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Evaluating a Performance Analysis of Slow FH Systems by Simulations

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Abstract

In this paper the approximate and simulated throughput of Bluetooth networks, which employ a packet-based frequency-hopping scheme, are compared. The approximate throughput is given as a function of the number of adjacent networks, the packet types available, and the probability of networks selecting a certain packet type for transmission. Furthermore, the approximation was derived under the assumption that collisions result in a total loss of the data in the colliding packets. In the simulations, the throughput of a reference network in the presence of interfering networks was measured. Free-space path loss was assumed and the interfering networks were randomly placed on a circular area with the reference network at its center. It was concluded that the approximation gives reasonable values on the throughput, with increasing accuracy the closer the interferers are to the reference network units.

1 Introduction

It is expected that the number of electronic consumer products with the ability to interconnect using short-range radio interfaces will increase dramatically in the near future. One technique that will be used in these interfaces is slow frequency hopping, where frequency hops are performed on a packet basis. It enables uncoordinated use of several networks in the same frequency band.

However, interference is unavoidable and will increase with the number of transmitting units, with decreased throughput as a result. Naturally, an expression that quantifies the impact of the interference on the throughput is desired. Therefore, we have in a previous paper [2] derived an approximate expression for the throughput as a function of the number of collocated units. The derivation was performed for the case where units can transmit packets of varying lengths. Furthermore, it was assumed that the slightest overlap in time and frequency, i.e., a collision, between packets results in a total loss of the information contained in the colliding packets.

In order to evaluate the validity of the system model introduced in [2], or more specifically the assumption that collisions result in lost packets, we in this paper compare the approximate throughput of a system of Bluetooth networks with the throughput obtained by more realistic simulations. The results give indications for which scenarios the system model is valid. In the simulations, Bluetooth networks are randomly placed over a circular area of a given radius and the signal attenuation is given by the free-space path loss.

In all, this paper indicates when the approximate throughput agrees well with more realistic system models, and a deeper understanding of frequency-hopping systems that transmit packets of varying lengths is given. Herein lies the novelty of our work since previous analyses of slow frequency-hopping systems have been limited to one packet size.

The outline of the paper is as follows. The system model is given in Section 2 and the throughput analysis is summarized in Section 3. The application example along with the simulations are presented in Section 4 and, finally, some concluding remarks are given in Section 6.

2 System Model

Our system is defined to consist of N networks. We further define a network to consist of an arbitrary number of units that communicate without interference. Specifically, there is exactly one ongoing transmission within a network at a time. This implies that units within a network are coordinated in some manner.

How the resources are divided between the network units or the resulting throughput of a specific unit is not of interest here; the performance of the networks and of the system is considered as a whole. The term network transmission is used for a transmission by any unit within a network.

Networks transmit packets that consist of the following components: a header of length h_i, a payload of length l_i, and a guard interval of length d_i, where i refers to the ith packet type. The components of a type i packet can be seen in Figure 1. The inter-

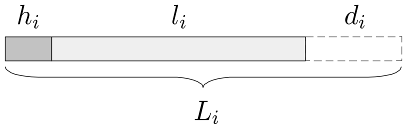

Figure 1: Definition of a packet and its components: header, payload, and guard interval. Their lengths are h_i, l_i, and d_i, respectively, and the sum of the lengths equals L_i.

val $h_i + l_i$ during which the transmitter is active, i.e., transmitting, is referred to as the *active interval.* In contrast, the transmitter is idle during the guard interval. The lengths l_i, h_i, and d_i are here specified in seconds, and $L_i = h_i + l_i + d_i$ is used for the entire packet length.

The probability of selecting a packet of type i for transmission is denoted r_i. The packet types and their corresponding probabilities are henceforth referred to as a *packet type distribution.* Further, it is assumed that networks always have packets to transmit and they are only idle during the guard interval.

When a new packet is to be sent, a packet type is selected from the set of available packet types and a new frequency channel is also selected. The new channel is selected from a set of q channels and all channels are selected with the same probability. In other words, a packet-based *slow* frequency-hopping scheme is employed. The scheme is termed slow since hops are not performed after each symbol or parts of a symbol, but after each packet. We further assume that all networks select their channels independently of all other networks.

