A Performance Analysis of Bluetooth Broadcasting Scheme

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Abstract

This paper [1] studies the performance of current Bluetooth broadcasting scheme. Current Bluetooth broadcasting scheme may repeat transmitting (broadcasting) the same broadcasted baseband ACL packet several times to increase the reliability of broadcast over an unreliable Bluetooth radio channel. We have analyzed the effects of different Bluetooth baseband ACL packet types, each of which has a different size and error protection scheme, on the broadcast performance in terms of reliability and effective throughput that can be achieved over a given radio channel characteristics (i.e. a given bit error rate). As the result of our analysis, we determined the optimal packet type and retransmission count combinations that can provide the highest effective throughput values for various practical BER ranges. These results can be used at Bluetooth baseband layer to dynamically adapt to varying channel conditions and to achieve a good broadcast performance.

1. Introduction

Among various short-range wireless technologies for local area and personal area networking, Bluetooth [1] plays an evolving and developing role. It is an industry standard to interconnect low-power devices and portable computers with short-range radio links, eliminating the need for wires. The first Bluetooth standards were made public in 1999 and nowadays we can see lots of different Bluetooth products available on the market, ranging from Bluetooth USB dongles to Bluetooth headsets and watches.

Bluetooth is a fairly new technology and therefore has a lot of issues to develop and improve. Broadcasting in Bluetooth piconets is one such issue whose performance can be improved. Broadcasting is the act of sending a packet from a source node to all the nodes in a region (a link, a subnet, an intranet) that are reachable from that source node. With broadcasting, data can be disseminated to some or all nodes in a more efficient way in terms of consumed network capacity than sending the same packet to all nodes one at a time using unicast strategy. Besides providing efficient dissemination of data, broadcasting is also the underlying mechanism to efficiently implement distributed and group communication applications in a network, which can be wired or wireless.

Some Bluetooth applications that benefit from Bluetooth's broadcasting mechanism for piconets can also require various degrees of reliability for correct delivery of broadcasted data to other nodes of a piconet. These applications may include multimedia (audio and video) applications, real-time control and sensing applications, software upgrade and cloning applications, and so on. This brings forth the necessity for some degree of reliability in delivering broadcasted Bluetooth baseband packets. A broadcast mechanism that is efficient in terms of utilizing the capacity of a Bluetooth radio channel and that can also provide some soft guarantees on the delivery of broadcasted data is needed. These two objectives can conflict with each other

[1]This work is supported in part by The Scientific and Technical Research Council of Turkey (TÜBITAK) under projects EEEAG-101E025, EEEAG-101E048 and EEEAG-103E014.

and therefore some trade-offs occur.

According to Bluetooth specification [2], broadcasting in a Bluetooth piconet is done at the Bluetooth baseband layer and only the master of the piconet can send broadcast packets. A broadcasted packet is intended for all slaves which desire and are able to receive the packet. A broadcast packet has the AM_ADDR field in the baseband packet header set to zero, whereas a unicast packet has the AM_ADDR field set to the temporary MAC address of the slave who should receive the packet. Since broadcast packets are not acknowledged, each broadcast packet is repeated for a fixed number of times to improve the reliability of the transmission (i.e. to have more slaves to correctly receive the packet). A packet is repeated N_{BC} times before the next packet of the same broadcast stream is repeated as shown Figure 1. Therefore, it is crucial to find the optimal N_{BC} value that will provide some sort of a bound on the loss rate of the packets. There is a trade-off here: we can increase reliability by increasing the N_{BC} value, but at the same time we are also increasing the overhead and decreasing the effective channel utilization.

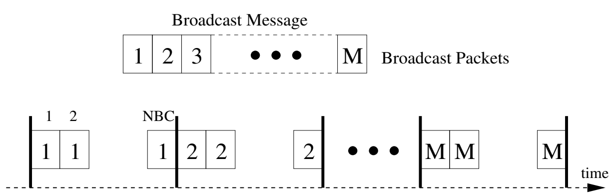

Figure 1. Bluetooth broadcasting scheme

The repetition count, N_{BC}, is decided between the master and a slave unit using the link manager (LM) protocol data units (PDU) [2]. A LM PDU that will be used for this purpose will include the N_{BC} value specified by the master node. Depending on the quality of service requirement for the connection between the master and a slave (or slaves), LMP_quality_of_service message is sent from the master node to a slave node and that message includes the desired QoS parameters and their values. A slave receiving this message can not reject the request. The slave can also send an LMP_quality_of_service_req message. In this case, the master has the option to accept or reject the request. If LMP_quality_of_service_req message sent from a slave to the master includes the N_{BC} parameter set to some value, the master will ignore this, since broadcasting is done only in one direction, from master to slaves. These link manager packets both have a length of 4 bytes and are of type DM1 [2].

