Bluetooth Network Performance in Nakagami-m Fading Channels

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Abstract: The Bluetooth standard is considered a promising technology for implementing ad-hoc networks. This paper addresses issues related to Bluetooth performance 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 is investigated. Useful relations between packet error rate and node distances are derived. These results can be used as benchmarks for performance analysis or incorporated into Bluetooth network simulation tools. As an example, we evaluate by computer simulation the performance of a scatternet in a Nakagami fading scenario.

Key Words: Bluetooth, Nakagami-m fading, wireless networks.

1. INTRODUCTION

Bluetooth is emerging as an important standard [1] for short range and low-power wireless communication. It operates in the 2.4 GHz ISM band employing a frequency-hopping spread spectrum technique. The transmission rate is up to 1 Mbps, using GFSK (Gaussian Frequency Shift Keying) modulation. The Bluetooth MAC protocol is designed to facilitate the construction of ad-hoc networks. 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 acts as slaves 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]. All packets use cyclic redundancy check (CRC) codes and retransmission strategy, except the packet type AUX1, where specific error control strategies can be applied [2]. The packet structure is formed by an access code (72 bits), a header (18 bits) and a variable length payload. The header is protected by a (3,1) repetition code, which is capable of correcting only one error. The payload employs a CRC code for error detection and is also protected by a Hamming code (15,10) in packets DM1, DM3 and DM5. The Bluetooth devices are classified in three power classes [1]. The class 3 is a typical Bluetooth device with an output power of 0 dBm. The class 1 operates with a maximum output power of 20 dBm and can cover ranges up to 100 meters. The class 1 makes possible the formation of scatternets for application in telemetry systems and sensor networks.

The throughput of Bluetooth links using asynchronous packets was investigated in [3] for the additive white Gaussian noise (AWGN) channel and for the Rayleigh fading channel. In this work we extend the results presented in [3] in order to investigate the performance of Bluetooth links in Nakagami fading [4] channels. This distribution allows a better characterization of real channels. Through the parameter *m* we can adjust different fading conditions. For m=1 we get the Rayleigh distribution. Using m<1 or m>1 we obtain fading intensities more and less severe than Rayleigh, respectively. In the proposed channel model we also consider the log-distance path loss model [5]. We evaluate the packet error rates in the forward and reverse channels as a function of the distance between devices in the network. These results are incorporated into the simulation software Blueware [6] in order to evaluate scatternet performance.

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 [3]. 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.

Denoting $\overline{A}$ the complement of event *A*, $P[A]$ the probability of event *A*, and so on, the packet retransmission probability is given by

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

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 [3]. From equation (1) we can define the packet error rate (PER) of the forward channel, $PER_f(\bar{\gamma}_f)$, and reverse channel, $PER_r(\bar{\gamma}_r)$,

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

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

The data rate *R* is given by

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

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*,

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

The Nakagami-*m* probability density function [4] is given by

$$f(\gamma) = \frac{m^m\gamma^{m-1}}{\Gamma(m)\,\bar{\gamma}^m}\cdot\exp(-\frac{m\gamma}{\bar{\gamma}}), \qquad m \geq 0{,}5 \tag{6}$$

Substituting equation (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*=0.5. For a given throughput value we read from Figures 3 and 4 the packet error rates associated with the forward and reverse links.

