Determination of the Multi-slot Transmission in Bluetooth Systems with the Estimation of the Channel Error Probability

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Abstract

Bluetooth is an open specification for a technology to enable short-range wireless communications that operate in an ad-hoc fashion. Bluetooth uses 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 transmission performance under high channel error probability. Thus, the length of multi-slot should be adjusted according to the current channel condition. Segmentation and Reassembly (SAR) operation of Bluetooth enables the adjustment of the length of multi-slot. In this paper, we propose an efficient multi-slot transmission scheme that 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 as a function of the length of a multi-slot and the channel error probability. A decision criteria which gives the optimal length of the multi-slot is presented under the assumption that the channel error probability is known. For the implementation in the real Bluetooth system the channel error probability is estimated with the maximum likelihood estimator (MLE). A simple decision rule for the optimal multi-slot length is developed to maximize the throughput. Simulation experiment shows that the proposed decision rule for the multi-slot transmission effectively provides the maximum throughput under any type of channel error correlation.

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Index Terms

Bluetooth, Segmentation and Reassembly, Channel Error Probability, Maximum Likelihood Estimator

I. 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 Bluetooth specification was developed by the Bluetooth SIG (Special Interest Group), which is an industry consortium with more than 1800 member companies. The objective of the Bluetooth technology is the design of low power, small sized, and low cost radio that can be embedded in portable devices such as PDAs, mobile phones, notebook computers, and so on. 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. Since ISM band is unlicensed, Bluetooth devices must coexist with existing technologies such as IEEE 802.11 wireless LAN and Home RF. Thus a frequency hop transceiver is applied to combat interferences. A set of 79 hop carriers is employed at 1 MHz spacing. The nominal hop duration is 625 μs which coincides with a length of the single slot. Each slot corresponds to a packet, and additionally 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 under the same channel condition and the damage by the channel error becomes critical. Thus, the use of multi-slot packet may degrade the performance under the high channel error probability. Therefore, the length of multi-slot should be adjusted with the current channel condition.

A Bluetooth connection may experience a dynamic change of channel condition because a large number of ad-hoc Bluetooth connections may coexist in the same transmission area without any mutual coordination. The impact of the interference generated from other ad-hoc

Bluetooth connections is studied in [3-5]. Moreover, the use of unlicensed ISM band such as IEEE 802.11 wireless LAN generates another source of interference to the Bluetooth connection. The influence of wireless LAN to Bluetooth connections is investigated in [6, 7].

Considering the frequent change of the wireless channel condition, the estimation of the channel error probability is necessary to determine an effective 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. Besides, the estimation should be simple enough to be run on Bluetooth devices that require low power consumption.

In Bluetooth, the determination of the multi-slot length is performed by the Segmentation and Reassembly (SAR) operation. Simple SAR schemes that enhance the link utilization are proposed in [8, 9]. Also, multi-slot transmission is used for Bluetooth piconet scheduling in [10]. However, the channel error is not considered in these works. SAR schemes proposed in [11, 12] consider the channel error probability. In these works, the best length of the packet to be transmitted is predicted from the error probability of currently used packet. However, the methods cannot provide an accurate estimator when the lengths of packets change frequently.

In this paper, an accurate error probability estimator is presented such that each Bluetooth device estimates the error probability from its past transmission history. The maximum likelihood estimator (MLE) is used to estimate the channel error probability from the history of the multi-slot errors. We propose an efficient multi-slot transmission scheme that adaptively determines the optimal length of slots of a packet that reflects the channel error probability. We first consider the throughput of a Bluetooth connection as a function of the multi-slot length and the channel error probability. Then the decision criteria which gives the optimal length of the multi-slot is presented with the assumption that the current channel error probability is known. The channel error probability is then estimated with the MLE, and a simple decision rule for the optimal length of multi-slot is developed. The proposed decision rule for the optimal length of the multi-slot is so simple that any Bluetooth device can employ the rule with low power consumption.

This paper is organized as follows. In Section 2, the throughput of Bluetooth is discussed and the decision criteria for the optimal lengths of the multi-slots are presented. In Section 3, the channel error probability is estimated with MLE and a simple decision rule of multi-slot transmission is developed. The performance of the proposed multi-slot decision rule is demonstrated in Section 4 and the conclusion is presented in Section 5.

II. Throughput of Bluetooth

In Bluetooth, user data are transmitted based on packet. The information of the upper layer is fragmented into packets with the lengths of 1, 3, or 5 slots. 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 durations are approximately 250 μs shorter than the respective multiple of the hopping duration to allow for synthesizer re-tuning [3]. Since the time required for re-tuning 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 one slot duration. A multi-slot packet which consists of *i* slots is assumed to consist of $2i-1$ mini-slots.

A fast, unnumbered ARQ scheme is used in the Bluetooth. An ACK or a NAK is returned in response to the receipt of previously received packet. Packets are retransmitted until an ACK is returned. 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 2*i* mini-slots. The concept of the *burst_set(i)* is depicted in Figure 2. We also define p and p_i as the error probability 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)*. As an example in the *burst_set(5)* of Figure 2, $N_p(5)=9$ and $N_t(5)=12$.