In Bluetooth baseband and link layer specifications, most of the parameters may be set to values that depend on application requirements. There are two parameters that are tunable for broadcast streams to achieve an optimal solution for the trade-off between reliability and utilization: baseband packet type, and repetition count (N_{BC}). Baseband packet type is an important parameter because different packet types have different lengths and apply different FEC coding schemes.

In this work, we have investigated the optimum values for packet type and retransmission times in terms of their effect on channel utilization under different bit error rates by using a custom simulator. We have also investigated the reliability and throughput relationship in broadcasting, and tried to find the optimal values for the parameters.

Depending on the characteristics of the data that will be transmitted, Bluetooth uses several types of data packets. These packets differ by their payload length and Forward Error Correction (FEC) options. The application chooses the packet type to use, depending on the requirements of data rate and degree of error protection. Among various packet types, the ones that are used in broadcasting are asynchronous connectionless (ACL) packets. The ACL packets are further classified as DM1, DM3, DM5, DH1, DH3 and DH5. Error protection properties and data-rates of these packets are given in Table 1 [2, 5]. There are two factors that affect packet type selection: one is current bit error rate (BER) of the radio channel (which is also related to the interference level) and the other is effectiveness of the FEC scheme applied in the selected packet type. In broadcasting, a master and its slaves may use any one of these packet types mentioned in Table 1.

Mode	FEC	Packet size (bytes)	Symmetric (kbps)	Asymmetric (kbps)	
DM1	2/3	17	108.8	108.8	108.8
DM3	2/3	121	258.1	387.2	54.4
DM5	2/3	227	286.7	477.8	36.3
DH1	no	27	172.8	172.8	172.8
DH3	no	183	390.4	585.6	86.4
DH5	no	339	433.9	723.2	57.6

Table 1. ACL packet types in Bluetooth

If the optimal packet types and number of necessary retransmissions in different channel conditions can be revealed, the master can adaptively adjust its parameters according to the channel conditions and quality. In this way, maximum throughput can be achieved with a desired level of reliability in broadcasting.

2. Methodology

In broadcasting, the absence of acknowledgments results in the need for a good algorithm for tuning broadcast parameters to achieve a desired level of reliability depending on channel conditions. The bit error rate of a radio channel is the dominant parameter that affects the effective throughput (goodput) and reliability of a transmission. In order to achieve effective channel utilization (hence high application level goodput) and some level of reliability, the behavior of the broadcasting scheme for practical BER ranges should be observed in a realistic simulation environment.

Taking the advantage of the flexibility of the packet selection scheme in Bluetooth broadcasting and also considering the feedback about channel conditions between the master and its slaves, we propose to switch to the packet type that yields the best performance for a given BER value. The master should also adjust the number of repetitions for a broadcasted packet based on the BER statistics obtained through the link manager feedback packets received from the slaves.

We need to find out the optimal values of the broadcast parameters as part of the broadcasting mechanism specified in the Bluetooth standards for different BER values (i.e. different channel conditions). We are not aiming to modify the already specified mechanism for broadcasting in Bluetooth piconets. We are just aiming to find a good policy that can be applied over the given mechanism. For determining optimum parameters, we simulate broadcasting in Bluetooth piconets to observe the relationship between packet types, repetition count, throughput and reliability, under different channel conditions.

A master node can acquire feedback about the channel conditions and the efficiency of broadcasting using Bluetooth link manager level messages. After broadcasting a determined number of packets to slaves, the master can poll the slaves in an arranged order to collect their statistics, which consist of the average number of repeated broadcast packets that each slave has received. After processing this information, the master decides the new NBC value in accordance to provide some soft guarantees for the delivery of the broadcasted packets and to minimize the number of redundant packet transfers.

3. Simulator Basics

Since the existing Bluetooth simulators do not fit into our research goal and scope, we have implemented our broadcasting simulator by following the standard mechanism for broadcasting and packet transmission in Bluetooth specifications [2].

3.1. Error Checking Mechanism

Different parts of a Bluetooth packet use different error correction and detection mechanisms, and therefore the relative locations of bit errors in a broadcasted Bluetooth packet with respect to the start of the packet, and the length of bit errors has extreme importance. A comprehensive discussion of the error protection mechanisms used in Bluetooth, FEC and CRC mechanisms, can be found in [2] and [7]. The $1/3$ FEC scheme requires adding two redundant bits for every single bit, and therefore can correct single errors occurring in a group of three consecutive bits. The $2/3$ FEC scheme uses Hamming Code protection, i.e. it can correct all single bit errors in a 15 bit block and can detect all double errors in the blocks, if $10/15$ shortened Hamming code is used.

