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Energy-Based Throughput Analysis of Packet Radio Networks

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Abstract— **The increasing use of wireless technology utilizing unlicensed frequency bands calls for more in-depth analysis of interference and coexistence between systems. In this paper a framework is presented for detailed analysis of the performance of coexisting networks in shared frequency bands. The framework allows for multiple packet lengths to be used by the communicating devices and the analysis is performed with respect to the received interfering energy, which in effect leads to a link budget analysis on a packet basis. A system of interfering Bluetooth piconets is analyzed to illustrate the use of the framework and the conceptual difference in basing the analysis on link budgets, rather than on packet collisions. Furthermore, some indications on throughput saturation in the analyzed Bluetooth system are presented.**

Keywords— **Packet radio network, frequency hopping, throughput, energy, multiple packet lengths.**

I. INTRODUCTION

In the last decade there has been an increasing use of radio technology for voice and data communications. The development of the circuit switched mobile communication solutions designed mainly for speech, has resulted in systems with packet switching capabilities more suitable for bursty Internet data traffic. The packet switching capabilities can be found in many of the currently deployed mobile phone systems, wireless local area networks (WLANs), and wireless personal area networks (WPANs).

As the WLAN and WPAN systems operating in the unlicensed parts of the spectrum are getting more and more popular, the interference situation is becoming a problem. Increasing numbers of devices sharing unlicensed frequency bands lead to higher levels of interference with performance degradations as a result. To eventually improve network and system performance, investigations must be carried out of the interference mechanisms involved. In this paper, we present an analytical framework that can be used to analyze the performance of interfering packet radio networks (PRNs) and the corresponding coexistence issues in the unlicensed bands.

The novelty of this contribution lies in the ability to perform an energy-based analysis of interfering PRNs that use different lengths of the transmitted packets, which is a common feature in currently used WLANs and WPANs. Previous publications within this area have been limited to fixed packet lengths or dwell time intervals. For example, detailed probabilistic analyses of different types of spread spectrum multiple access (SSMA) systems have been presented by Vlachos and Geraniotis in [1], by Mohamed and Pap in [2] and more recently by Hamdi in [3, 4], but they have all been limited to fixed dwell time intervals and slotted packet transmissions. Howitt [5] has presented work more focused on coexistence issues, specifically that of IEEE 802.11b and Bluetooth coexistence in the unlicensed industrial, scientific and medical (ISM) band at 2.4 GHz, but the system model does not allow for detailed analysis of networks using multiple packet lengths.

To address the problem of analyzing networks using multiple packet lengths a new system model was introduced in [6] and analyzed with respect to packet collisions. In this paper, we reuse parts of that system model and analyze it with respect to the interfering energy received during packet receptions, which allows for path loss and receiver sensitivity to be included in the analysis.

This paper is organized in the following way: the system model used is described in Section II. In Section III, we present the definition of throughput and the method used to analyze the system based on the amount of interfering energy received during the reception of packets. To illustrate the method of analysis we analyze an example system of Bluetooth networks in Section IV, calculating the average throughput and comparing with previously published results. Finally, in Section V, we give some concluding remarks and comment on future work.

II. SYSTEM MODEL

To be able to analyze PRNs with respect to different packet lengths we reuse a system model which in parts has been described and used in previous publications [6, 7].

The systems we will analyze consist of a collection of N networks (as illustrated in Fig. 1) sharing a set of q frequency channels for packet-based communications. Within each network, the units are coordinated in such a way that only one packet is transmitted at a time using packet-based slow frequency hopping, which means that a new channel is selected at random after each packet transmission. This results in packet transmissions like the ones illustrated in Fig. 2.

There is no coordination of units belonging to different

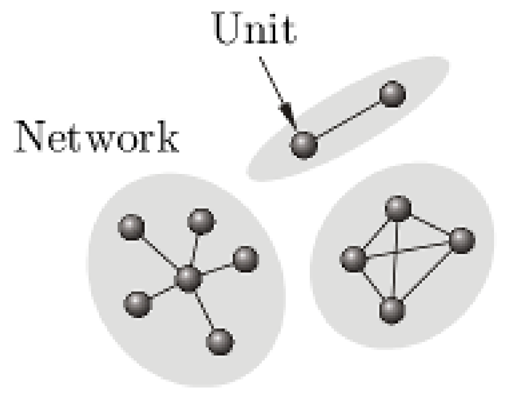

Fig. 1. A system consisting of three networks.

