Evaluating and Improving Bluetooth Piconet Performance over Nakagami-*m* Fading Channels

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Abstract

Bluetooth is a promising wireless technology designed for short-range ad hoc networks. This paper addresses issues related to Bluetooth performance in Nakagami-m fading channels. This distribution can model different fading intensities through parameter m. We evaluate the throughput and the packet loss rate of Bluetooth links using asynchronous packets. Relations between packet error rate and node distances are then derived, and a new piconet scheduling algorithm based on the estimated channel state information is then proposed. This polling scheme detects fading conditions and avoids transmission in bad channel conditions. The best strategy is defined using the received signal-to-noise ratio and the Nakagami fading parameter m. Simulation results demonstrate the algorithm performance for different traffic conditions.

1. Introduction

Bluetooth is emerging as an important standard [1] for wireless personal area networks (WPANs). Rather than competing with wireless local area networks (WLANs), Bluetooth adds new applications and usage scenarios and will operate in conjunction with WLANs. It operates in the 2.4 GHz ISM band employing a frequency-hopping spread spectrum (FHSS) technique. The transmission rate is up to 1 Mbps, using GFSK modulation. The devices can communicate with each other forming a network with up to eight nodes, called piconet. Within a piconet, one device is assigned as a master node and the others devices act as slave nodes. Devices in different piconets can communicate using a structure called *scatternet*. The channel is divided in time slots of 625 μs. A time-division duplex (TDD) scheme is used for full-duplex operation. For data transmission Bluetooth employs seven asynchronous packets types [1].

A signal passed over a wireless channel is affected by path loss, narrow and wideband fading, and co-channel interference. The impulse response of the channel is time variant and depends on the particular location. Estimations can be made with statistical models. The throughput of Bluetooth links using asynchronous packets was investigated in [2] for the Rayleigh fading channel. This work focuses on the performance of Bluetooth links in Nakagami fading channels [3]. The Nakagami-*m* distribution spans, via the fading parameter *m*, the widest range of multipath distributions. It has excellent agreement with measured fading and scintillation data over a wide range of frequency bands. The Nakagami distribution has the property that it includes the one sided Gaussian distribution (m=0.5) and the Rayleigh distribution (m=1) as special cases. Using m<1 or m>1 we obtain fading intensities more and less severe than Rayleigh, respectively. When $m \to \infty$, the Nakagami fading converges to the AWGN channel. For $m \geq 1$, a mapping between the fading parameter *m* and the Rician factor K allows a closely approximation to the Rice distribution. One important issue in Bluetooth networks is the interference caused by other Bluetooth nodes and devices that operate in the same band, such as cordless phones, microwave ovens and the IEEE 802.11b standard for WLANs. The Nakagami parameter *m* indicates the quality of the channel, considering both fading and interference. In the proposed channel model we also consider the log-distance path loss model [4]. We evaluate the packet error rates in the forward and reverse channels as a function of the distance between devices in the network. The main motivation of the analysis of Bluetooth in Nakagami channels is how to use this information to improve network performance. A new piconet scheduling algorithm using the parameter *m* is proposed.

This paper is structured as follows: Section II presents the throughput and packet error rate evaluation for Nakagami-*m* fading channels. In section III, the log-distance path loss model is applied in order to relate the packet error rates in the forward and reverse channels with the distance between devices. Section IV shows a scheduling algorithm using channel state information and simulation results are shown in Section V. Finally, conclusions are drawn in section VI.

2. Throughput evaluation in Nakagami-*m* fading channels

In order to investigate the throughput of Bluetooth links in the presence of Nakagami-*m* fading we follow the derivation used in [2]. The throughput can be computed using the packet retransmission probability. There are five packet retransmission events:

A: the destination fails to synchronize with the access code of the forward packet.

B: the header of the forward packet is corrupted after the triple redundancy code is decoded.

C: the payload of the forward packet is corrupted after the Hamming code is decoded, causing the CRC check to fail.

D: the source is unable to synchronize with the access code of the reverse packet.

E: the header of the reverse packet is corrupted.