A Bluetooth baseband packet consists of mainly three parts: an access code, a packet header, and the payload. In the access code, the expurgated code guarantees large Hamming distances (d_{min} = 14) between sync words based on different addresses. Pseudo-random noise is assumed to protect this section whose d_{min} = 14. Final 4 bits constitutes the trailer, which is a 4 bit pattern of either 1010 or 0101, and used for DC compensation. Thus, the errors on this part of a packet are going to be ignored in the simulator [4].

The header is protected by $1/3$ FEC, providing a code distance d_0=3. Due to whitening, the aggregate code distance used in a header is d_0=6, so the code is capable to correct all single and detect all quadruple errors.

For the remaining bits, protection depends on the packet type that is used. DH packets do not have any protection scheme applied on the data. Errors in DH packets can not be corrected, but they can be detected by using CRC bits added to the end of the packets. DM packets have $1/3$ FEC applied on their data bits.

3.2. Error Generation

The bit errors occuring on a radio channel and the protection scheme that is applied on the data affect the packet loss rate for the packets transmitted over that channel. Therefore, we need to be able to relate the packet loss rate that we will use in our simulator to the bit error rate of the simulated radio channel. The bit error rate will be an input to our simulator. After computing the packet loss rate based on BER, we can drop some of the broadcasted packets in a random manner to simulate a noisy radio channel. The dropping rate will be equal to the packet loss rate.

The analytical approach discussed in [3] clearly reflects the BER and Packet Loss Rate (PLR) relationship. For packet types that do not any have FEC protection, the packet loss rate p is related to BER and payload size s (in bits) with the following formula:

$$p = 1 - (1 - BER)^s \tag{1}$$

For packets with $2/3$ FEC protection, 15 bits are used to encode 10 bits of data, and this can correct one bit in every

15 bits. So the packet loss rate *p* becomes:

$$p = 1-((1-BER)^{15}+15*BER*(1-BER)^{14})^{s/15} \quad (2)$$

The second equation can be derived by taking conjugate of correctly received packet probability, which consists of independent events that 15 bit sub-frames have no errors or one correctable error. In our simulations, when the packet type is specified, our simulator calculates PLR from BER and payload size. It then decides if the packet is corrupted or not by using that probability and a uniform random variable. By this elegant way, we have established the BER and PLR relationship in our simulator, which is an important issue in simulation of erroneous channels.

3.3. Performance Analysis

We use two performance metrics to evaluate various settings of values for packet type and repetition count. These are throughput and reliability.

- Throughput: The effective data that can be transmitted over a unit time interval have extreme importance for efficiently utilizing the radio channel capacity (bandwidth) and allocating resources to multiple streams competing for the same channel. If we can maximize the effective throughput that an application can obtain, a user of the application can perceive a better quality. For example, if we know that we will have higher effective throughput for a real-time audio or video application, we can increase the sampling rate, the frame rate, or the resolution of frames. Or, for some pure data transfer applications, the transfer time will be decreased if the effective throughput can be increased. Throughput is our main performance metric and each packet type will be evaluated in terms of its effect on the throughput of a broadcast stream under different BER values.

- Reliability: Various applications may require different degrees of reliability in terms of correct delivery of baseband baroadcast packets to slaves from a master. For example, multimedia applications may tolerate packet losses, but the less is the packet loss rate, the better is the quality of the multimedia objects (audio packets or video frames) received at a receiver. On the other end, file download and some class of data dissemination applications can not tolerate missing data at a receiver. In general, we can say that it is important to minimize the packet loss rates without sacrifying much the bandwidth efficiency and application level throughput. Therefore, it is also important to observe the packet loss rates under various channel conditions and for different broadcasting parameters (N_{BC} and packet type), besides observing the effective throughput. For this reason, our simulator also measures the packet loss rates.

4. Simulation Results

In order to find the optimum packet types that provide best throughput for various BER and N_{BC} combinations, we simulated the Bluetooth broadcast mechanism model for various practical radio channel BER values. For each BER value that is fixed, we have evaluated the performance of each of the Bluetooth baseband packet types.

The simulations were done first for piconet models where each slave has different BER value. This is due to the fact that each slave is in a different location with respect to the master node and therefore has different noise and multipath characteristics. After our initial simulation results, we observed that the slave with the highest BER value affects the throughput dominantly and become the bottleneck. Therefore, we have shifted our attention to single slave analysis in which we assume a single BER value for all slaves connected to the master.