The time required for frequency re-tuning 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-transmission 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 Bluetooth is given by

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

The transmission of a *burst_set(i)* is successful only when all mini-slots in the *burst_set(i)* is successfully transmitted. Thus, p_i is given as follows:

$$p_i = 1 - (1-p)^{2i} \tag{2}$$

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

$$E[N_b(i)] = \frac{1}{1-p_i} \tag{3}$$

Therefore, the throughput becomes

$$T(p,i) = \frac{(2i-1)(1-p)^{2i}}{(2i+2)} \tag{4}$$

As shown in Equation (4), the throughput is a function of the length *i* of the multi-slot and the mini-slot error probability p. If a channel has no error, i.e., when p =0, we have $T(0,1) = 0.25$, $T(0,3) = 0.625$, and $T(0,5) = 0.75$. These values are the maximum throughputs with *burst_set(1)*, *burst_set(3)*, and *burst_set(5)*, respectively. However, as the channel error probability increases, the throughput decreases. Moreover, the throughput degrades fast for long multi-slot packets because the probability of the packet error increases as the number of mini-slot increases.

Figure 3 shows the throughput of multi-slot transmission computed by the Equation (4). In the figure, it is clear that the optimal length of the multi-slot that 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. In the figure, *burst_set(5)* gives the best throughput when the mini-slot error probability is less than 0.04. When the error probability lies between 0.04 and 0.2, *burst_set(3)* shows the best throughput. For the error probability which exceeds 0.2, the best throughput is obtained by *burst_set(1)*. From the figure, a decision criteria for the selection of the optimal *burst_set(i)* can be obtained as in Table 1. Note that the mini-slot error probability p =0.04 and p =0.2 corresponds to bit error rates of 1.5×10^{-4} and 8.0×10^{-4}, respectively from the equation $p = 1 - (1 - BER)^{\text{Number of Bits}}$ and the approximate number of payload bits of 280 in a mini-slot.

III. Determination of the Multi-slot Transmission

The decision criteria shown in the 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 mini-slot error probability is difficult due to different types of transmitted *burst_set(i)*s during a single Bluetooth connection. However, to obtain an accurate mini-slot error probability the information of all three types of *burst_set(i)*s should be employed. For example, suppose that 3 of 10 *burst_set(1)*s, 2 of 6 *burst_set(3)*s, and 3 of

5 *burst_set(5)*s have errors, then what is the mini-slot error probability p? 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 error probability changes dynamically by other interferers such as other Bluetooth connections, wireless LAN, or Home RF. Thus the estimation of mini-slot error probability should be executed periodically. To satisfy the frequent estimation of the mini-slot error probability of the Bluetooth devices with low power consumption, a simple estimation process is required. We propose a simple mini-slot error probability estimation scheme by employing the past transmission history of each Bluetooth device. Maximum likelihood estimator is employed for the estimation.

Let N_i be the number of total transmitted *burst_set(i)*s used for the history information to estimate the mini-slot error probability. Also, let F_i be the number of failed *burst_set(i)*s among N_i. First, the likelihood function of p_i is considered. The number of failed *burst_set(i)*s among N_i follows a binomial distribution with probability p_i. Therefore, the likelihood function of p_i is given by

$$L(p_i) = \binom{N_i}{F_i} p_i^{F_i} (1 - p_i)^{N_i - F_i} \tag{5}$$

Further, the transmission of a *burst_set(i)* is independent of other *burst_set(i)*s. Thus, the likelihood function of mini-slot error probability p becomes

$$L(p) = \binom{N_1}{F_1} p_1^{F_1} (1 - p_1)^{N_1 - F_1} \binom{N_3}{F_3} p_3^{F_3} (1 - p_3)^{N_3 - F_3} \binom{N_5}{F_5} p_5^{F_5} (1 - p_5)^{N_5 - F_5} \tag{6}$$

The MLE $\hat{p}$ of the mini-slot error probability p is the value which maximizes the likelihood function.

$$\hat{p} = \max_{p} L(p) \tag{7}$$

Thus, $\hat{p}$ is the solution of the following equation.

$$\frac{dL(p)}{dp} = 0 \tag{8}$$

In the Appendix, it is proved that Equation (8) has a unique solution for $0 < p < 1$.

Now, using the decision criteria of Table 1 and the MLE $\hat{p}$ of the mini-slot error probability p, we develop a decision rule for the multi-slot transmission as in Figure 4. In the figure, $F(x)$ is the numerator of $\frac{d \ln L(x)}{dx}$, which appears in Equation (13) in the Appendix. In the range of $0 < p < 1$, $F(1-p)$ is monotonically increasing function, and $F(1-\hat{p}) = 0$. Therefore, if $F(1-p) > 0$, then $\hat{p}$ lies between 0 and p. In other words, if $F(1-0.04) > 0$, $\hat{p}$ is less than 0.04, which means that *burst_set(5)* gives the best performance among the three *burst_set(i)*s. In the same way, if $F(1-0.2) < 0$, $\hat{p}$ is larger than 0.2. Thus we should select *burst_set(1)* to obtain the highest throughput. In other cases, *burst_set(3)* should be selected. The decision of *burst_set(i)* depends on N_i *burst_set(i)*s used for the history information in the proposed decision rule. The influence of N_i on the performance of the proposed multi-slot transmission scheme is discussed in the next section.