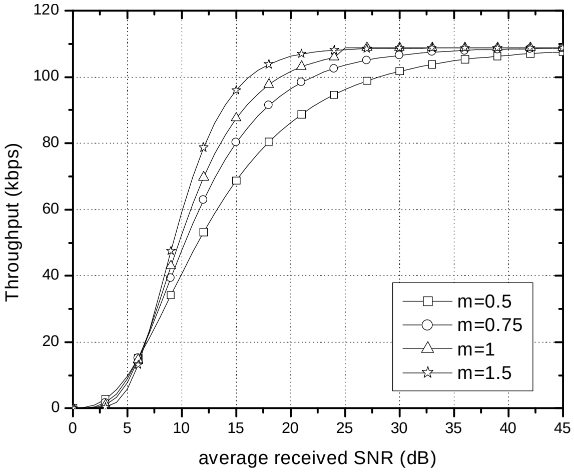

Figure 1 - Performance of DM1 packet

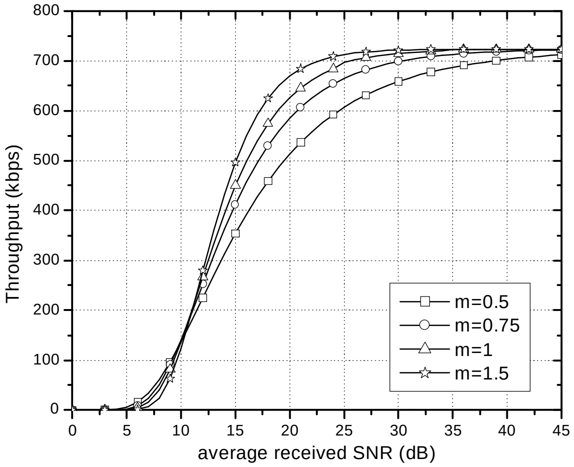

Figure 2 - Performance of DH5 packet

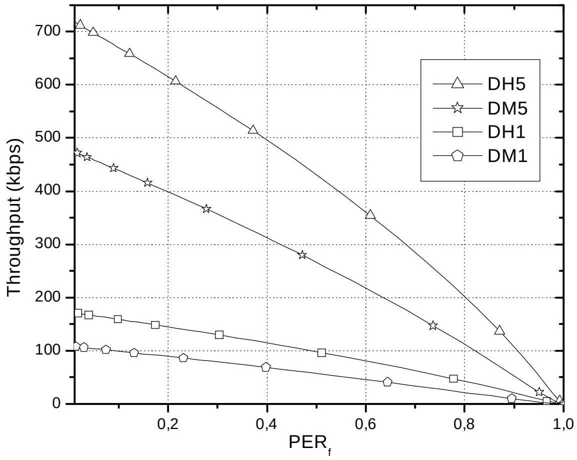

Figure 3. Throughput versus PER$_f$ for $m = 0.5$

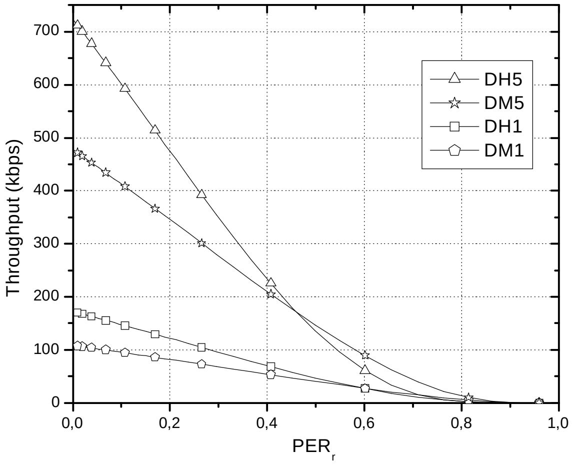

Figure 4. Throughput versus PER$_r$ for $m = 0.5$

3. PATH LOSS MODEL

In our study we apply the log-distance path loss model [5] to predict the mean received power for class one devices, which can cover theoretically a distance range up to 100 meters. A power control is required for class one devices. However, in the path loss computation it was always assumed the maximum transmitted power. The Bluetooth transceiver requires a minimum received power of –70 dBm. The log-distance model [5] is given by

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

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 [5],

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

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 $P_r = P_t - \overline{PL}$. Thus, the average received signal-to-noise ratio is $SNR = E_b / N_0 = P_r (R \cdot N_0)$, where R is the transmission rate (1 Mbps for Bluetooth) and N_0 is the one-sided noise power spectral density. The thermal noise floor for a 1 MHz bandwidth is –114 dBm. Assuming a Bluetooth receiver with noise figure of 23 dB [7] 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 dBm (receiver sensitivity). The intersection of this line with the SNR curves represents the maximum transmitter-receiver separation.

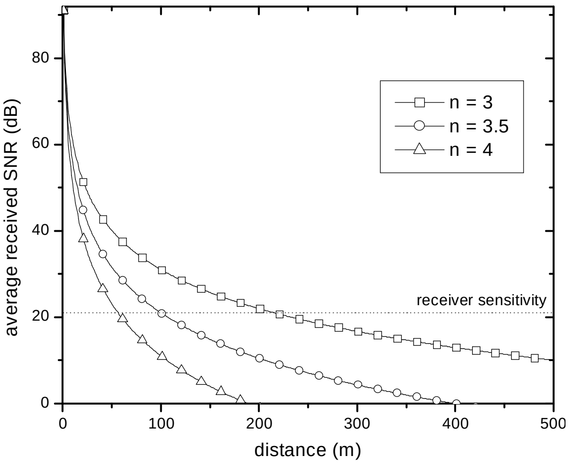

Figure 5. SNR versus distance

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.