In our simulations, we first wanted to see the effect of BER of a Bluetooth radio channel on the effective throughput of Bluetooth broadcast applications. To observe this relationship, we implemented a simulation case in which the master node of a piconet re-transmits the same broadcast packet until the packet is correctly received by the slave (we are using a single slave analysis). Each re-transmission has a negative effect on the effective throughput. When a packet is successfully received by all slaves, the master continues transmitting the next broadcast packet. It is not very realistic for the master to know if the packet is received correctly by a slave, but our aim in this simulation case is to see the negative effect of BER on throughput assuming perfect feedback information. The master sends a total of 5 Mbits worth of broadcast data to slaves before the simulation ends. As a result, we have obtained application level throughput versus BER relationship, and average N_{BC} versus BER relationship. These results are shown in Figures 2, 3, and 4.

Figure 2 shows the performance (in terms of throughput) of using DM type packets under various channel conditions (BER values). At error rates below 10^{-3}, DM5 packet type (i.e. DM5 transmission mode) dominates in terms of throughput, which is expected since DM5 packet type has less overhead than DM3 and DM1 packet types. In a small BER range, from 10^{-2} to $2*10^{-2}$, DM3 has better throughput. At error rates above $2*10^{-2}$, DM1 remains as the only possible DM packet mode to transmit data as it has the shortest length (1 slot).

Figure 3 shows the performance of using DH type of packets under various channel conditions. A major differ-

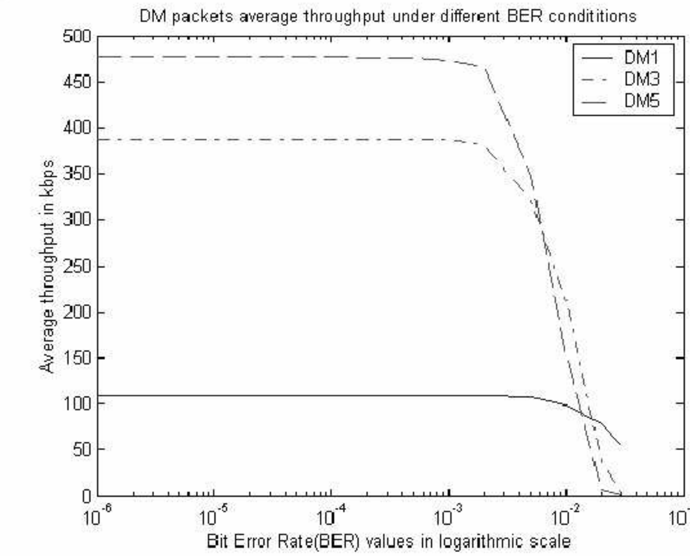

Figure 2. DM modes througput

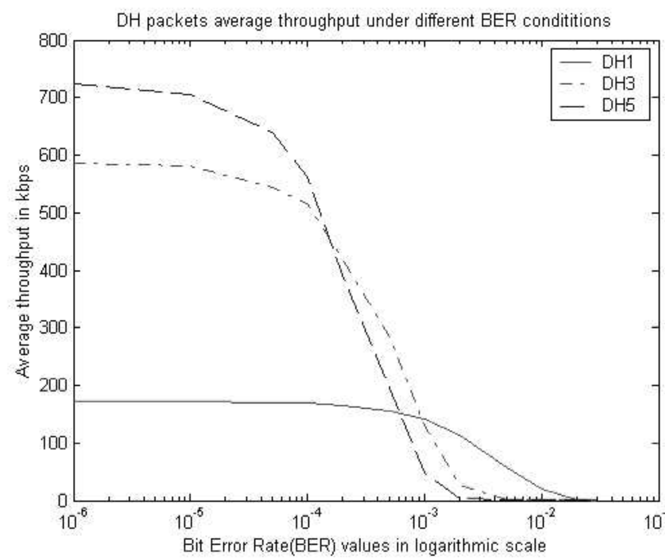

Figure 3. DH modes throughput

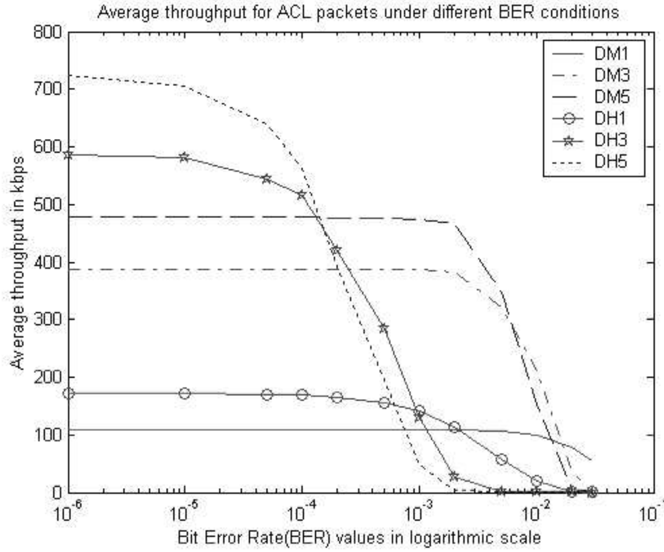

Figure 4. Throughput for all modes

ence from DM mode of transmission is the higher throughput in low error rates. This is expected because in noise-free channels redundant FEC protection bits are not needed. But at a BER of 10^{-2} or higher, transmission using DH packets is nearly impossible since these packets have no error correction schemes and the packet loss probability is much higher than transmission with DM packets.

