An Efficient Multi-Slot Transmission Scheme for Bluetooth Systems

Chae Young Lee and Ki Won Sung
Dept. of Industrial Engineering, KAIST,
373-1 Kusung Dong, Yusung Gu, Taejon, Korea
{cylee, bestre}@mail.kaist.ac.kr

Abstract

Bluetooth is an open specification for a technology to enable short-range wireless communications. Bluetooth uses a frequency hopping with a slot length of 625 µs. Each slot corresponds to a packet and multi-slot packets of 3 or 5 slots can be transmitted to enhance the transmission efficiency. However, the use of multi-slot packet may degrade the performance under the high channel error probability. Thus, the length of multi-slot should be adjusted according to the current channel condition. In this paper, we propose an efficient multi-slot transmission scheme which adaptively determines the optimal length of slots for a packet according to the channel error probability. We derive the throughput of a Bluetooth connection and develop the decision criteria and the decision rule which give the optimal length of the multi-slot. Maximum likelihood estimator (MLE) is used to estimate the channel error probability.

Keywords

Bluetooth, Throughput, Multi-slot Packet, Mini-slot Error Probability, and Maximum Likelihood Estimator (MLE)

1. Introduction

Bluetooth [1] is an open specification for a technology to enable short-range, point to multi-point wireless communications that operate in an ad-hoc fashion. The objective of the Bluetooth technology is the design of low power, small sized, and row cost radio that can be embedded in portable devices such as PDAs, mobile phones, and notebook computers. More detailed review of Bluetooth can be found in [2].

Bluetooth operates in the unlicensed ISM (Industrial, Scientific, and Medical) band at 2.4 GHz. A frequency hop transceiver is applied to combat interference. A set of 79 hop carriers is employed at 1 MHz spacing. The nominal hop duration is 625 µs which coincides with the length of a single slot. Each slot corresponds to a packet and multi-slot packets of 3 or 5 slots can be transmitted to enhance the transmission efficiency. In cases of multi-slot packets, they are sent on a single hop carrier. Figure 1 depicts the multi-slot transmission.

As the length of multi-slot increases, the probability of the packet error increases and the damage by the channel error becomes large. Thus, the use of multi-slot packet may degrade the performance under the high channel error probability. Therefore, the length of multi-slots should be adjusted with the current channel condition.

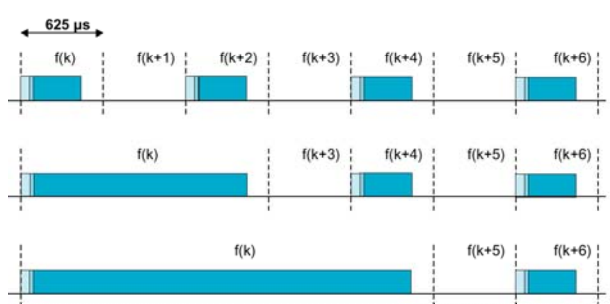

Fig. 1 Multi-slot Transmission

Since a large number of ad-hoc Bluetooth connections may coexist in the same transmission area without any mutual coordination, a Bluetooth connection may experience a dynamic change of channel condition. Moreover, the use of unlicensed ISM band generates another source of interference to the Bluetooth connection. Thus, the estimation of the channel error probability is an important factor for the determination of the optimal length of a multi-slot. However, the estimation of the channel error probability is difficult because multi-slot packets with different lengths are transmitted during a single Bluetooth connection.

In Bluetooth, the determination of the length of multi-slots is performed by the Segmentation and Reassembly (SAR) operation. Simple SAR schemes which enhance the link utilization are proposed in [3, 4]. However, the channel error is not considered in these works. In [5], the channel error probability is considered with an "interpolation method" in which packet error probabilities of different packet types are predicted from the error probability of the current packet type. However, the method does not provide an accurate estimator of the packet error probability when the length of packets changes frequently.