Transmissions are not synchronized between networks, i.e., there is no coordination between networks of the start of packet transmissions.

In the analytical throughput analysis we assume that should there occur a collision, all packets involved in the collision will be destroyed and the information contained in the colliding packets is lost. On the other hand, if no collisions occur packets are assumed to be correctly received. In the simulations we use more realistic assumptions and take into account the amount of interfering energy when determining if a packet is successfully received. These two approaches are further detailed in the coming two sections.

3 Throughput Analysis

The method employed for obtaining an expression for the throughput of FH systems is the introduction of a variable-length reference packet, for which an approximation of the probability of successful transmission is found.

Consider a system of N networks. One of these networks will act as a reference network and the other $N-1$ networks will act as interferers. It is assumed that the interferers all use the same packet type distribution although extending the analysis to a case without this restriction poses no major difficulties.

Here follows the results of the derivation of the approximate throughput as presented in [2].

Let T be the length of the active interval of the reference packet and $P(\mathrm{S};T)$ be the probability of successful transmission of reference packet of length T. This probability can be expressed as

$$P(\mathrm{S};T) = \sum_{n=0}^{\infty} p_{\mathrm{tot}}(n;T)\left(1-\frac{1}{q}\right)^{n}. \tag{1}$$

Here, $p_{\mathrm{tot}}(n;T)$ PDF for the total number of overlaps generated by the interfering networks during the transmission of the reference packet and $(1-1/q)^n$ is the probability of successful transmission given n overlaps.

Although the exact probability function of the sum of the number of overlaps $p_{\mathrm{tot}}(n;T)$ is possible to evaluate, it it quite tedious and the result is difficult to analyze. Therefore, $p_{\mathrm{tot}}(n;T)$ is approximated with a Dirac pulse located at the mean of the number of overlaps, i.e., at $\bar{n}_{\mathrm{tot}} = \sum_{n=0}^{\infty} n p_{\mathrm{tot}}(n;T)$.

By applying the approximation, (1) reduces to

$$P(\mathrm{S};T) = \sum_{n=0}^{\infty} p_{\mathrm{tot}}(n;T)\left(1-\frac{1}{q}\right)^{n} \approx \left(1-\frac{1}{q}\right)^{\bar{n}_{\mathrm{tot}}}, \tag{2}$$

and the approximation of $P(\mathrm{S};T)$ is denoted $\tilde{P}(\mathrm{S};T)$, i.e.,

$$\tilde{P}(\mathrm{S};T) = \left(1-\frac{1}{q}\right)^{\bar{n}_{\mathrm{tot}}}. \tag{3}$$

As derived in [2], the average total number of overlapping packets $\bar{n}_{\mathrm{tot}}$ generated by the $N-1$ interfering networks is given by

$$\bar{n}_{\mathrm{tot}} = (N-1)\frac{T + \sum_{i=1}^{M} r_i\,(L_i - d_i)}{\sum_{k=1}^{M} r_k L_k}, \tag{4}$$

where M is the number of packet types.

Substitution of (4) into (2) yields a closed form approximation for the probability of successful transmission of a reference packet whose active interval length is T

$$\tilde{P}(\mathrm{S};T) = \left(1-\frac{1}{q}\right)^{(N-1)\frac{T+\sum_{i=1}^{M} r_i(L_i-d_i)}{\sum_{k=1}^{M} r_k L_k}}. \tag{5}$$

The throughput, which is denoted by R, is the mean fraction of the channel time that is used for successful transmission of data in the payloads. Hence, throughput is given by the ratio between the mean length of

Parameter	Value
Number of channels	$q = 79$
Header length	$h = 160\,\mu\text{s}$
Guard interval	$d = 220\,\mu\text{s}$
Payload lengths	$l_1 = 250\,\mu\text{s}$
	$l_2 = 1500\,\mu\text{s}$
	$l_3 = 3000\,\mu\text{s}$
Packet type probabilities	$r_1 = r_2 = r_3 = \frac{1}{3}$

Table 1: The Bluetooth parameters.

the successfully transmitted payloads and the mean packet length, including the guard interval. If the reference network uses the same packet type distribution as the interfering networks, we have

$$R = \frac{\sum_{n=1}^{M} r_n l_n P(\mathrm{S}; L_n - d_n)}{\sum_{k=1}^{M} r_k L_k}. \tag{6}$$