With the decision rule in Figure 4, the optimal length of multi-slot can be easily obtained. The computation of the proposed decision rule is so simple that it can be used with small amount of computing power in any Bluetooth device in real time.

IV. Simulation Results

Simulation experiments are performed to evaluate the performance of the proposed multi-slot transmission scheme. A piconet that consists of one master and one slave is considered in this paper. In case of a multi-slave piconet, the proposed scheme can be employed for each master-slave connection. We assume that the packet to be transmitted is generated continuously in downlink (from master to slave). In uplink, only ACK or NACK is transmitted without piggybacking. FEC is not used in the experiments.

In wireless environment it is generally considered that the channel error undergoes correlation. Thus, we consider the correlation of the channel errors between the successive mini-slots in the simulation experiments. The channel error model employed in [13] is considered for the correlation. The channel error of mini-slot is assumed to follow two-state discrete Markov chain. Let p_s be the probability that the transmission of next mini-slot is successful given that the current mini-slot has an error. Also, let p_e be the probability that the transmission of next mini-slot has an error given that the current mini-slot has been successfully transmitted. Then, the probability transition matrix *M* is given as follows:

$$M = \begin{bmatrix} 1-p_e & p_e \\ p_s & 1-p_s \end{bmatrix} \tag{9}$$

Let P_S and P_E respectively be the steady-state probability that the transmission of a mini-slot succeeds or fails. Then from (9), P_S and P_E is computed as

$$P_S = \frac{p_s}{p_s + p_e} \quad \text{and} \quad P_E = \frac{p_e}{p_s + p_e} \tag{10}$$

Note in the above equations that P_E is equivalent to the mini-slot error probability p. Clearly, as $p_s + p_e$ converges to zero, error probabilities of successive mini-slots are more correlated. When $p_s + p_e = 1$, the consecutive mini-slots are uncorrelated [13].

In order to determine the channel correlation, it is important to investigate a proper Markov chain. By partitioning the range of received signal to noise ratio (SNR) into a finite number of intervals, a Markov chain can be constructed. Let $0 = A_0 < A_1 < A_2 = \infty$ be the thresholds of received SNR. Then a channel is said to be in state s_k if the received SNR is in the interval $[A_k, A_{k+1}]$. In a time-varying channel environment, p_s is approximated by the ratio of crossing rate from s_0 to s_1 divided by the portion of state s_0. Similarly, p_e is approximated by the ratio of crossing rate from s_1 to s_0 divided by the portion of state s_1. Detailed discussion on the design of the Markov chain is given in [14] with references.

In the simulation, the following three cases of correlation are examined:

1. $p_s + p_e = 1.0$: uncorrelated
2. $p_s + p_e = 0.5$: moderately correlated
3. $p_s + p_e = 0.1$: strongly correlated.

The simulation results of above three cases are shown in Figure 5, 6, and 7, respectively. In each case, the mini-slot error probability is changed 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}. The throughput in the three figures illustrates that the proposed multi-slot decision rule is well suited both for the correlated and the uncorrelated error cases. The proposed scheme forms the envelop of the maximum throughput for all three cases.

In Figure 5, the throughput by the proposed transmission scheme almost coincides with the maximum throughput, and the optimal *burst_set(i)* crosses at p=0.04 and p=0.2 which is identical to the analysis in Section 2. It illustrates that the proposed multi-slot decision rule selects an appropriate *burst_set(i)* according to the current channel error probability when the channel errors are uncorrelated.

Figure 6 shows the throughput with moderately correlated errors. *Burst_set(5)* gives the best performance in the range of $0 \le p \le 0.1$, and *burst_set(3)* shows the highest throughput in the range of $0.1 \le p \le 0.3$. When the channel error is strongly correlated as in Figure 7, *burst_set(5)* always gives the highest throughput. Also, the overall throughput by the *burst_set(5)* is increased compared to Figure 5 and 6. It seems to be due to the burstiness of the channel errors that are concentrated on a few *burst_set*s. As the mini-slot error probability becomes more correlated, mini-slot errors occur intensively in a few short-term periods. Consequently, the error probability of *burst_set(5)* decreases and the throughput increases.

Now, notice in Figure 7 that 20 *burst_set*s (N_i =20) are used for the history information to estimate the mini-slot error probability. Since the amount of information required to estimate the error probability largely depends on the correlation among successive mini-slots, we investigate the effect of N_i on the throughput for the three cases of correlation. In the experiments N_i is increased from 20 to 400 while the steady-state mini-slot error probability is fixed to 0.2.