Let X be an event. $\overline{X}$ denotes the complement of event X and P[X] is the probability of event X. The packet retransmission probability is then given by

$$P_r(\bar{\gamma}_f,\bar{\gamma}_r) = 1-\int_0^\infty f(\gamma_f)P[\overline{A}]P[\overline{B}]P[\overline{C}]\,d\gamma_f \cdot \int_0^\infty f(\gamma_r)P[\overline{D}]P[\overline{E}]\,d\gamma_r \qquad (1)$$

where $\bar{\gamma}_f$ and $\bar{\gamma}_r$ are the average received signal-to-noise ratios (SNR) in the forward and reverse channels and $f(\gamma_f)$ and $f(\gamma_r)$ are the probability density functions (*pdf*) of γ_f e γ_r. The average received SNR is a function of the path loss model or distance between nodes. The analytical expressions for the retransmission probabilities, $P[\cdot]$, were derived in [2]. From equation (1) we can define the packet error rate (PER) of the forward channel, $PER_f(\bar{\gamma}_f)$, and reverse channel, $PER_r(\bar{\gamma}_r)$,

$$PER_f(\bar{\gamma}_f) = 1-\int_0^\infty f(\gamma_f)P[\overline{A}]P[\overline{B}]P[\overline{C}]\,d\gamma_f\ , \qquad (2)$$

$$PER_r(\bar{\gamma}_r) = 1-\int_0^\infty f(\gamma_r)P[\overline{D}]P[\overline{E}]\,d\gamma_r\ . \qquad (3)$$

The data rate *R* is given by

$$R = \frac{K}{D\cdot N\cdot 625\cdot 10^{-6}}, \qquad (4)$$

where *D* is the number of occupied slots per transmission including the reverse packet, *K* is the number of data bits in the packet and *N* is a random variable representing the total number of times a particular packet must be transmitted. The average throughput is the expected value of *R* with respect to *N*,

$$\overline{R} = E\{R\} = \sum_{N=1}^{\infty}\left[1-P_r(\bar{\gamma}_f,\bar{\gamma}_r)\right]\cdot\left[P_r(\bar{\gamma}_f,\bar{\gamma}_r)\right]^{N-1}\cdot R \qquad (5)$$

The Nakagami-*m* probability density function [3] is given by

$$f(\gamma) = \frac{m^m\gamma^{m-1}}{\Gamma(m)\,\bar{\gamma}^m}\cdot\exp\left(-\frac{m\gamma}{\bar{\gamma}}\right), \qquad m\geq 0.5 \qquad (6)$$

Substituting (6) in (1), we can evaluate the throughput using (5) for different values of *m*. It was assumed a GFSK modulation index *h*=0.32 and a threshold *T*=65. The parameter *T* is the minimum number of bits from the access code that must be properly demodulated for synchronization.

Figures 1 and 2 show the throughput for packets DM1 and DH5 for *m*=1, *m*=0.5, *m*=0.75 and *m*=1.5. Figures 3 and 4 show the throughput for packets DM1, DH1, DM5 and DH5 as a function of PER_f and PER_r for *m*=1.5.