We have made a final comparison between all packet types, and the result is shown in Figure 4. All these result so far reflect the throughput of a broadcast scheme where a slave can receive all transmitted information since we retransmit a packet until it is successfully received. We show a result curve for each packet type. One important result is that the throughput stays reasonable upto a threshold BER value, but after that it falls down quite fast. The threshold BER value depends on the packet type. A packet type that has error protection has a higher value for this threshold, which is what we have expected.

As a second step, the relationship between BER and average number of retransmissions is investigated. Figure 5 shows the results. What we can infer from the curves in Figure 5 is the importance of packet length and FEC mechanism on affecting the packet loss rate. The error tolerance of a DH5 packet is lowest compared to packets of other types. This is because a DH5 packet has the longest packet length (occupying 5 time-slots) and has no protection scheme. Packet types can be ordered with respect to their error tolerance as follows (from lowest tolerance to highest) : DH5, DM5, DH3, DM3, DH1 and finally DM1. We would like to underline the fact that DM1 packet type has the most reliability in terms of single transmission due to its small packet length and FEC protection.

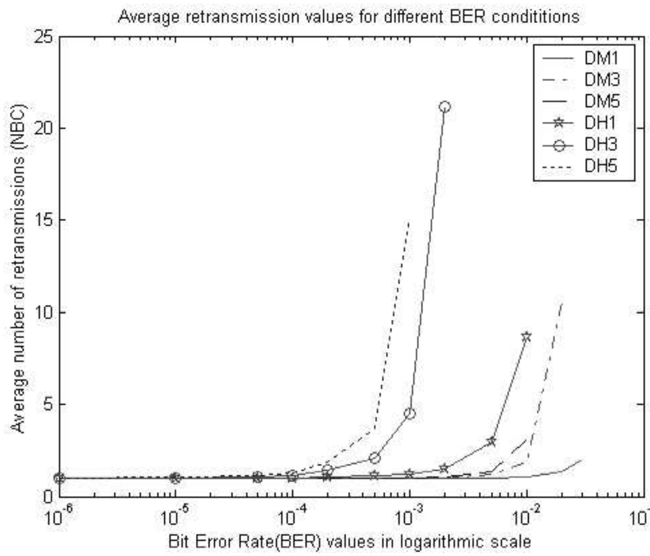

Figure 5. Averate retransmission count versus BER

As a next step, we wanted to see the effect of packet repetitions on reducing the packet loss rate (i.e. providing reliable transmission). For this simulation case, we have fixed the radio channel BER value. Our performance metric in this step is only reliability and it is calculated as the number of successfully received packets divided by the total number of transmitted packets. These results are shown in Figures 6 and 7. Figure 6 gives N_{BC} - Reliability relationship for a BER value of 10^{-4}, and Figure 7 gives N_{BC} - Reliability relationship for a BER value of 10^{-3}. As the channel BER increases, DH packets lose their ability to provide necessary reliability for a successful transmission. Only at very high values of N_{BC}, DH packets regain high reliability. Thus DM packets are more favorable in terms of reliability over DH packets, which was eminent from the protection mechanism they have been using. These two figures give suggestions about how to tune the N_{BC} parameter for a required reliability level when the packet type parameter is fixed and channel conditions remain stationary at a BER value of 10^{-4} or 10^{-3}.

Our most prominent contribution is presented in Figures 8, 9, 10, and 11. For these simulation cases, we fix the reliability level we expect from the broadcasting model. We want to observe the maximum attainable effective throughput for all packet types and different BER values. Based on our observations, we want to determine the optimal packet types and repetion counts for different channel conditions.