Figure 8 and 9 respectively shows the case of no correlation and moderate correlation. It turns out that the throughput by the proposed scheme shows good performances when $N_i \geq 100$. Figure 10 shows the result when the strong correlation exists among mini-slots. It is evident that the large number of historical *burst_*sets does not provide an accurate estimation when strong correlation exists among mini-slots. In other words, since the error rate changes frequently by a short-term period, the number of *burst_*sets required for the historical information should be reduced to reflect the most recent trend of the error probability.

V. Conclusion

An efficient multi-slot transmission scheme that adaptively determines the optimal length of Bluetooth slots of a packet is developed according to the channel error probability. The concept of mini-slot and *burst_set(i)* are introduced to measure the throughput in the wireless channel. The throughput of *burst_set(i)* is obtained as a function of the multi-slot length and the mini-slot error probability. The maximum likelihood estimator is employed to estimate the mini-slot error probability of a Bluetooth connection. A simple decision rule for the optimal length of the multi-slot is developed based on the error probability estimation. The proposed decision rule is simple enough to be implemented in any Bluetooth device with small computing power in real time.

Simulation experiment is performed by assuming that the channel error of mini-slot follows two-state discrete Markov chain. Three cases of mini-slot error correlation are examined: uncorrelated, moderately correlated, and strongly correlated error. For all cases, the proposed multi-slot decision rule forms the envelop of the maximum throughput compared to other fixed *burst_set*s. The effect of the amount of historical information required to estimate the error probability is also investigated. When strong correlation exists among mini-slots, relatively small number of historical *burst_set(i)s* provides better performance due to the burstiness of mini-slot errors.

Appendix: Proof of the uniqueness of the solution of Equation (8)

From Equation (6) we have

$$L(p) = \binom{N_1}{F_1} p_1^{F_1} (1-p_1)^{N_1-F_1} \binom{N_3}{F_3} p_3^{F_3} (1-p_3)^{N_3-F_3} \binom{N_5}{F_5} p_5^{F_5} (1-p_5)^{N_5-F_5},$$

where $p_i = 1-(1-p)^{2i}$, $N_1 \ge F_1$, $N_2 \ge F_2$, and $N_3 \ge F_3$.

When $F_i = 0$ for all i, $\hat{p} = 0$ satisfies Equation (8). Also, when $F_i = N_i$, $\hat{p} = 1$ solves the equation. Thus, the case of $0 < p < 1$ is considered in the proof.

Let $1-p = x$ ($0 < x < 1$) and $2(N_1 - F_1) + 6(N_3 - F_3) + 10(N_5 - F_5) = A$. Then, by taking the natural log of $L(p)$ we have

$$\ln L(x) = \ln\binom{N_1}{F_1} + \ln\binom{N_3}{F_3} + \ln\binom{N_5}{F_5} + F_1 \ln(1-x^2) + F_3 \ln(1-x^6) + F_5 \ln(1-x^{10}) + A \ln x \quad (11)$$

By differentiating the above equation,

$$\frac{d\ln L(x)}{dx} = \frac{-2F_1 x}{1-x^2} + \frac{-6F_3 x^5}{1-x^6} + \frac{-10F_5 x^9}{1-x^{10}} + \frac{A}{x}$$

$$= \frac{A(1-x^2)(1-x^6)(1-x^{10}) - 2F_1 x^2(1-x^6)(1-x^{10}) - 6F_3 x^6(1-x^2)(1-x^{10}) - 10F_5 x^{10}(1-x^2)(1-x^6)}{x(1-x^2)(1-x^6)(1-x^{10})}$$

(12)

Note that the denominator of Equation (10) is not zero. Let the numerator of Equation (10) be $F(x)$. Then,

$$F(x) = A - \frac{2F_1 x^2}{1-x^2} - -\frac{6F_3 x^6}{1-x^6} - \frac{10F_5 x^{10}}{1-x^{10}}$$

$$= 2N_1 + 6N_3 + 10N_5 - \left(\frac{2F_1}{1-x^2} + \frac{6F_3}{1-x^6} + \frac{10F_5}{1-x^{10}}\right) \tag{13}$$

Note that $F(0) = 2N_1 + 4N_3 + 6N_5 - 2F_1 - 4F_3 - 6F_5 \geq 0$ and $\lim_{x \to 1} F(x) = -\infty$. Furthermore,

$$\frac{dF(x)}{dx} = \frac{-4F_1 x}{(1-x^2)^2} + \frac{-16F_3 x^3}{(1-x^4)^2} + \frac{-36F_5 x^5}{(1-x^6)^2} < 0 \tag{14}$$

Equation (14) illustrates that $F(x)$ is a monotonically decreasing function of x. Thus, $F(x) = 0$ has a unique solution. Consequently, $\frac{d\ln L(x)}{dx} = 0$ has a unique solution for $0 < x < 1$ and $\frac{dL(p)}{dp} = 0$ has a unique solution for $0 < p < 1$.