Finally, by using the approximation (5) in (6), the approximate throughput, $\tilde{R}$, for the reference network becomes

$$\tilde{R} = \frac{\sum_{n=1}^{M} r_n l_n \left(1 - \frac{1}{q}\right)^{\left(\frac{L_n - d_n + \sum_{i=1}^{M} r_i (L_i - d_i)}{\sum_{k=1}^{M} r_k L_k}\right)(N-1)}}{\sum_{k=1}^{M} r_k L_k}. \tag{7}$$

4 Simulations

In order to investigate the validity of the system model presented in Section 2, a Bluetooth scenario is examined. The throughput of a Bluetooth reference network in the presence of other interfering Bluetooth networks is both calculated and simulated. It is assumed that all networks, including the reference network, use the same packet type distribution.

The parameters roughly describing Bluetooth networks, can be found in Table 1 and these are used in (7) to obtain the throughput for $N-1$ interfering networks. Note that all packet types in the packet type distribution have the same header length, h, and guard interval, d.

The simulation setup is as follows. At the center of a circle with a radius of ρ meters a reference network is placed. The reference network, as well as the interfering networks, consist two communicating units and the distance between the two units of the reference network is y meters. The interfering units are randomly placed according to a uniform distribution over the surface of the circle. This is illustrated in Figure 2.

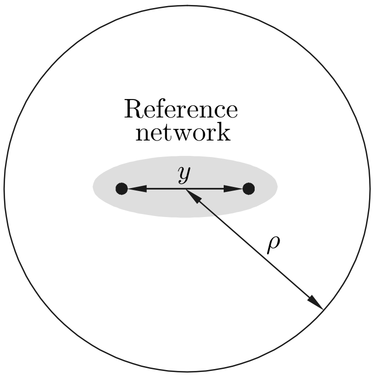

Figure 2: Illustration of the simulation setup where the reference network is placed at the center of a circle of radius ρ. The distance between the two units of the reference network is y.

Parameter	Value
Transmit power	P_{t} =1 mW
Minimum received power	$C_{\min}$ =-70 dBm
Minimum SIR	$\mathrm{SIR}_{\min}$ =11 dB
Center frequency	f_c =2.4 GHz

Table 2: The Bluetooth radio parameters used in the simulations.

For simplicity we assume that the transmission of a packet is successful if the requirements for both the minimum received power and the minimum signal-to-interference ratio (SIR) are satisfied. This is not entirely realistic either, but it is sufficient for the comparison in this paper. The parameter values used in the simulations, including transmit power and center frequency, are given in Table 2. Further details about the radio parameters can be found in [1].

To determine if a packet has been successfully received in the simulations, both the received useful energy in the packet, E_C, and the interfering energy generated by the interferers, E_I, must be calculated. We assume a static environment and the path loss, Λ, between two units is assumed to be given by the free-space path loss between isotropic antennas. Hence,

$$\Lambda = \left(\frac{4\pi x f_c}{c}\right)^2, \tag{8}$$

where x is the distance between the units, c is the speed of light, and f_c is the center frequency, which we have set to 2.4 GHz in the simulations.

The received useful power, C, at the receiver of a reference packet is

$$C = \frac{P_{\mathrm{t}}}{\Lambda_{\mathrm{ref}}}, \tag{9}$$

where Λ_{ref} is the path-loss between the two units in the reference network and P_{t} is the transmitted power.

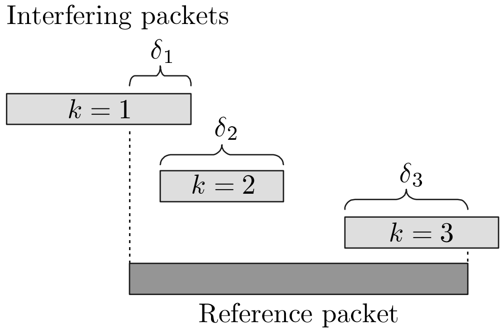

Figure 3: Three interfering packets overlapping a reference packet in both time and frequency. The length δ_k of the overlap from each packet k is shown.