In this paper, we propose an efficient multi-slot transmission scheme which adaptively determines the optimal length of slots of a packet according to the channel error probability. We first discuss the throughput of a Bluetooth connection, then the decision criteria which gives the optimal length of the multi-slot is developed under the assumption that the channel error probability is known. The channel error probability is then estimated from the past transmission history of each Bluetooth device. The maximum likelihood estimator (MLE) is used to estimate the channel error probability from the history of the multi-slot errors. Finally, a simple decision rule for the optimal length of the multi-slot is developed from the estimation. The proposed decision rule is suitable for Bluetooth devices which require low power consumption. Simulation experiments show an outstanding performance of the proposed scheme.

2. Throughput of Bluetooth

In Bluetooth, the duration of one slot is 625 μs, which corresponds to one hop duration. Multi-slot occupies multiple of one slot duration. However, the actual multi-slot duration is approximately 250 μs shorter than the respective multiple of the hopping duration to allow for synthesizer re-turning [6]. Since the time required for re-turning cannot be used for data transmission, the per-slot payload size of 1 slot packet (27 bytes/slot) is smaller than that of 3 slot packet (61 bytes/slot) and 5 slot packet (67.8 bytes/slot). We introduce the concept of mini-slot to take the above aspect into account. The duration of a mini-slot is half of the one slot duration. A multi-slot packet which consists of i slots is assumed to consist of $2i-1$ mini-slots. Moreover, the ACK and the NAK is assumed to occupy one mini-slot in this paper.

Let us define *burst_set(i)* to be the set of multi-slot of i slots and an ACK or a NAK. In other words, *burst_set(i)* consists of $2i$ mini-slots. We also define p and p_i as the error probabilities of one mini-slot and a *burst_set(i)*, respectively. Let $N_p(i)$ denote the number of payload mini-slots in a *burst_set(i)*, and $N_t(i)$ be the total number of mini-slots during the transmission period of one *burst_set(i)*. The time required for frequency re-turning is considered as one mini-slot both after the transmission of the payload and the ACK/NAK. Then, it is clear that $N_p(i)=2i-1$ and $N_t(i)=2i+2$. Let $N_b(i)$ be the number of repeated *burst_set(i)*s for the transmission of a *burst_set(i)*. It includes the re-transmissions in case of error. Also, let $T(p,i)$ be the throughput of *burst_set(i)* with mini-slot error probability p. Then, the throughput of the Bluetooth is given by

$$T(p,i)=\frac{N_p(i)}{N_t(i)E[N_b(i)]}=\frac{2i-1}{2i+2}\frac{1}{E[N_b(i)]}. \quad (1)$$

The transmission of a *burst_set(i)* is successful only when all mini-slots in the *burst_set(i)* are successfully transmitted. Thus, p_i is given by $p_i=1-(1-p)^{2i}$.

Since $N_b(i)$ follows geometric distribution with success probability $(1-p_i)$, the throughput becomes

$$T(p,i)=\frac{(2i-1)(1-p)^{2i}}{(2i+2)}. \quad (2)$$

Figure 2 shows the throughput of multi-slot transmission computed by the Equation (2). In the figure, it is clear that the optimal length of the multi-slot which gives the maximum throughput varies according to the mini-slot error probability. Hence, an appropriate *burst_set(i)* should be selected depending on the channel error probability p. The optimal *burst_set(i)* crosses at p=0.04 and p=0.2. From the figure, a decision criteria for the multi-slot transmission can be obtained as in Table 1. Note that mini-slot error probabilities of 0.04 and 0.2 approximately correspond to bit error rates of 1.5×10^{-4} and 8×10^{-4}, respectively.