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Figures and Tables

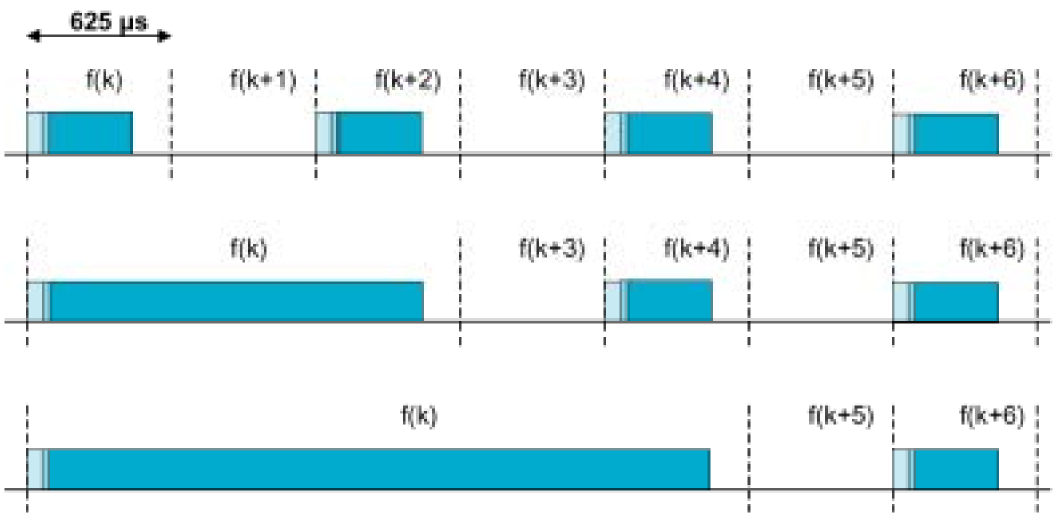

Fig. 1 Multi-slot Transmission

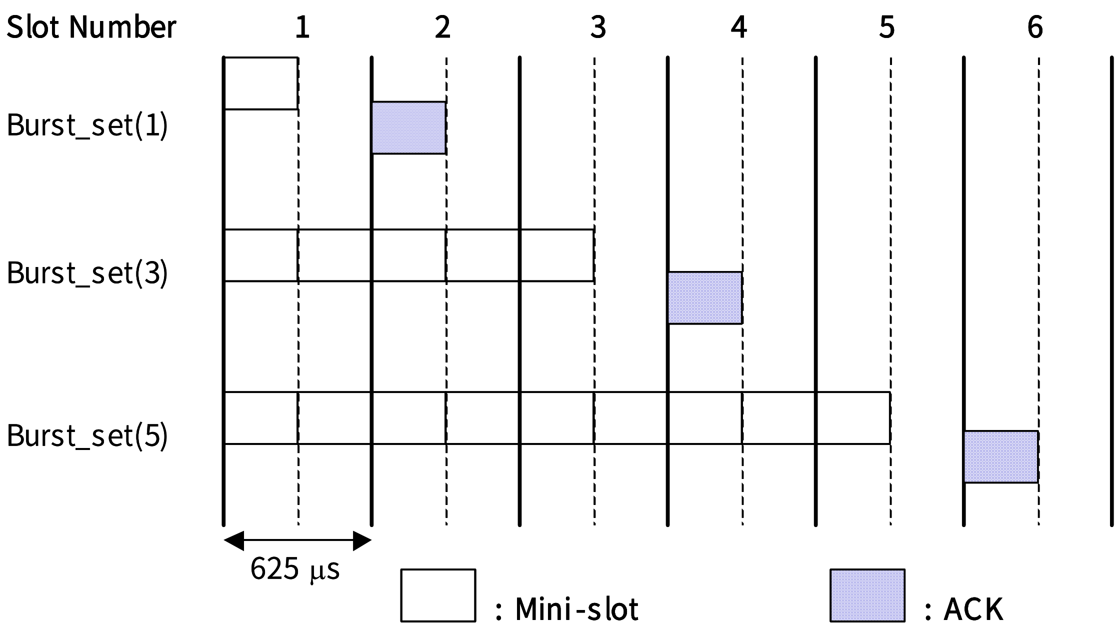

Fig. 2 ***Burst_set(i)***

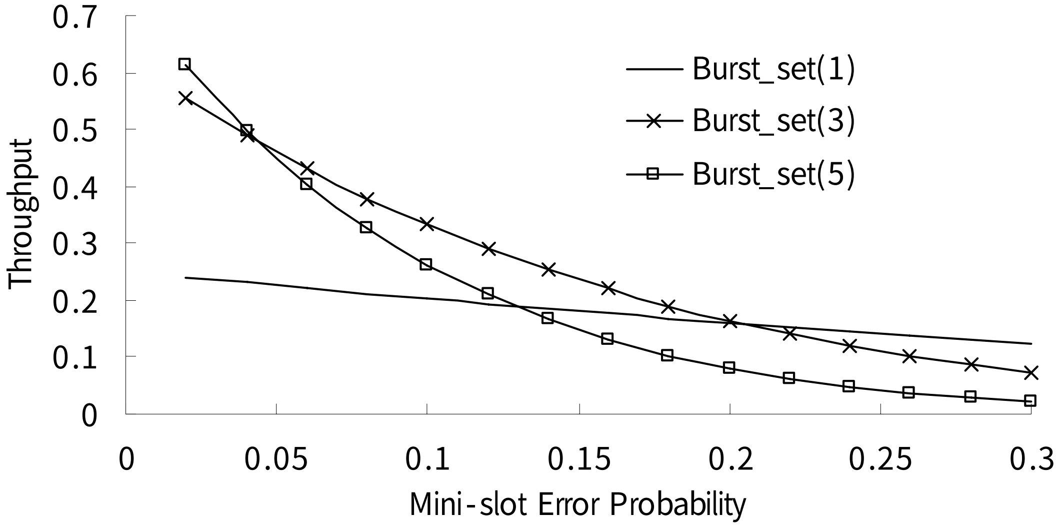

Fig.3 Throughput of Bluetooth

Table 1 Decision criteria for the multi-slot transmission