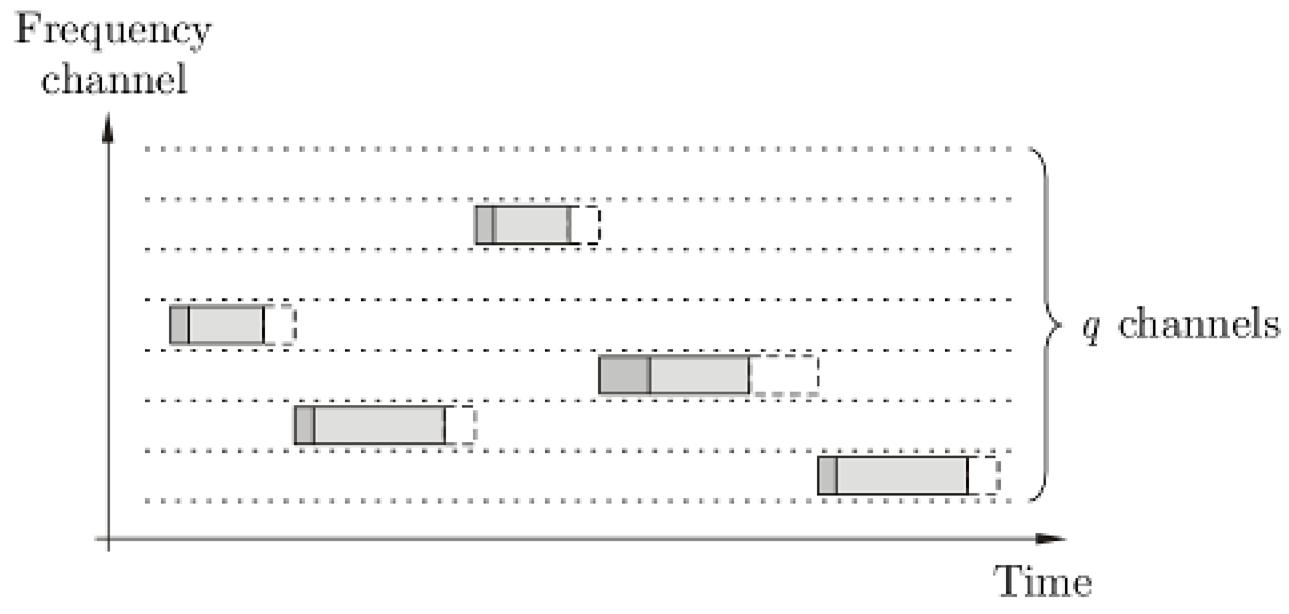

Fig. 2. Packets of different types transmitted by a single network on a set of frequency channels.

networks. Since they share the same set of frequency channels, two packets from different networks are sometimes transmitted simultaneously on the same channel, resulting in packet collisions like the one depicted in Fig. 3.

Furthermore, each network in the system has a set of available packet types that can be used for packet transmissions. The packets can have different lengths, carry different amounts of data and can have different robustness properties against interference. More specifically, a packet consists of header with length h, a payload with length l, and a guard interval with length d, as shown in Fig. 4. Since payload data can be transmitted with different data rates we use D for the number of uncoded bits of payload data transferred per unit time in a packet. Finally, each packet type i in the set of packet types is used by the network units with a probability r_i.

It should be noted that by assuming that one packet is transmitted at a time within a network, we will obtain performance results for networks with full traffic load in the worst case interference environment. The extension to model networks with less than full load, e.g., by introducing activity factors, is straight forward but has not been included in this work.