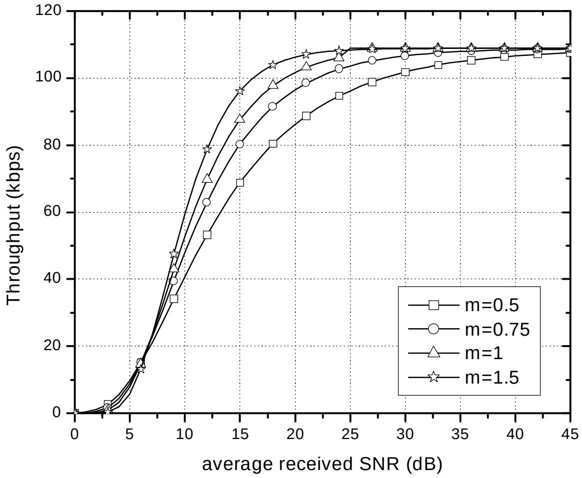

Figure 1. Performance of DM1 packet

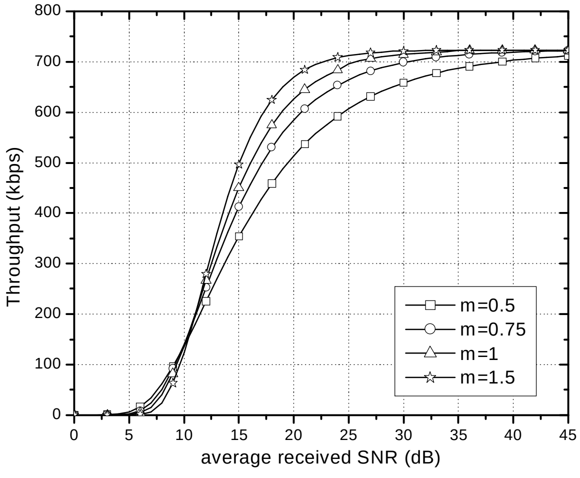

Figure 2. Performance of DH5 packet

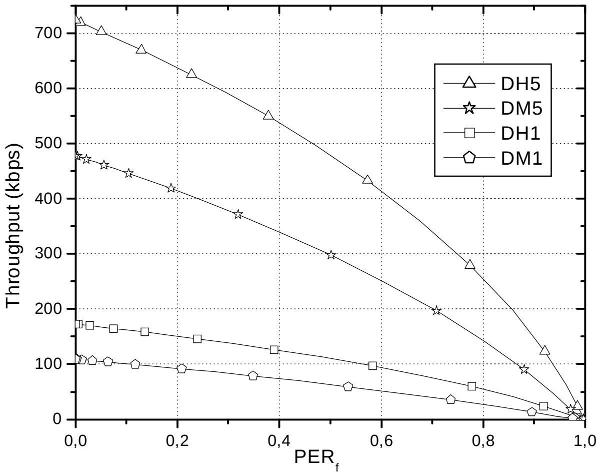

Figure 3. Throughput versus PER$_f$ for $m = 1.5$

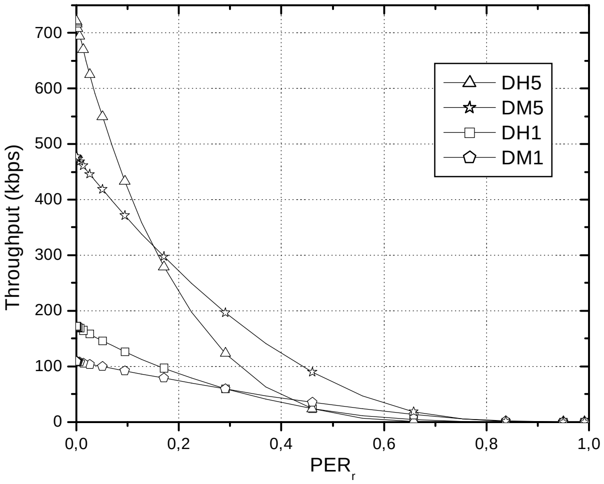

Figure 4. Throughput versus PER$_r$ for $m = 1.5$

3. Channel path loss model

In our study we apply the log-distance path loss model [4] to predict the mean received power for class 1 devices, which can cover theoretically a distance range up to 100 meters requiring power control. However, in the path loss computation it was always assumed the maximum transmitted power. Although only the results for class 1 devices are presented here, the equations can be used for the other classes as well. The Bluetooth transceiver requires a minimum received power of –70 dBm. The log-distance model [4] is given by

$$\overline{PL}(\text{dB}) = \overline{PL}(d_0) + 10 \cdot n \cdot \log\left(d / d_0\right), \tag{7}$$

where n is the path loss exponent which indicates the rate the path loss increases with distance, d is the transmitter-receiver separation and d_o is a reference distance. The value of n can be selected based on the environment where the devices will operate. The reference path loss $\overline{PL}(d_0)$ is computed using the free space path loss model [4],

$$P_r(d) = P_t \frac{\lambda^2}{(4\pi)^2 d^2}, \tag{8}$$

where P_t is the transmitted power, d is the distance and λ is the wavelength. The wavelength can be evaluated by $\lambda = c/f$, where c is the speed of light and f is the carrier frequency (2.4 GHz for Bluetooth). The received power, P_r, is given by $P_r = P_t - \overline{PL}$. With R being the transmission rate (1 Mbps for Bluetooth) and N_0 the one-sided noise power spectral density, the average received signal-to-noise ratio is

$$SNR = \frac{E_b}{N_0} = \frac{P_r}{R \cdot N_0}. \tag{9}$$

The thermal noise floor for a 1 MHz bandwidth is -114 dBm. Assuming a Bluetooth receiver with noise figure of 23 dB [5] we get a noise power $N = N_0 B = -91\text{dBm}$.

Applying the log-distance model we evaluated the average received SNR for different transmitter-receiver separations. This result is shown in Figure 5 for a path loss exponent $n = 3$, $n = 3.5$ and $n = 4$. The dashed line indicates the minimum required received power of $-70\,\text{dBm}$ (receiver sensitivity). The intersection of this line with the SNR curves represents the maximum transmitter-receiver separation.