In wireless networks, since channel error rates are considerably higher compared to wired networks, 99.9% reliability can be taken as the basis for packet transmission re-

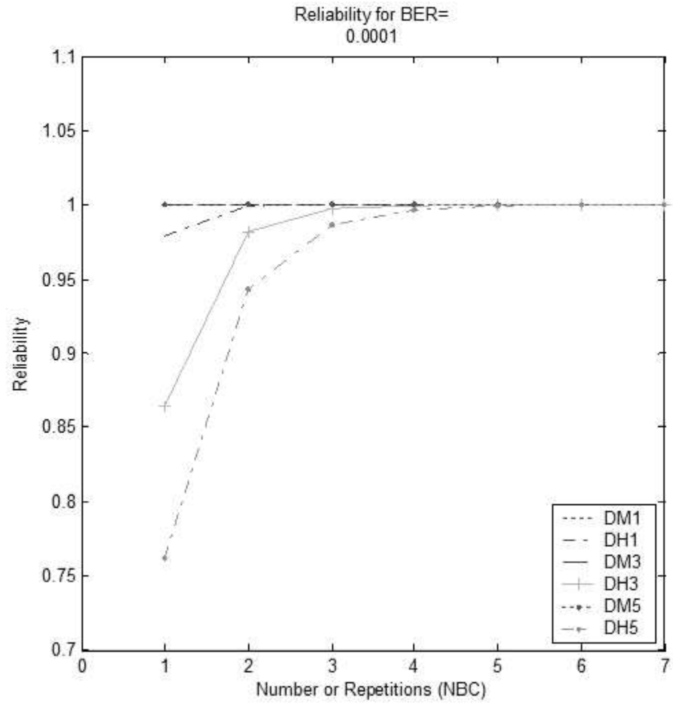

Figure 6. Reliability versus N_{BC} for BER of 10^{-4}

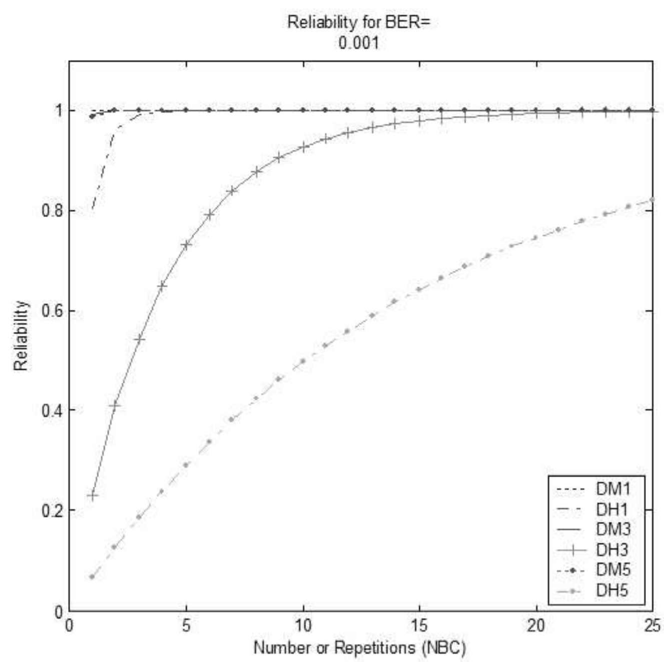

Figure 7. Reliability versus N_{BC} for BER of 10^{-3}

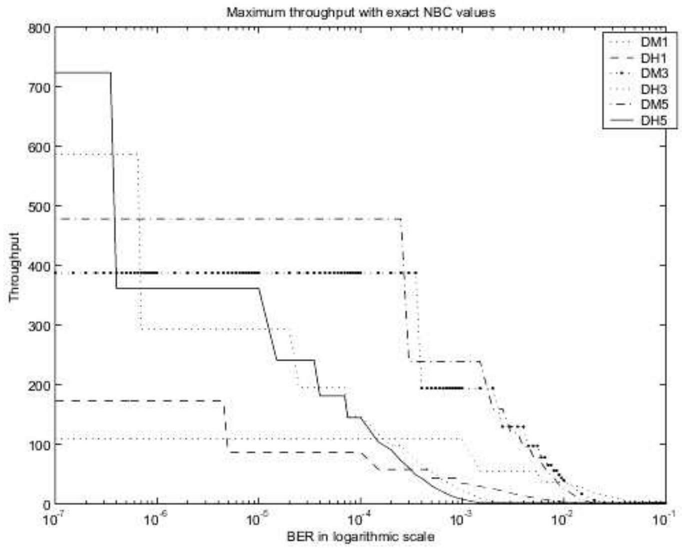

Figure 8. Maximum throughput for 99.9% reliability

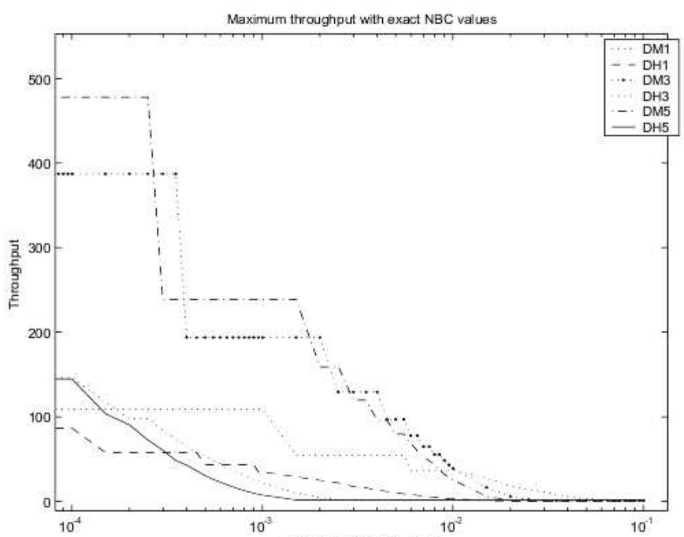

Figure 9. Detailed view of throughput for moderate BER

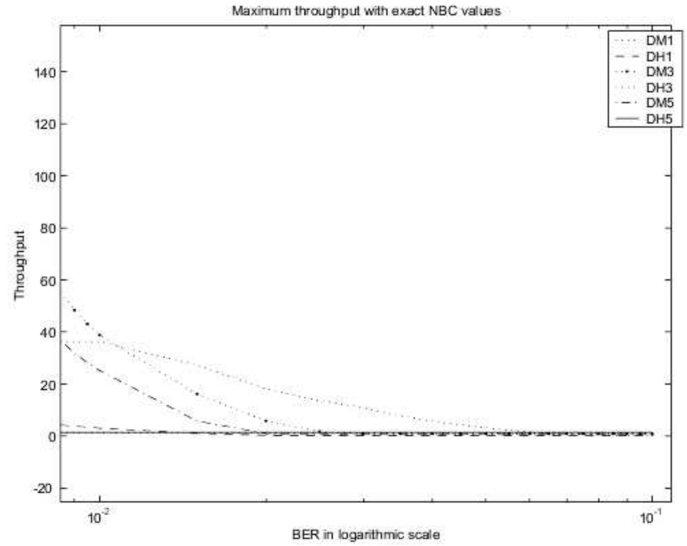

Figure 10. Detailed view of throughput for high BER

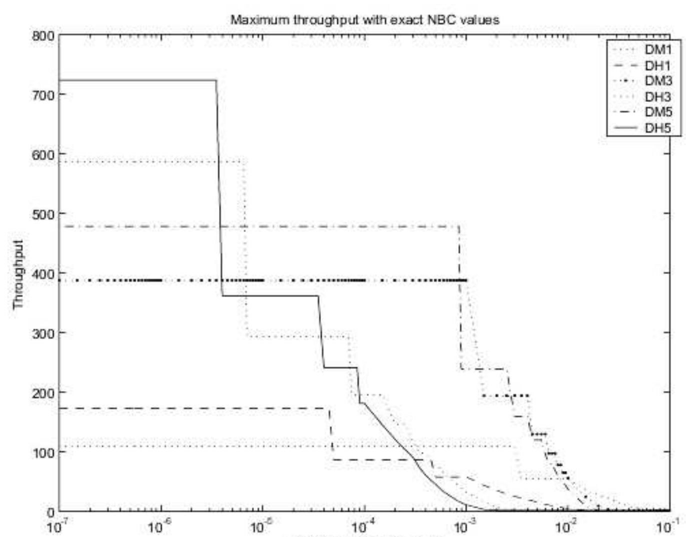

Figure 11. Maximum throughput for 99% reliability

Bit Error Rate	Optimum Mode Selection	N_{BC}	Throughput (kbps)