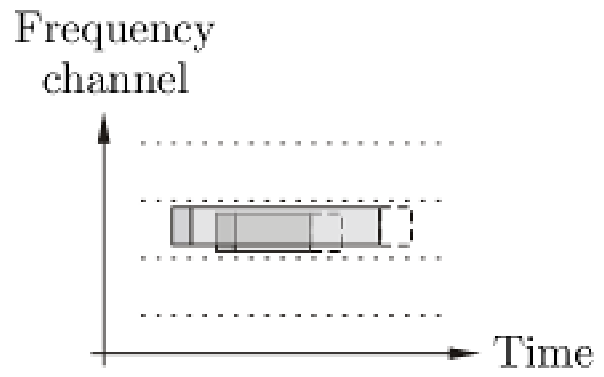

Fig. 3. Two interfering packets overlapping in both time and frequency. The apparent frequency offset is just for visibility of the shorter packet.

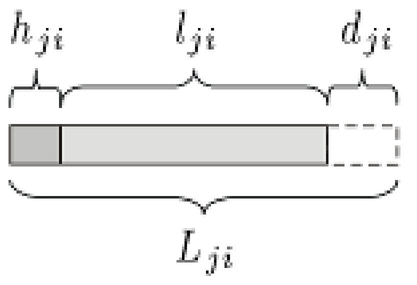

Fig. 4. Notation used for the components of a packet type i transmitted by units in network j.

III. ANALYSIS

Before we can start analyzing systems using the system model presented we must introduce a performance measure. As a measure of network performance we will use the ensemble average network throughput in the analysis. The throughput can be associated with the data transfer rate, and is based on the probabilities of successful packet receptions of the packet types used by the networks.

The definition adopted here for the throughput is the amount of data received per unit time in the payload, times the fraction of channel time used for successful payload transmissions. Consider a network with index μ, using a set of M_μ packet types. Denote the probability of successful reception of a packet of type k by a unit in network μ, by $\Pr\{\text{success}; \mu, k\}$. Then

$$\sum_{k=1}^{M_\mu} r_{\mu k} D_{\mu k} l_{\mu k} \Pr\{\text{success}; \mu, k\} \tag{1}$$

is the average number of successfully transferred bits of payload data per packet. Since the average length of the packets used by network μ is

$$\sum_{n=1}^{M_\mu} r_{\mu n} L_{\mu n}, \tag{2}$$

the throughput, R_μ, of network μ can be defined as the average number of successfully transferred payload bits per packet, divided by the average packet length,

$$R_\mu = \frac{\sum_{k=1}^{M_\mu} r_{\mu k} D_{\mu k} l_{\mu k} \Pr\{\text{success}; \mu, k\}}{\sum_{n=1}^{M_\mu} r_{\mu n} L_{\mu n}}. \tag{3}$$

This throughput measure will be referred to as the network throughput.

If the performance of the system as a whole is of interest, the system throughput, R_{sys}, can be used. This is defined to be the sum of the throughput quantities for the individual networks,

$$R_{\text{sys}} = \sum_{\mu=1}^{N} R_\mu. \tag{4}$$

Similarly, the aggregated throughput of any group of networks can be obtained by summing the network throughput for each of the networks in the group.

Now that the performance measure has been defined, the analysis consists of finding an expression for the quantity $\Pr\{\text{success}; \mu, k\}$ for the successful packet reception probability in (3). The successful packet reception probability

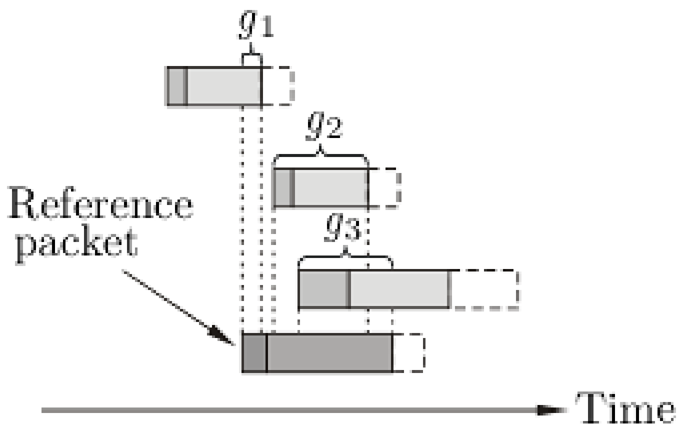

Fig. 5. Three interfering packets overlapping the lowermost reference packet in both time and frequency. To clarify, all packets are transmitted on the same channel. The received interfering energy is a weighted sum of the length of the overlaps of active intervals and the received interfering power.