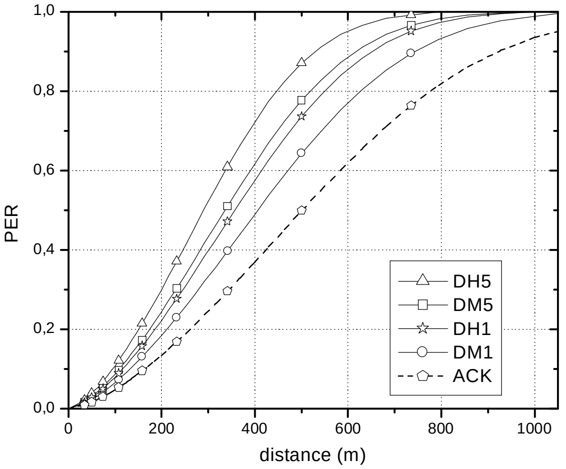

Figure 6. PER versus distance, $m = 0.5$, $n = 3$

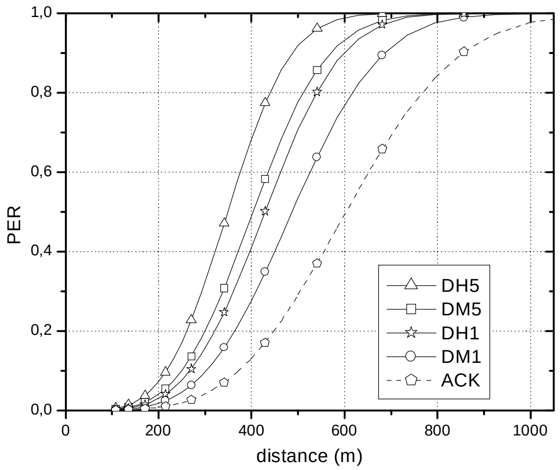

Figure 7. PER versus distance, $m = 1.5$, $n = 3$

4. NETWORK PERFORMANCE

The results obtained in Section 3 were incorporated into Blueware [6] simulator. Originally, Blueware only supports class 3 devices. We also implemented class 1 devices, to allow the formation of a scatternet with different power classes devices.

As an example, we present in Figure 8 a simulation scenario with six Bluetooth nodes to analyze the effects of Nakagami fading in the network performance. In general, near devices (class 3) will have better channel conditions (m=m_1) than devices separated by a long distance (class 1), that will experience severe fading conditions (m=m_2). The scatternet is formed using the *Tree Scatternet Formation (TSF)* algorithm [8] implemented in the simulator. The scatternet topology constructed is shown in Figure 9. Throughput simulation results for different values of m_1 and m_2 are presented in Table 1. It was used a path loss exponent n=3 and DH5 packets for CBR traffic of 720 kbps. The results are dependent of the intra-piconet and inter-piconet scheduling schemes. The inter-piconet scheduling algorithm utilized was the *Locally Coordinated Scheduling (LCS)* [9].

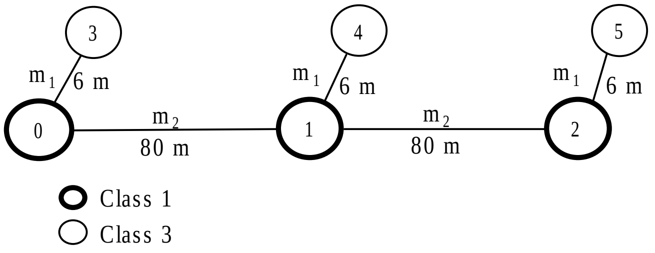

Figure 8. Scatternet with different power classes devices

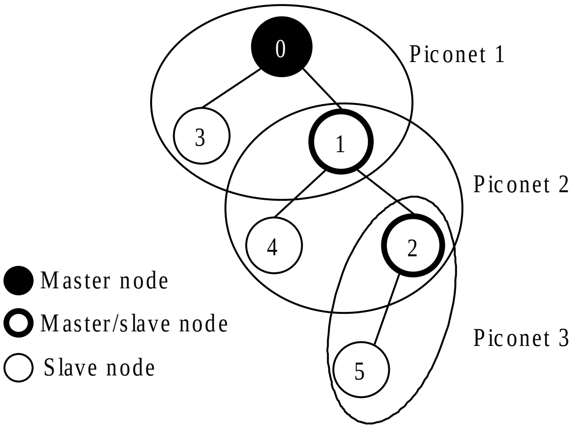

Figure 9. Scatternet topology

Nodes	Throughput (kbps)		
Source - Destiny	$m_1 = 1$ $m_2 = 0.5$	$m_1 = 1$ $m_2 = 0.75$	$m_1 = 1.5$ $m_2 = 0.75$
3-0	648	648	668
3-1	197	248	262
3-4	188	233	243
3-2	40.9	224	214
3-5	32.1	206	209

Table 1 – Throughput for different values of m

5. FINAL REMARKS

In this paper is analyzed the Bluetooth performance 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.

Others scenarios with different topologies, number of nodes and piconets must also be considered. Using devices of class 1 and class 3 in the same network can facilitate the formation of scatternets for applications that have to cover great distances. For future works, the parameter m of each link can be estimated and used as a metric for scatternet formation protocols and routing strategies.

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