[BER <7.5x10^{-7}]	DH5	1	723.00
[7.5x10^{-7}, 10^{-6}]	DH3	1	585.60
[10^{-6}, 10^{-4}]	DM5	1	477.80
[10^{-4}, 5x10^{-4}]	DM3	1	387.30
[5x10^{-4}, 5.5x10^{-4}]	DM5	2	238.90
[5.5x10^{-4}, 2.5x10^{-3}]	DM3	2	193.50
[2.5x10^{-3}, 3x10^{-3}]	DM5	3	159.30
[3x10^{-3}, 5x10^{-3}]	DM3	3	129.00
[5x 10^{-3}, 6.5x10^{-3}]	DM3	4	96.80
[6.5x10^{-3}, 7x10^{-3}]	DM3	5	77.40
[7x10^{-3}, 8x10^{-3}]	DM3	6	64.50
[8x10^{-3}, 9.5x10^{-3}]	DM3	7	48.40
[9.5x10^{-3}, 10^{-2}]	DM3	8	45.00
[10^{-2}, 1.5x10^{-2}]	DM1	4	27.20
[1.5x10^{-2}, 2x10^{-2}]	DM1	5	21.76
[2x10^{-2}, 2.5x10^{-2}]	DM1	7	15.54
[2.5x10^{-2}, 3x10^{-2}]	DM1	9	12.10
[3x10^{-2}, 3.5x10^{-2}]	DM1	13	8.35
[3.5x10^{-2}, 4x10^{-2}]	DM1	17	6.40
[4x10^{-2}, 4.5x10^{-2}]	DM1	23	4.73
[4.5x10^{-2}, 5x10^{-2}]	DM1	31	3.51
[5x10^{-2}, 5.5x10^{-2}]	DM1	43	2.53
[5.5x10^{-2}, 6x10^{-2}]	DM1	61	1.78