will depend on what is assumed to cause packet losses in the system, and in this paper we will make the assumption that the outcome of packet receptions is determined by the amount of interfering energy received during reception.

With the energy as a measure of the level of interference, we will in effect perform a link budget analysis on a packet basis, which allows for distance, transmitted power and receiver sensitivities to be accounted for to some extent.

Let the success of packet receptions be given by the amount of received useful energy, E_C, in a received packet and the total amount of interfering energy, E_I, from other packet transmissions that are simultaneously received, as visualized in Fig. 5. In the figure, three interfering packets overlapping the lowermost reference packet in both time and frequency are shown. The received interfering energy is a weighted sum of the length of the overlaps of active intervals (i.e., g_1, g_2 and g_3 in Fig. 5) and the interfering power (i.e., I_1, I_2 and I_3) at the receiver of the reference packet. Thus, the total amount of interfering energy from K colliding packets is

$$E_I = \sum_{m=1}^{K} I_m g_m, \tag{5}$$

where I_m is the interfering power from a packet m at the receiver, and g_m the length of the overlap in time of headers and payloads between the received packet and the interfering packet. We will let the total interfering energy, E_I, received during the reception of a packet determine the outcome of the reception. The explicit packet reception model used in this paper is a threshold at $E_{I,\max}$ for the maximum amount of interfering energy that can be tolerated for successful reception of a packet. Thus, if a packet is received with a total amount of interfering energy above $E_{I,\max}$ the packet reception fails and the data in the payload is lost.

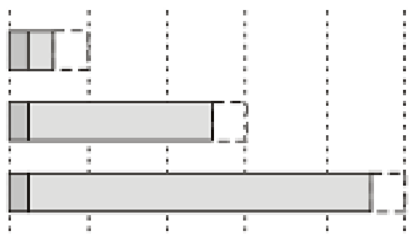

Fig. 6. The three Bluetooth packet types used.

With Pr{success} denoting the probability of successful packet reception we have

$$\Pr\{\text{success}\} = \int_{e=0}^{\infty} f_{E_I}(e) \Pr\{\text{success}|E_I = e\} de, \tag{6}$$

where $f_{E_I}(e)$ is the probability distribution function (PDF) of E_I, and $\Pr\{\text{success}|E_I = e\}$ is the conditional probability for successful packet reception given a total received interfering energy e. Using the threshold at $E_{I,\max}$, we have

$$\Pr\{\text{success}|E_I = e\} = \mathrm{u}(E_{I,\max} - e), \tag{7}$$

where $\mathrm{u}(\cdot)$ is the Heaviside step function. Accordingly, if the received interfering energy within the packet exceeds $E_{I,\max}$, the reception fails since the conditional probability for success (7) is then zero. To find an expression for Pr{success} in (6) we must now find an expression for $f_{E_I}(e)$. This is done in detail in [8] and is not included in this paper due to space limitations.

IV. Bluetooth Example

Bluetooth [9] is a short range radio system for wireless data communications. It is mainly intended for data cable replacements and can provide data rates in the order of 700 kb/s. A Bluetooth network, referred to as a piconet, consists of one master unit and a maximum of seven active slave units that communicate using time division multiple access (TDMA) and packet-based slow frequency hopping over 79 frequency channels in the ISM-band at 2.4 GHz. The master unit controls the data transmissions so that only one packet is transmitted at a time within a piconet. The type of modulation (binary Gaussian frequency shift keying – GFSK) and symbol rate (1 Mbaud) used result in a raw data rate of 1 Mb/s.