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

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.4 Decision Rule for the Multi-slot Transmission

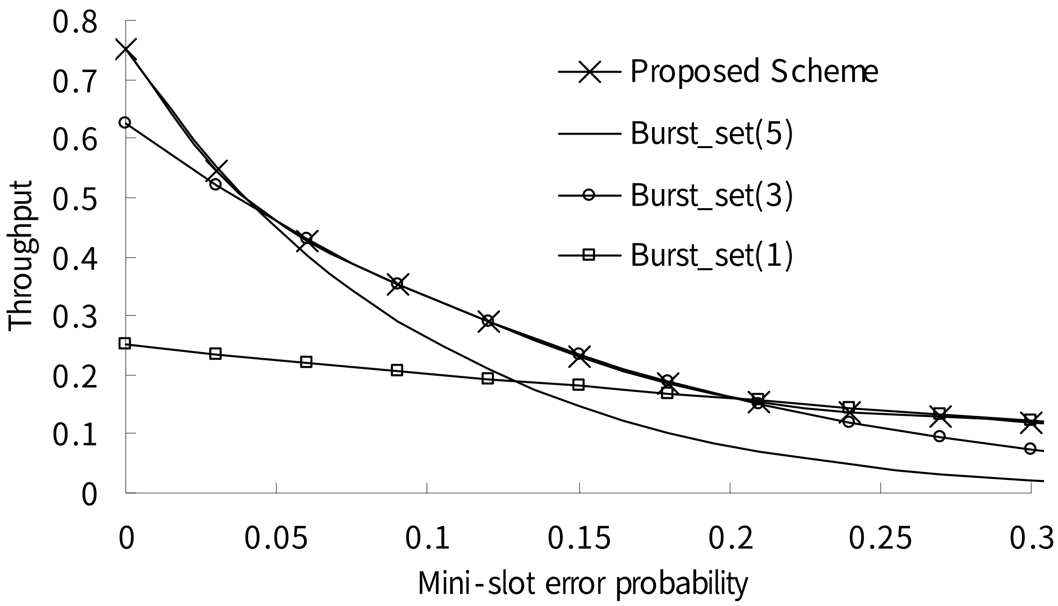

Fig.5 Throughput when channel errors are uncorrelated (N_i=100)

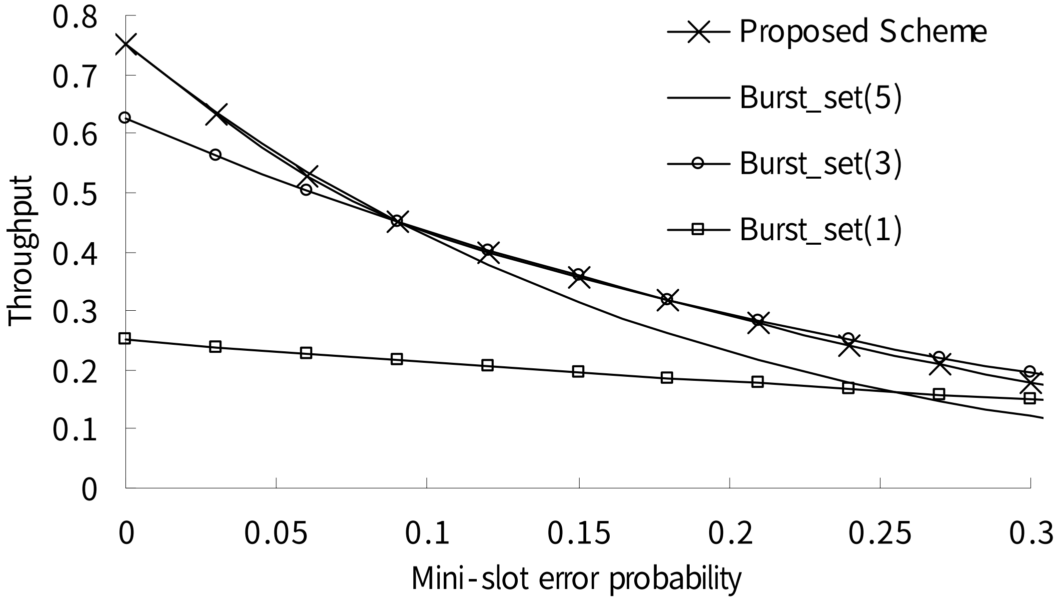

Fig.6 Throughput when channel errors are moderately correlated (N_i=100)