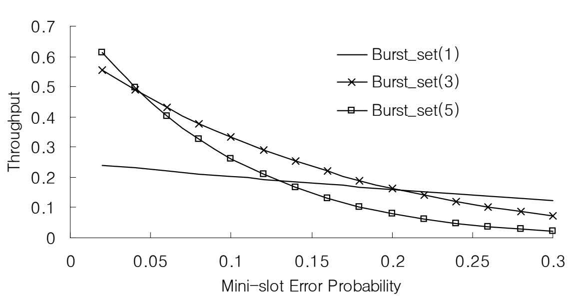

Fig.2 Throughput of Bluetooth

Table 1 Decision criteria for the multi-slot transmission

Mini-slot error probability	Optimal *Burst_set(i)*
$0 \le p < 0.04$	*Burst_set(5)*
$0.04 \le p < 0.2$	*Burst_set(3)*
$p \ge 0.2$	*Burst_set(1)*

3. Proposed Multi-slot Transmission Scheme

The decision criteria shown in Table 1 is based on the assumption that the mini-slot error probability is known. However, this is not the case in the real world. In the real Bluetooth environment, we can only measure the errors of the *burst_set*s. Therefore, mini-slot error probability should be estimated from the *burst_set* error rate.

The estimation of the channel error probability is difficult because multi-slot packets with different lengths are transmitted during a single Bluetooth connection. Note that error probability of each *burst_set(i)* is different even with the same mini-slot error probability due to the different number of mini-slots. Moreover, the requirement of low power consumption for Bluetooth devices needs simple estimation of the error probability. We propose an estimation of the mini-slot error probability from the past transmission history of each Bluetooth device. The maximum likelihood estimator (MLE) is employed for the estimation.

Let N_i be the number of transmitted *burst_set(i)*s used for the history information to estimate the mini-slot error probability. Let F_i be the number of failed *burst_set(i)*s among N_i. Then, the number of failed *burst_set(i)*s among total transmitted *burst_set(i)*s follows a binomial distribution with probability p_i. Since the transmission of a *burst_set(i)* is independent of other *burst_set(i)*s, the likelihood function of mini-slot error probability p is given as follows:

$$L(p)=\binom{N_1}{F_1}p_1^{F_1}(1-p_1)^{N_1-F_1}\binom{N_3}{F_3}p_3^{F_3}(1-p_3)^{N_3-F_3}$$

$$\times \binom{N_5}{F_5} p_5^{F_5} (1-p_5)^{N_5-F_5} . \quad (3)$$

The MLE $\hat{p}$ of the mini-slot error probability p is the value which maximizes the likelihood function. Therefore $\hat{p}$ is the solution of the equation (4).

$$\frac{dL(p)}{dp} = 0 . \quad (4)$$

It can be proved that Equation (4) has a unique solution for $0 < p < 1$. In this paper, a brief sketch of the proof is presented as follows.

Let $1 - p = x$ ($0 < x < 1$) and consider $\frac{d \ln L(x)}{dx}$. Let the numerator of $\frac{d \ln L(x)}{dx}$ be $F(x)$. Then,

$$F(x) = 2N_1 + 6N_3 + 10N_5 - \left(\frac{2F_1}{1-x^2} + \frac{6F_3}{1-x^6} + \frac{10F_5}{1-x^{10}} \right) \quad (5)$$

Note that $F(0) \geq 0$ and $\lim_{x \to 1} F(x) = -\infty$. Furthermore, $\frac{dF(x)}{dx} < 0$. Thus $F(x)$ is a monotonically decreasing function of x. Therefore, $\frac{dL(p)}{dp} = 0$ has a unique solution for $0 < p < 1$. □

Using the decision criteria of Table 1 and the MLE of the mini-slot error probability $\hat{p}$, we develop a simple decision rule for the multi-slot transmission as in Figure 3. In the range of $0 < p < 1$, $F(1-p)$ is monotonically increasing function, and $F(1-\hat{p})$ = 0. Therefore, if $F(1-0.04) > 0$, $\hat{p}$ is less than 0.04, which means *burst_set(5)* gives best performance among *burst_set(i)*s. In the same way, if $F(1-0.2) < 0$, $\hat{p}$ exceeds 0.2. Thus we should select *burst_set(1)* to obtain the optimal throughput.