The packet types defined in the Bluetooth specification [10] for use by the piconet units can have lengths specified as multiples of a common time slot length of 625 μs. In this example we will consider three of these packet types, namely the ACL packets DH1, DH3 and DH5, which occupy one, three and five time slots, respectively, as shown in Fig. 6. The payloads of these packets are transmitted without error correcting coding, which make them more sensitive to interference than packets with coded payloads. The lengths of the headers, payloads and guard intervals of the three packet types presented below, and the data rate of the payloads can be determined by consulting the Bluetooth specification [10]. In addition, we assume that the packet types are selected for transmission with equal probabilities in this example. The resulting set of parameters is

Packet selection prob.	$r =$	$[\ 1/3 \quad 1/3 \quad 1/3\ ]$
Header length	$h =$	$[\ 150 \quad 158 \quad 158\ ]$ μs
Guard interval length	$d =$	$[\ 275 \quad 269 \quad 271\ ]$ μs
Packet duration	$L =$	$[\ 625 \quad 1875 \quad 3125\ ]$ μs
Payload bit rate	$D =$	$[\ 1 \quad 1 \quad 1\ ]$ bits/μs,

and $q = 79$ frequency channels.

To be able to use the energy-based framework in the analysis we need the following set of additional link budget parameters for the Bluetooth system

Eff. isotr. rad. power	EIRP $=$	0 dBm
Path loss (ref. units)	$L_{\mathrm{PL,ref}} =$	40 dB
Path loss (int. units)	$L_{\mathrm{PL,interf}} =$	$[\ 40 \quad 50 \quad 54\ ]$ dB
Receiver loss	$L_{\mathrm{r}} =$	2 dB
Min. received SNIR	$\gamma_{\min} =$	20 dB.

The path loss figures 40, 50 and 54 dB correspond to typical path loss in a line-of-sight (LOS) situation for distances of 1, 3 and 5 meters at 2.4 GHz [11][1], which are assumed to be typical values for distances between interfering units. We have assumed a transmit power of 2 dBm and transmitter losses of 2 dB to obtain an effective isotropically radiated power (EIRP) of 0 dBm. Since all networks in the system are characterized by the same set of parameters, each one will be experiencing the same interfering environment from the $N-1$ other networks. Thus, considering a single reference network, the propagation loss between the units of that network has been set to 40 dB, which corresponds to a distance of approximately 1 m. This is assumed to be a typical distance between communicating Bluetooth units. We will consider three scenarios where the distances between the units of the reference network and the units of the interfering networks are either 1, 3 or 5 meters.

To find the parameter $E_{I,\max}$, we will assume that the Bluetooth receivers in the system are characterized by the parameters

Noise figure	$F_{\mathrm{sys}} =$	20 dB
Noise bandwidth	$B =$	60 dBHz
Reference noise power density	$N_0 =$	-174 dBm/Hz,

which results in a noise power of

$$\begin{aligned} N_{\mathrm{noise}} &= F_{\mathrm{sys}} + B + N_0 \\ &= -96 \text{ dBm}. \end{aligned} \tag{8}$$

It should be noted that current Bluetooth receiver implementations generally have lower noise figures than 20 dB. For successful packet reception, the per-packet signal-to-noise and interference ratio (SNIR) must be above the specified threshold $\gamma_{\min}$, which means that

$$\frac{C}{N_{\mathrm{noise}} + E_I / (L-d)} > \gamma_{\min} \tag{9}$$

must be fulfilled, where the parameters are all in a linear scale. From (9) we get

$$E_I < \left(\frac{C}{\gamma_{\min}} - N_{\mathrm{noise}} \right) (L-d)\,, \tag{10}$$

and thus, the maximum amount of interfering energy for successful reception of a network l packet type k is

$$E_{I,lk,\max} = \left(\frac{C}{\gamma_{\min}} - N_{\mathrm{noise}} \right) (L_{lk} - d_{lk})\,. \tag{11}$$

With the numbers specified in this example we obtain

$$E_{I,\max} = \quad [\ 0.22 \quad 1.0 \quad 1.8\ ] \text{ pJ},$$

which are the thresholds for the maximum received interfering energy that can be tolerated for successful receptions of the three packet types.