Table 2. Optimum packet types & N_{BC} values for 99.9% reliability in all BER range

liability. That is, only one packet is allowed to be lost in a group of 1000 packets. Therefore we have fixed the reliability level at 99.9%. We run our simulator for all practical BER ranges a Bluetooth piconet can face, and found the minimum N_{BC} value that satisfies this 99.9% reliability level. And this simulation is repeated for all packet types. Figure 8 shows the maximum achieved throughput versus BER for different packet types. Figures 9 and 10 reveals similar information, but focuses on a smaller range on BER axis.

When Figures 4 and 8 are compared, we can see that we have sharp falls in the effective throughput at some certain BER values. The reason for this behaviour is the following. While broadcasting is done at specific N_{BC} value, a slight increase in BER may cause sometimes the reliability constraint to be not satisfied anymore with the same N_{BC} value; hence the N_{BC} value needs to be incremented in this case, and this causes a sharp decrease in effective throughput.

Figure 9 focuses on the BER range between 10^{-4} and 10^{-1}. In this range, all applications that use DH packets

	N_{BC}	R%	T	N_{BC}	R%	T
	DH5			DM5		
10^{-5}	2	100.0	361.6	1	100.0	477.87
10^{-4}	4	100.0	180.8	1	100.0	477.87
10^{-3}	>50	94.59	14.46	2	100.0	238.93
0.01	>50	0.000	14.46	13	100.0	36.76
0.03	>50	0.000	14.46	>50	1.071	9.56
	DM3			DM1		
10^{-5}	1	100.0	387.2	1	100.0	108.8
10^{-4}	1	100.0	387.2	1	100.0	108.8
10^{-3}	2	100.0	193.6	1	99.97	108.8
0.01	8	99.80	48.4	3	100.0	36.266
0.03	> 50	29.01	7.744	10	99.97	10.88
	DH3			DH1		
10^{-5}	2	100.0	292.8	1	99.82	172.8
10^{-4}	4	100.0	146.6	2	99.95	86.4
10^{-3}	20	100.0	29.28	4	99.82	43.2
0.01	> 50	0.000	11.712	50	99.65	3.927
0.03	> 50	0.000	11.712	>50	6.825	3.456

Table 3. Several reliability levels and throughtput values for different BER values

will have poor throughputs. There are some sharp falls in throughput for packet types DM5 and DM3 until BER gets increased to 10^{-2}. That is also an expected result since longer packet lengths are affected more drastically with increasing BER.

For BER above 10^{-2}, all other packet types except DM1 lose their ability to provide reliable transmission. DM1 packets can still be used and can provide acceptable throughputs in the neighborhood of BER value of 10^{-2}, and can survive till a BER value of $5x10^{-2}$. Figure 10 provides our results for high BER values in a detailed fashion.

When we relax the reliability constraint to 99%, we can see that the effective throughput increases for all the BER ranges, as expected. Figure 11 is more suitable for loss-tolerant applications to used as a guideline in maximizing the throughput in broadcasting.

Table 2 and 3 constitutes the final output of our simulations and can be used as an input to adaptive packet type and N_{BC} determination algorithms.

5. Conclusion

Bluetooth is a new technology and the Bluetooth broadcasting scheme specified in Bluetooth standards [2] is not analyzed yet throughly. In this paper, we analyze the current Bluetooth broadcasting scheme and provide results that can be used to improve broadcasting throughput and reliability. We used previously covered methods of reliability calculations in Bluetooth to come up with a novel method to create an adaptive packet type and repetition count (N_{BC}) selection scheme. Our packet type scheme succesfully improves the performance of current Bluetooth reliable broadcasting scheme under different radio channel conditions.

An important parameter of the current Blueooth broadcasting scheme is the N_{BC} value that is determined by the master of a piconet. We tabulate in Table 2 the optimal packet types and N_{BC} values to be used at Bluetooth baseband layer while transferring broadcast application traffic over noisy Blueooth radio channels with various BER values. Based on this information, the baseband layer can adapt to BER variations to achieve a good trade-off between effective throughput and reliability.

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