Then, if the payload length of the reference packet is l_{ref}, the received useful signal energy is

$$E_C = C(h + l_{\mathrm{ref}}). \tag{10}$$

The interfering power generated by the kth packet overlapping the reference packet in time and frequency, I_k, is given by

$$I_k = \frac{P_{\mathrm{t}}}{\Lambda_k}, \tag{11}$$

where Λ_k is the is the path-loss between the receiver of the reference packet and the unit transmitting the kth interfering packet. Then, if there are K interfering packets overlapping the reference packet in time and frequency, the total interfering energy received is

$$E_I = \sum_{k=1}^{K} I_k \delta_k, \tag{12}$$

where δ_k is the length of the overlap by the kth interfering packet, as illustrated in Figure 3.

For each packet received by a unit in the reference network, the SIR is calculated as

$$\mathrm{SIR} = \frac{E_C}{E_I} \tag{13}$$

and compared to the threshold, $\mathrm{SIR}_{\mathrm{min}}$, specified in Table 2. As mentioned above, we assume that the packet is successfully received if both

$$C \geq C_{\mathrm{min}} \tag{14}$$

and

$$\mathrm{SIR} \geq \mathrm{SIR}_{\mathrm{min}}. \tag{15}$$

The condition (14) in combination with the distance attenuation model used, results in a maximum distance y_{max} between the reference network units for possible packet transmissions. This distance can be calculated using (8) and (9) to be $y_{\mathrm{max}} = 31.5$ m. If the reference network units are farther away from each other than y_{max}, then throughput will be zero since the condition (14) will not be fulfilled for any packet transmissions within the reference network. In our simulations, the network units will always be closer than the maximum of 31.5 m, hence making the SIR the limiting parameter. The careful reader have noticed that 31.5 m is more than the stated 10 m reach of Bluetooth, which is a result of the simplified conditions under which we perform the simulations.

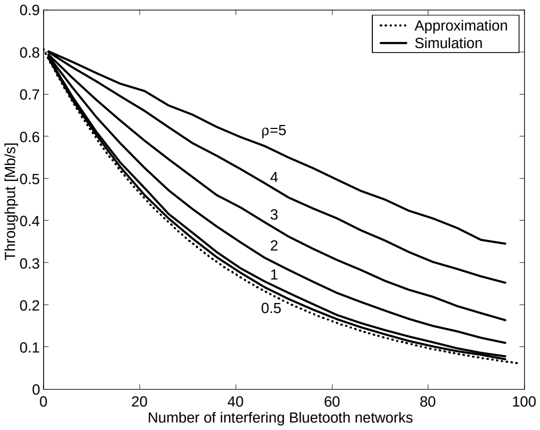

Figure 4: Throughput from both approximate expression and simulations as a function of number of interfering networks. The distance between the reference network units is $y = 1$ m. It can be seen that the agreement between simulations and analytical expression is high only for a small radius, ρ, of the area where the interferers are placed.

5 Results

The results of the simulations and the results from the approximative expression are shown in Figure 4. The distance y between the units of the reference network is 1 meter and it can be seen that the simulated throughput for the reference network deviates from the approximation quite substantially when the interfering networks are spread over the larger simulation areas, i.e., when the radius ρ is large. However, for smaller radii of the simulation area, the throughput is well approximated by the expression in (7). This is of course a consequence of putting more networks in the immediate neighborhood of the reference network, making each packet collision more severe in terms of SIR.

Common for the simulated curves is that the approximation seems to be a lower bound for the throughput, which agrees well with the assumptions used in the analytical derivation of throughput.

6 Conclusions

The results in Section 5 show that the approximate analytical expression for the throughput of packet-based slow frequency-hopping networks derived in [2] gives reasonable values when the impact of the interference from adjacent networks is severe. As we have seen, this is the case when the interfering networks are close to the reference network. For our setup, with 1 m between the reference units, the accuracy is very good if the interferers are within a radius smaller than about 1 m. In terms of Bluetooth user scenarios this implies that our simplified analytical model should be useful when analyzing, *e.g.*, body-area networks where we can expect the communicating units to be located within these dimensions. Further, the analytical expression is conservative in the sense that it does not over-estimate the throughput. This investigation is of course limited to a special case, but it still indicates the possibility of a more general use.

This initial study will be extended with more detailed comparisons and more realistic simulation setups.

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