To calculate the probabilities for successful packet receptions based on the interfering energy we first calculate the PDF of the total received interfering energy, $f_{E_I}(e)$, which is done in detail in Chapter 5 in [8]. Then we use the parameter $E_{I,\max}$ in (7), and evaluate the integral in (6) for each packet type used. Once the successful packet reception probabilities have been evaluated, the throughput can be calculated using (3) and (4).

By plotting the network throughput from (3) as a function of number of interferers, $N-1$, in the system, we obtain the curves in Fig. 7. As the number of piconets in the system is increased, an increasing number of packets will be transmitted on the 79 shared frequency channels, which consequently leads to reduced probabilities for successful packet receptions and thus lower throughput. Recall that the distance between the units of the reference network has been fixed to 1 m, and that the distances between the reference network units and the interfering units, are either 1 m (dashed curve), 3 m (dash-dot) or 5 m (dotted). In addition, we have plotted the network throughput obtained from the corresponding collision-based analysis, which results in a lower bound[2] (solid curve) on network throughput. The collision-based results are obtained by assuming that all packet collisions result in lost packets [6].

By adding the throughput quantities from all piconets in the system, the system throughput is obtained from (4) and plotted as a function of number of piconets, N, in the system. The results can be found in Fig. 8, where the system throughput has been plotted for distances between the reference network units and the interfering units of either 1 m (dashed curve), 3 m (dash-dot) or 5 m (dotted). The result from the collision-based case has also been included, represented by the solid line. For lower numbers of piconets in the system, adding a single piconet will increase the system throughput up to a certain number of piconets (e.g., about 40 in the collision-based case). With this many piconets in the system, the system performance is saturated by the total interference, and as can be seen, adding more networks will reduce the system throughput.

It is clear from Fig. 7 and Fig. 8 that when the network separation is about one meter, the results from the considerably simpler collision-based analysis yields approximately the same results as the energy-based analysis presented in this paper. Apparently, the amount of received interfering energy from small overlaps in time and frequency between colliding packets is then so high that, in effect, all packet collisions result in lost packets. As the interferers are moved farther away from the reference network, small packet overlaps do not always result in lost packets, as predicted by the collision-based method of analysis.

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[1] We have used the path loss model in eq. (12) in [11]. For simplicity we have chosen the parameters $S_0 + b = 40$ dB and $a = 2.0$.

[2] Note that adjacent channel interference is not considered in this paper.

