TO}}/{a\delta} \right\rfloor - 1$.

The error checking of L2CAP identifies errors due to the failures of the Header Error Check (HEC) or Cyclic Redundancy Check (CRC) error checks on the baseband packets. L2CAP retransmits the PDU if any error occurs.

As elaborated in [2], CRC is not infallible. For an n-bit checksum, 1 of $2^n$ random blocks will have the same checksum for nonequivalent data blocks. Therefore, for the n-bit CRC coding, 1 in $2^n$ errors cannot be detected. The probability of having undetected errors in HEC (8bit) and CRC (16bit) of a Baseband packet is given as follows:

$$p_{un} = {(B(p_b)+E(p_b))}/{2^{8}} + {C(p_b)}/{2^{16}} \quad (2)$$

If a Baseband packet is retransmitted more than $N$ times, Flush Timeout expires. At this stage, the whole L2CAP PDU, which this Baseband packet belongs to will be discarded. Thus, L2CAP needs to retransmit the PDU. By considering the probability of L2CAP retransmission, the time to successfully transmit the L2CAP PDU with 1, 2, … , Baseband packets is derived:

$$T_1 = T_{BS} + T_1(p^N + p_{un}) = \frac{T_{BS}}{1-(p^N + p_{un})} \quad (3)$$

$$T_2 = T_1 + (T_{BS} + T_2(p^N + p_{un})) = \frac{T_1 + T_{BS}}{1-(p^N + p_{un})} \quad (4)$$

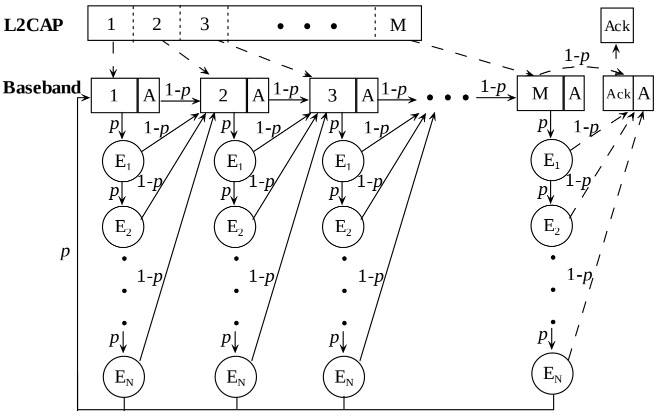
Since the ack of L2CAP is only the L2CAP header, one 1-slot Baseband packet is enough to carry the L2CAP ack. Due to the small size of the L2CAP ack packet, we assume it is transmission error free. By including the Baseband ack, as shown in Fig.1, two time slots are needed to transmit the L2CAP ack ( $T_{ack} = 2\delta = 1.25ms$ ). By including $T_{ack,}$ for a L2CAP PDU that is fragmented into $M$ Baseband packets, the average time to send the L2CAP PDU is:

$$T_M = T_{M-1} + (T_{BS} + T_M(p^N + p_{un})) + T_{ack} = \frac{T_{M-1} + T_{BS} + T_{ack}}{1-(p^N + p_{un})} \quad (5)$$

where $M = \left\lceil {(l_{L2CAP} + l'_{L2CAP})}/{l_{PL}} \right\rceil$, $l_{L2CAP}$ and $l'_{L2CAP}$ are the payload and the 8Byte header of the L2CAP PDU respectively, $l_{PL}$ is the payload size of a Baseband packet.

Finally, the Bluetooth throughput at the L2CAP layer can be derived as:

$$D = \frac{l_{L2CAP}}{T_M} \quad (6)$$



Note: **A** stands for the acknowledgement of Baseband packet, whereas **Ack** stands for the acknowledgement of the L2CAP packet

Fig.1. Bluetooth transmission model.

## Conclusion

In this paper, we carry out a mathematical analysis for the Bluetooth L2CAP protocol. The throughput equation of L2CAP is derived by considering the effect of the Baseband layer and taking into account the presence of errors. Simulation is to be carried out in the future to verify the mathematical model.

## Reference

[1] Bluetooth Core Specification, Version 1.2, Bluetooth SIG, Nov, 2003.

[2] Valenti, Press, W. H.; Flannery, B. P. and Vetterling, W. T. "Cyclic Redundancy and Other Checksums" *Cambridge University Press*, pp. 888-895, 1992.