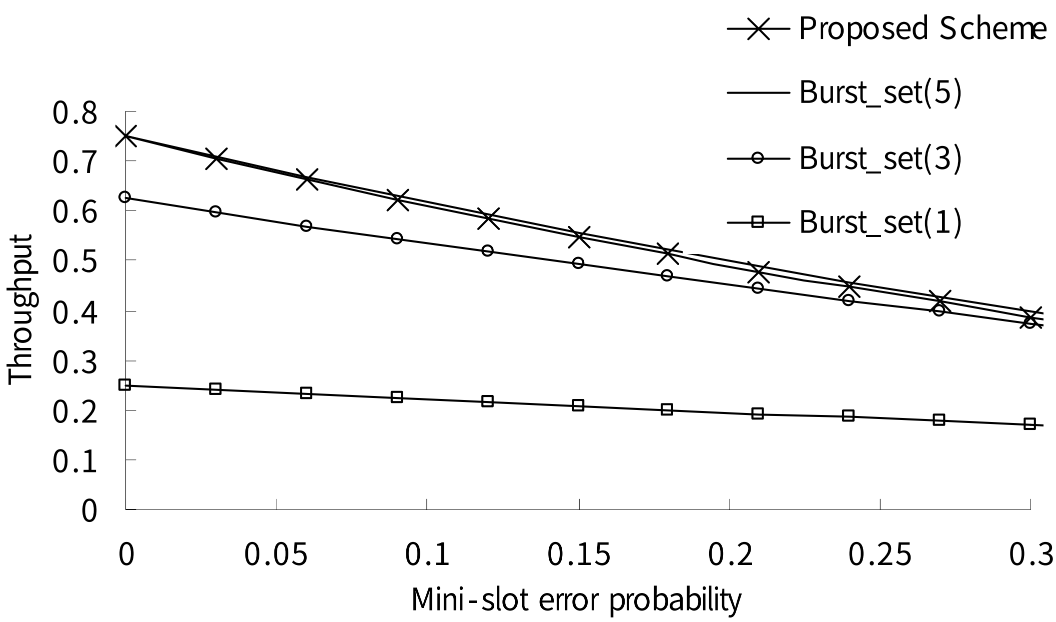

Fig. 7 Throughput when channel errors are strongly correlated (N_i=20)

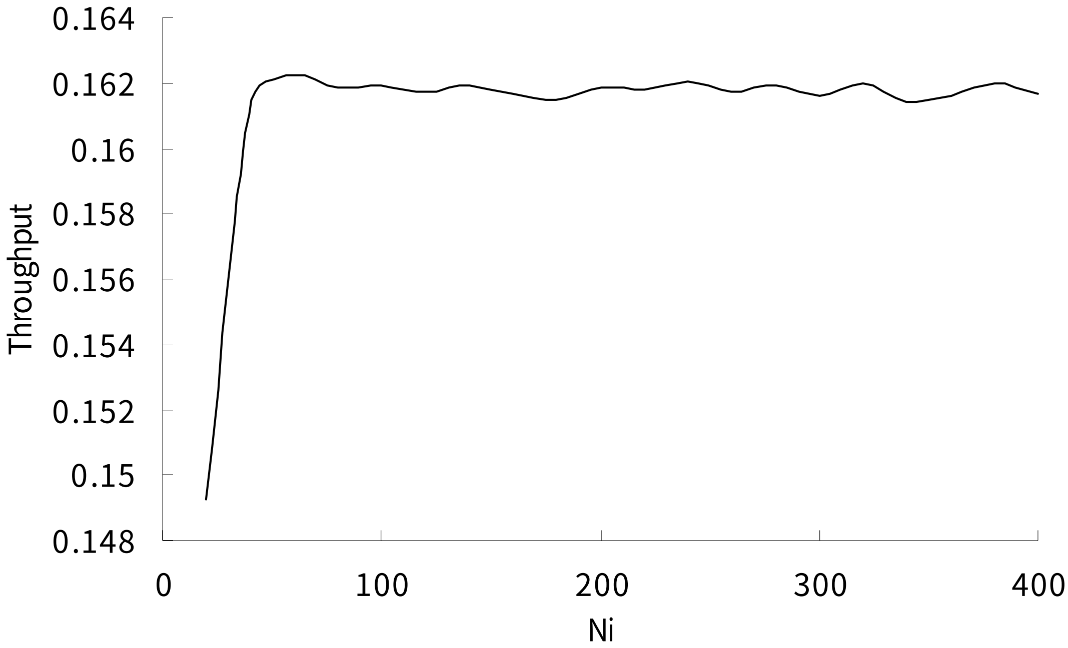

Fig. 8 Effect of N_i when errors are uncorrelated (p=0.2)