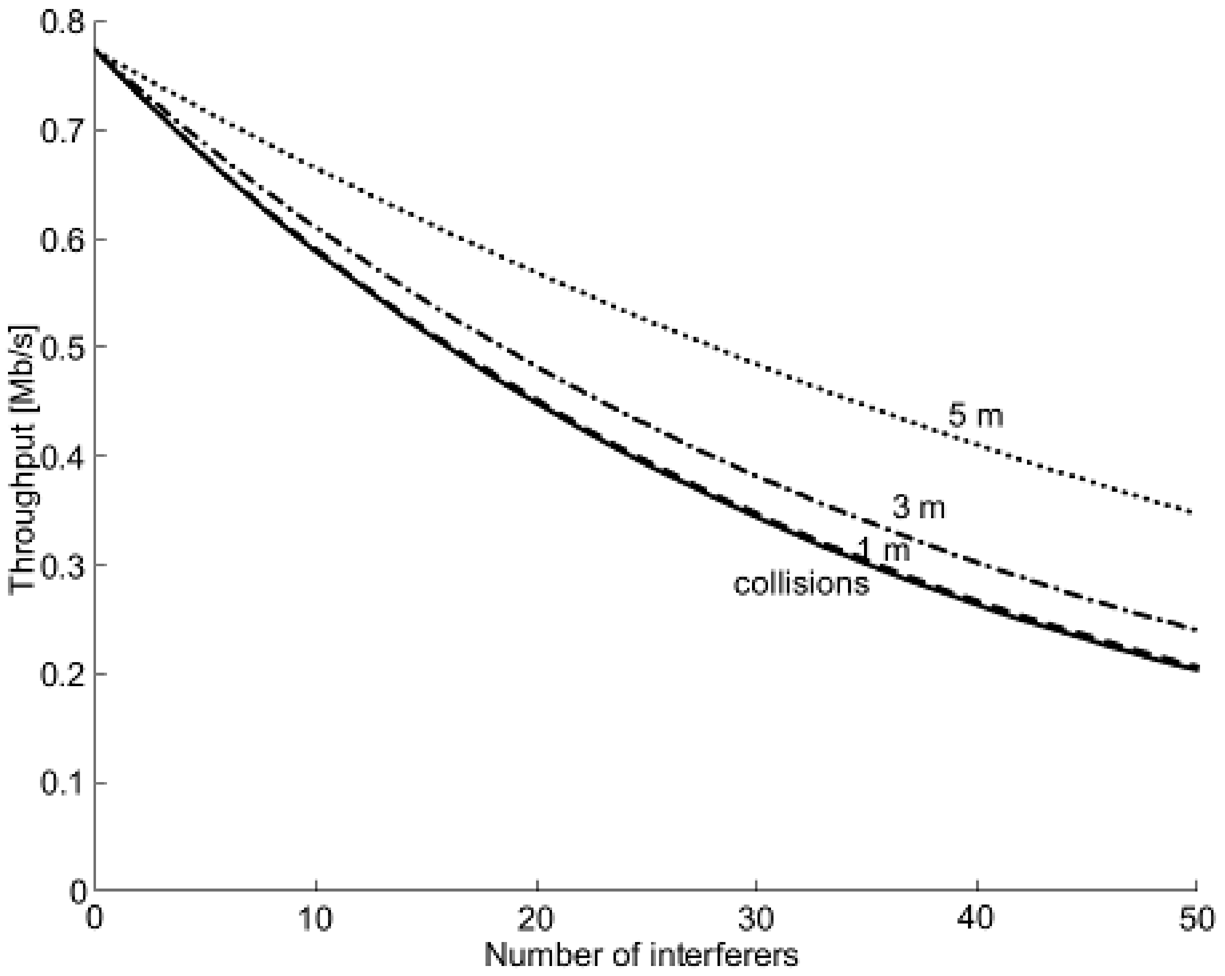

Fig. 7. Network throughput as a function of number of interfering piconets. The lower-most solid curve is the result from the collision-based analysis, which gives a lower bound on throughput. The dashed curve is the result from using the energy-based analysis with 1 m between units in the reference network and units in the interfering piconets. The dash-dotted curve corresponds to 3 m and the dotted curve to 5 m.