Figures 6 and 7 also relate the transmitter-receiver separation with the PER for the asynchronous packets. For the reverse packet (ACK) the PER axis represents the PER_r probability. For packets DM1, DM5, DH1 and DH5 the PER axis represents the PER_f probability.

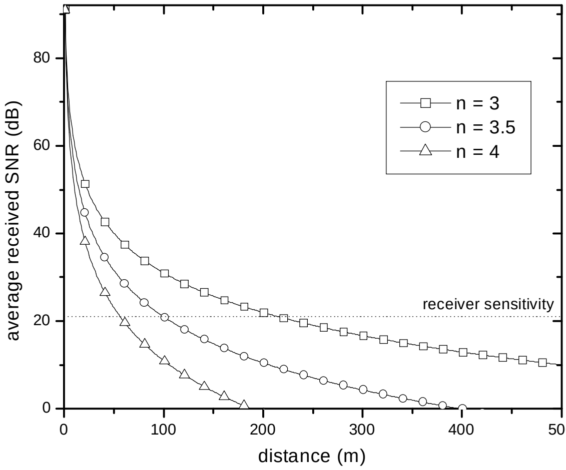

Figure 5. Signal-to-noise ratio versus distance

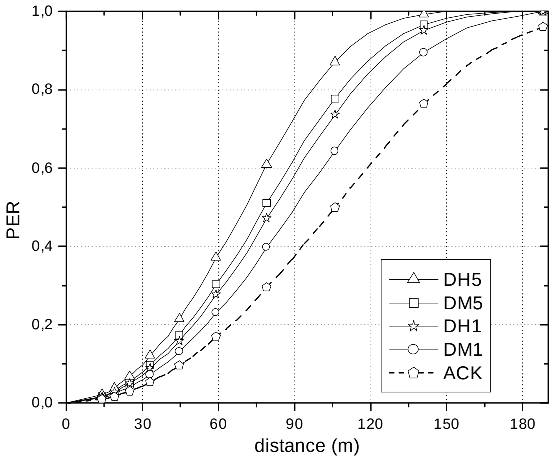

Figure 6. PER versus distance, *m=0.5*, *n=4*

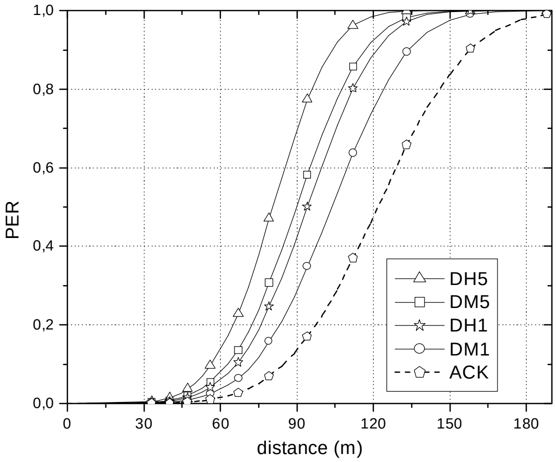

Figure 7. PER versus distance, *m=1.5*, *n=4*

4. Bluetooth piconet scheduling using channel state information

4.1. Related work on piconet scheduling

In a Bluetooth piconet, the channel access is controlled by the master. A slave can send a packet only if it receives a polling packet from the master. The master transmits packets to the slave in even slots while the slave transmits packets to the master in odd slots. Thus, Bluetooth is a master driven TDD standard and this poses several challenges in scheduling algorithms since there could be a waste of slots if only the master or the slave has data to send. Recently, many schemes have been proposed in the literature for piconet and scatternet scheduling.

In [6], several polling schemes are compared. In the round robin scheme a fixed cyclic order is defined and a single chance to transmit is given to each master-slave queue pair. The exhaustive round robin (ERR) also uses a fixed order but the master does not switch to the next slave until both the master and the slave queues are empty. The main disadvantage of the ERR is that the channel can be captured by stations generating traffic higher than the system capacity. A limited round robin (LRR) scheme that limits the number *t* of transmissions can solves this problem. A new scheme called LWRR (limited and weighted round robin) with weights dynamically changed according to the observed queue status is also presented in [6]. Other works about piconet scheduling consider QoS issues in Bluetooth, such as [7] and [8]. The results in [6], [7] and [8] do not consider any loss model for the wireless channels.