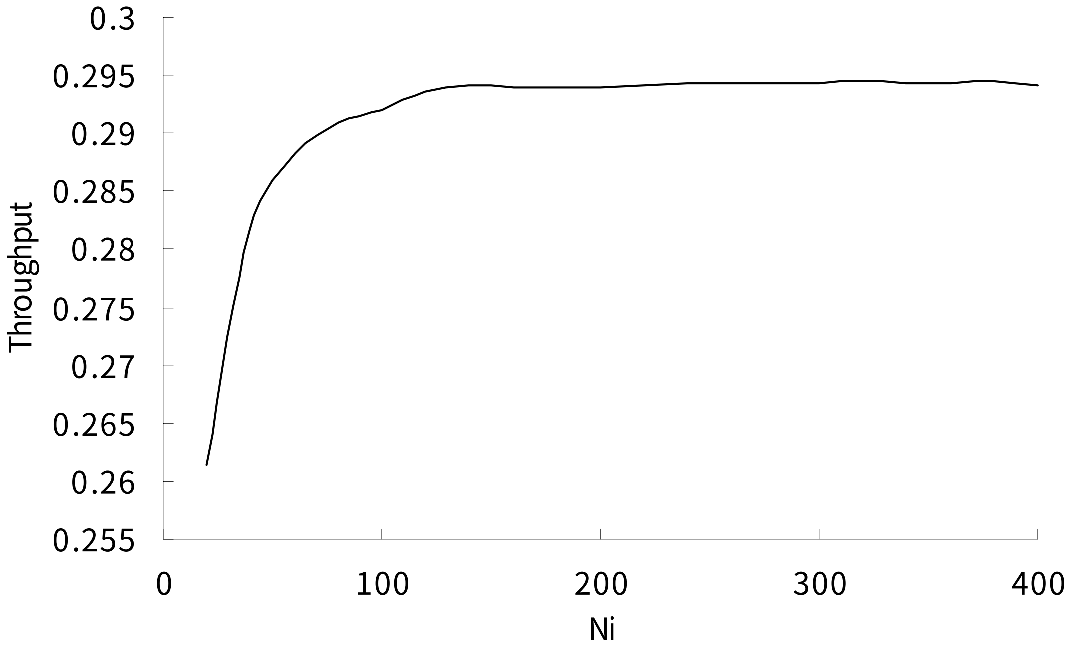

Fig.9 Effect of N_i when errors are moderately correlated (p=0.2)

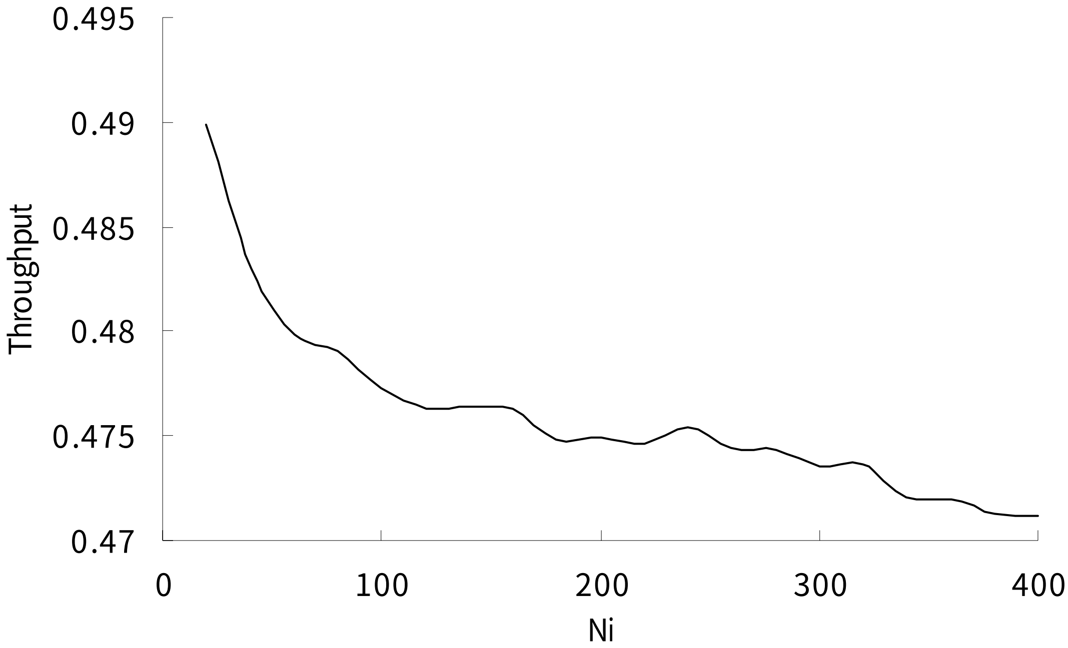

Fig.10 Effect of N_i when errors are strongly correlated (p=0.2)