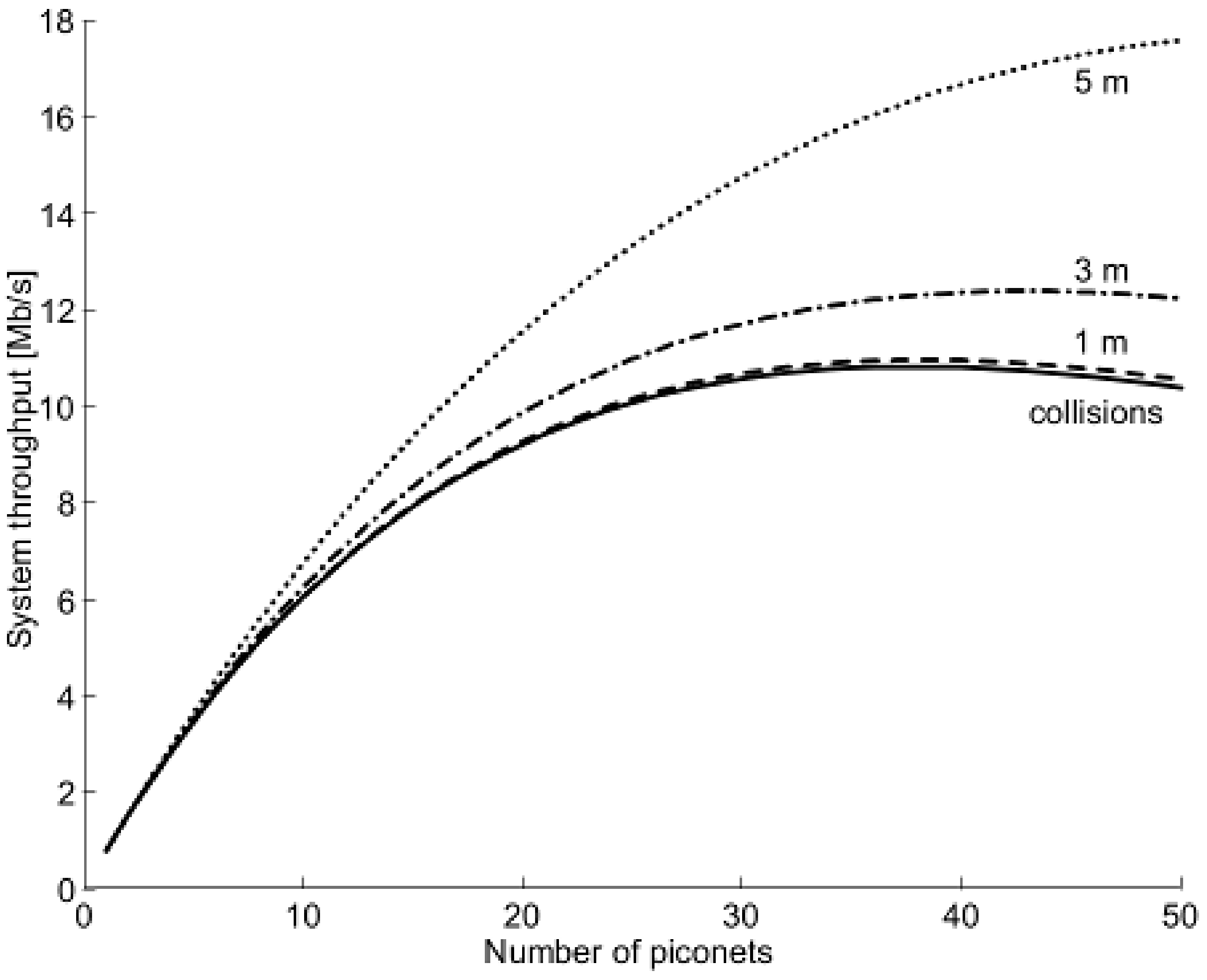

Fig. 8. System throughput as a function of number of piconets in a system where the distance between reference units is 1 m, and the distance between reference units and interfering units is either 1 m (dashed curve), 3 m (dash-dot) or 5 m (dotted). The curves can be compared to the result from using the collision-based analysis (solid curve).

V. CONCLUSIONS

We have introduced a framework for analytical analysis of the throughput of interfering PRNs. The analysis is based on the interfering energy received during packet receptions, and the system model allows for different packet lengths to be used by the networks units, which has not, to the authors' knowledge, been presented previously. The framework enables detailed studies of the coexistence issues in unlicensed frequency bands.

An analysis of an example system of Bluetooth networks has been included to illustrate the use of the framework and the conceptual difference in performing an analysis with respect to packet collisions and received interfering energy. The analysis of the Bluetooth system clearly shows that the assumption that collisions always result in lost packets is valid when the interfering networks are close to a given reference network. In the specific Bluetooth case presented, considering only co-channel interference, this is within approximately one meter.

It was shown that for the Bluetooth system under consideration, the presented energy-based analysis indicates a system throughput saturation somewhere above 40 piconets, with 40 piconets as a lower bound given by the collision-based method of analysis. As many as 40 piconets with distances between units of the order of 1 m, appears to be an extremely crowded system and an uncommon situation at present. It should however be noted that the presented results include only co-channel interference. Taking adjacent channel interference into account would provide more realistic figures.

Applications of the presented framework to the analysis of networks based on different versions of the IEEE 802.11 standard and Bluetooth is a future work item, specifically to address the coexistence problems in unlicensed frequency bands.

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