If $F(1-0.04) > 0$
    Then select *burst_set(5)*
Else if $F(1-0.2) < 0$
    Then select *burst_set(1)*
Else
    Then select *burst_set(3)*

Fig.3 Decision Rule for the Multi-slot Transmission

In other cases, *burst_set(3)* should be selected because $\hat{p}$ lies between 0.04 and 0.2.

With the decision rule in Figure 3, the optimal length of multi-slot can easily be obtained. The computation of the proposed decision rule is so simple that it can be operated in any Bluetooth device in real time.

4. Simulation Results

Simulation experiments are performed to evaluate the performance of the proposed multi-slot transmission scheme. We consider a piconet which consists of one master and one slave. We assume the packet to be transmitted is generated continuously and generated in downlink (from master to slave) only. In uplink, only ACK or NACK is transmitted without piggybacking. FEC is not used in the experiments.

Figure 4 shows simulation results for throughputs of *burst_set(i)*s by changing mini-slot error probability from 0 to 0.3. Note that mini-slot error probability of 0.3 roughly corresponds to bit error probability of 1.3×10^{-3}. N_i is fixed to 100 because the proposed scheme shows good performance when $N_i \geq 100$. The effect of N_i on the throughput is discussed later.

From Figure 4, it is clear that each *burst_set(i)* has its range of the best throughput, *burst_set(5)* in $0 \leq p \leq 0.04$, *burst_set(3)* in $0.04 \leq p \leq 0.2$, and *burst_set(1)* in $p \geq 0.2$. The proposed scheme forms the envelop of the maximum throughput throughout the range of the mini-slot error probabilities. It shows that the proposed scheme selects an appropriate *burst_set(i)* according to the current channel error probability.

The effect of N_i on the throughput is also investigated. By increasing N_i from 20 to 400 while the mini-slot error probability is fixed to 0.2, the throughput is as in Figure 5. It turns out that the proposed scheme shows good performance when $N_i \geq 100$.

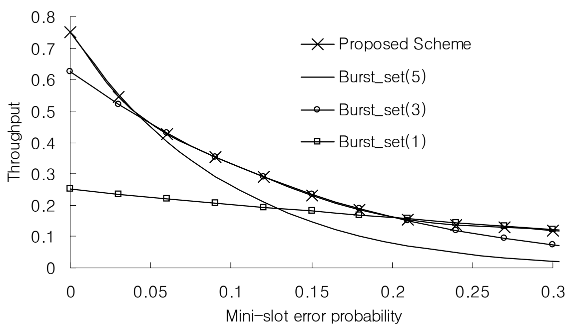

Fig.4 Throughput of each *burst_set(i)* and the proposed scheme with N_i=100

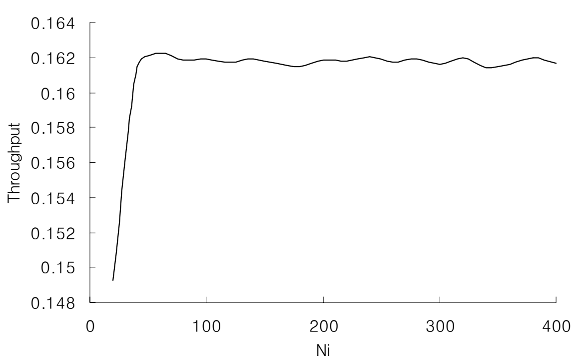

Fig. 5 Effect of N_i with p=0.2

5. Conclusion

In this paper, we proposed an efficient multi-slot transmission scheme which dynamically determines the optimal length of slots of a packet according to the channel error probability. We derived the throughput of multi-slot transmission and estimate the mini-slot error probability. MLE is used to estimate the mini-slot error probability. Decision rule for the length of the multi-slot is developed with the estimation. The proposed decision rule is simple enough to be calculated in real time with very small computing power of Bluetooth devices. Simulation experiments show the proposed scheme enhances the throughput of a Bluetooth connection.

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