In [9], a scheduling policy based on slave and master queues is shown. The master-slave pairs are distinguished based on the size of the Head-of-the-Line (HOL) packets at the master and slave queues. Then, the pairs are classified in three classes according to slot waste. This information is used in the HOL K-fairness policy (HOL-KFP) [9]. When the authors introduced channel errors, the HOL-KFP had its performance reduced. An extension for HOL-KFP called wireless adapted-KFP (WAKFP) was proposed and the results indicate that a better performance is achieved in the presence of channel errors [9].

In [10] an algorithm called Bluetooth Interference Aware Scheduling (BIAS) is presented that uses a channel estimation procedure in order to detect the presence of other wireless devices in the same band (such as other Bluetooth or IEEE 802.11b devices). The scheduling algorithm will avoid packet transmission in frequencies that have a high bit error rate (BER), called bad frequencies. This fact reduces the packet loss due to interference of other near devices. Few of the scheduling schemes presented here consider a loss model for the wireless channel. The works in [9] and [10] use a simple error model. In this paper we use the Nakagami fading for the transmission channel and propose a new scheduling algorithm based on channel state information.

A channel estimation procedure is based on measurements conducted in the channel in order to determine the presence of interference and fading. There are several methods available, like BER, Received Signal Strength Indicator (RSSI), packet loss rate and negative ACKs. In this work we consider two parameters to obtain the channel state information and that have to be estimated: the average received signal-to-noise ratio (SNR) and the Nakagami fading parameter *m*. In [11] is proposed an online SNR estimator for generalized fading channels, which does not require the transmission of known training symbols. It is based on a block observation of the demodulated symbols. In [11], the values of SNR had a good accuracy for an analyzed block size of 5000 bits and a reasonable accuracy for 1000 bits. This technique could be as well applied to the Bluetooth link SNR estimation with a low computational cost.

Also many estimators have been proposed in the literature for the parameter *m*. In [12], Cheng and Beaulieu proposed a family of new moment-based estimators, using both integer and non-integer sample moments. These estimators are efficient for moderate number of samples and are suitable for implementations of low complexity where computation of roots is undesirable.

4.2. Proposed scheduling algorithm

Therefore, the condition of the channel can affect the performance of the piconet and the polling strategy. In mobile environments, the status of the wireless channel changes very rapidly and this means that a better performance will be achieved if a node is polled at the moment it has a good channel condition and not polled when the conditions are bad. Since Bluetooth is a technology designed for WPANs, channels errors due to mobility and interference of other devices are very common. A good scheduling algorithm must consider these issues.

We propose an algorithm – called Bluetooth Channel State Scheduling (BCSS) algorithm – that uses the channel state information for piconet scheduling. The values of the fading parameter *m* and the SNR can be easily estimated. The master will carry out the estimations using the data packets exchanged with the slaves. Every time a master receives a packet, the values of *m* and SNR for that link will be updated. Since this task does not require extra information to be exchanged between the master and the slaves, no extra time is added to the scheduling policy. The estimation accuracy of *m* and SNR will be low at the beginning of the transmission, when few packets were exchanged and the amount of bits to be analyzed is not significant. However after a few time slots transmission, the estimated values will quickly converge to the true values. In the new scheduling policy, the master will poll only the slaves that are above a certain threshold for *m* and SNR, indicating a good channel state. The slaves that are below the threshold, indicating that they are at a bad channel state, will be jumped for at most t_j times. It can be seen that if the channel state is always good the algorithm is reduced to a round robin policy.

5. Simulation results

We developed an event driven simulator in C++ to compare the BCSS algorithm with round robin and ERR strategies. The effects of Nakagami fading are simulated using the models described in the previous sections. A Poisson traffic source was assumed for the traffic generation in each piconet node.

In the first simulation scenario we investigate the influence of the fading parameter *m* in a round robin scheduling. It consists of a piconet with a master and 7 slaves separated by a distance *d* from the master (using class 3 devices). The distance is related to the signal-to-noise ratio using a path loss exponent $n = 4$. The graphic of Figure 8 shows the average delay for this scenario for three different values of *m*, using DM1 packets. In this scenario all nodes have the same traffic conditions. The parameter λ is the mean arrival rate in packets per time slot. The Poisson distribution is used to generate traffic in the 14 queues. Figure 8 shows that the state of the channel has great influence in the average delay of the piconet, affecting the performance of the network.

In the second simulation scenario a piconet with the master and 4 slaves is considered. Figures 9 and 10 compare the average delay for different traffic conditions and DM1 packets using round robin, ERR and BCSS algorithm, for distances of seven and ten meters. In the BCSS algorithm we choose t_j=6 and a threshold *m*=1. This means that only the slaves with *m* greater than one will be polled, and the others will be jumped for at most six times. The traffic is the same in the master and the slave queues. In the simulation we assume that the channel conditions are changing every two rounds of the polling scheme. From Figures 9 and 10 we note that the BCSS algorithm improves its performance when the traffic is high. For low traffic, ERR has the best performance. In [6] and [13] was also concluded that the exhaustive service (ERR) does not have good performance under high traffic.

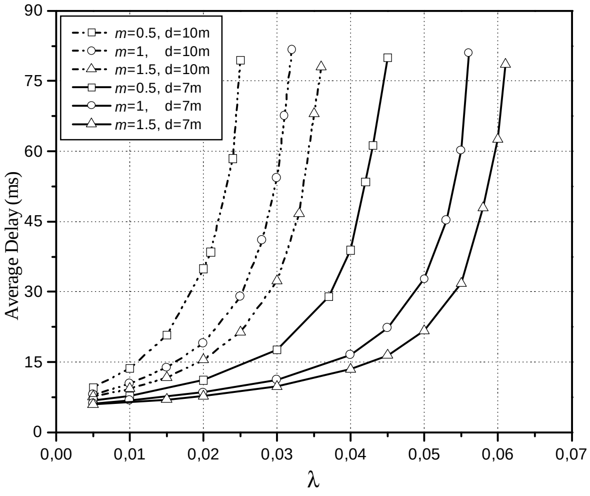

Figure 8. Average delay for different values of *m*

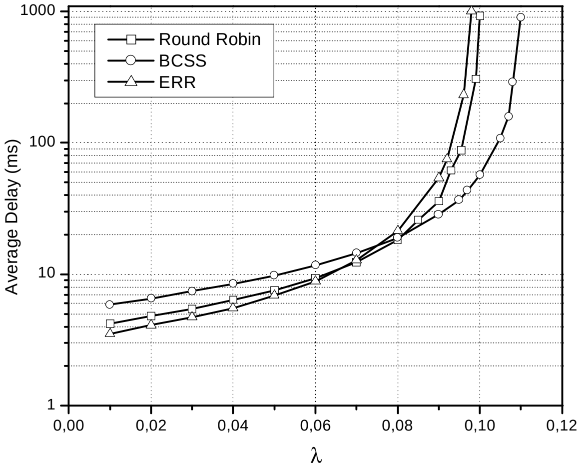

Figure 9. Average delay for *d* = 7m

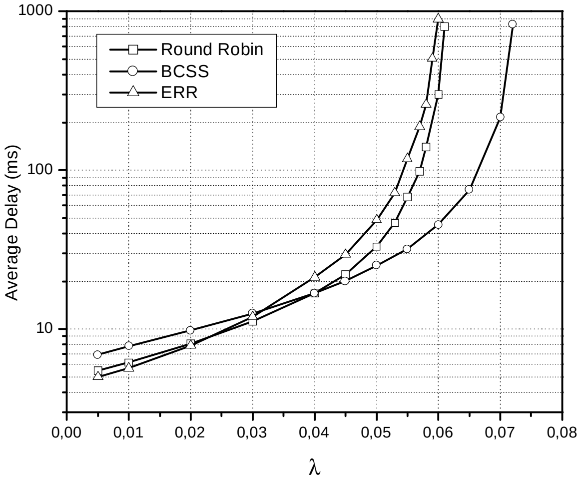

Figure 10. Average delay for *d* = 10m

6. Conclusions

This paper analyzed the performance of Bluetooth in Nakagami-*m* fading channels. This distribution allows a better channel characterization for mobile and wireless communications. The throughput of Bluetooth links using asynchronous packets was investigated. Scheduling algorithms were studied in the presence of errors and a new piconet scheduling algorithm based on the estimation of the channel state using the signal-to-noise ratio and the Nakagami fading parameter *m* was proposed. The BCSS algorithm is considerably efficient for high traffic loads if the channel conditions change frequently. These variations in channel conditions are present in many applications of Bluetooth technology in mobile and interference-prone environments. The BCSS algorithm can be combined with other scheduling policies to improve their performance. This work can be extended to evaluate the performance of the proposed algorithm under different traffic sources, such as FTP, HTTP and voice. Our future works include improvements to the intra-piconet scheduling policy and implementation of an inter-piconet scheduling scheme for scatternets. The parameter *m* and the SNR can also be used for other important issues in Bluetooth, like scatternet formation, routing and energy saving techniques.

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