Experimental Verification of An Analytical Interference Model for Bluetooth Networks

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EXPERIMENTAL VERIFICATION OF AN ANALYTICAL INTERFERENCE MODEL FOR BLUETOOTH NETWORKS

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Abstract

In this paper, measurement results are presented providing experimental support for the validity of a theoretical framework for analysis of heterogeneous systems of interfering packet radio networks. Specifically, an analytical Bluetooth interference model is considered in this paper, where calculated distributions of energy quantities from interfering Bluetooth networks are compared with distributions obtained from measurements. The measurements indicate that the closed form expressions for the distributions of the received interfering energy in the analytical model capture important mechanisms in real Bluetooth networks. It is also evident from the measurements that adjacent channel interference must be taken into account when analyzing interfering Bluetooth networks.

I. Introduction

With the increasing use of unlicensed frequency bands for wireless data communications, interference between adjacent radio devices sharing the same bands can become a problem. Since many different types of radio interfaces are typically used in these bands, analysis of the performance of the interfering radio devices is far from trivial. Recent research efforts within this area have been focused on coexistence issues in the unlicensed industrial, medical and scientific (ISM) band at 2.4 GHz, and specifically on the interference between Bluetooth [1] and IEEE 802.11b devices [2] (see, e.g., [3, 4, 5, 6, 7]).

Presented research has been based on simulations and measurements as well as on analytical models. Although it is viable to simulate complex setups there are several advantages using analytical methods, e.g., the ability to describe the generic properties of a system and the applicability of an analytical model on a large variety of system setups. Within the field of analytical models, closed form expressions for the performance of interfering packet radio networks (PRNs) have mainly been derived based on packet collisions that occur in the networks (see, e.g., [8, 9, 10, 11, 12]) or on a per-packet signal-to-noise and interference ratio (SNIR)/signal-to-interference ratio (SIR) (see, e.g., [13, 14, 15, 16, 17, 18]). To date, however, not much work has been published on real-world measurements in order to verify analytical models. In [14], Howitt has studied various aspects of interference between Bluetooth units, however limited to fixed packet lengths. Important conclusions from his paper though, are that both co-channel interference and adjacent channel interference (ACI) must be taken into account. In this paper, we focus on the applicability of the analytical framework presented in [16, 18], which allows for analysis of heterogeneous networks transmitting multiple packet types over different channel sets. In addition, the framework takes both co-channel and adjacent channel interference into account. Furthermore, the framework is based on a theoretical analysis, in contrast to the work presented by Howitt in [19, 20, 14] which proposes a model based on empirical data. The analytical framework [16, 18] which we try to verify is more general than the one used by Howitt, in the sense that it can handle multiple packet types. However, it should be noted that for practical purposes the measurements in this paper only cover single packet types used by the interferers.

The analytical framework presented in [16, 18] uses closed form expressions for the average achievable data rates. It takes into account the strengths and the spectral shapes of the interfering signals, the lengths of the packet overlaps in time, and the receiver characteristics. The basic strategy of the approach is to describe the interference statistically using the distribution of the interfering energy received by the units in each of the networks. The calculated distributions are then, in turn, used to calculate the network throughput, defined as the amount of successfully transferred payload data per unit time, under the influence of interference from the environment.

To calculate the network throughput, the successful packet reception probabilities for each of the packet types used by a reference network must be known. Consider a packet of a specific type, referred to as the reference packet, and denote the average probability of its successful reception by $\Pr\{\text{success}\}$. The successful packet reception probability is written as

$$\Pr\{\text{success}\} = \int_{e=0}^{\infty} f_{E_{I,\text{tot}}}(e) \Pr\{\text{success}|E_{I,\text{tot}} = e\} de, \tag{1}$$

where $f_{E_{I,\text{tot}}}(e)$ is the probability density function (PDF) of the total interfering energy, $E_{I,\text{tot}}$, received during the reference packet reception, and $\Pr\{\text{success}|E_{I,\text{tot}} = e\}$ is the conditional successful reference packet reception probability. In practice $f_{E_{I,\text{tot}}}(e)$ is determined through the corresponding cumulative distribution function (CDF), $\Pr\{E_{I,\text{tot}} < e\}$, which can be determined recursively if the interfering networks are transmitting independently of each other [16, 18]. In addition, by using some suitable function for $\Pr\{\text{success}|\ E_{I,\text{tot}} = e\}$, the successful reference packet reception probability and the network throughput can be calculated. In [16, 18] a simple threshold was used to describe $\Pr\{\text{success}|E_{I,\text{tot}} = e\}$, i.e., if $E_{I,\text{tot}} < E_{I,\max}$ the reception is assumed successful and otherwise it is not.

The aim of the investigation presented in this paper is to validate the analytical framework in [16, 18] by comparing theo-

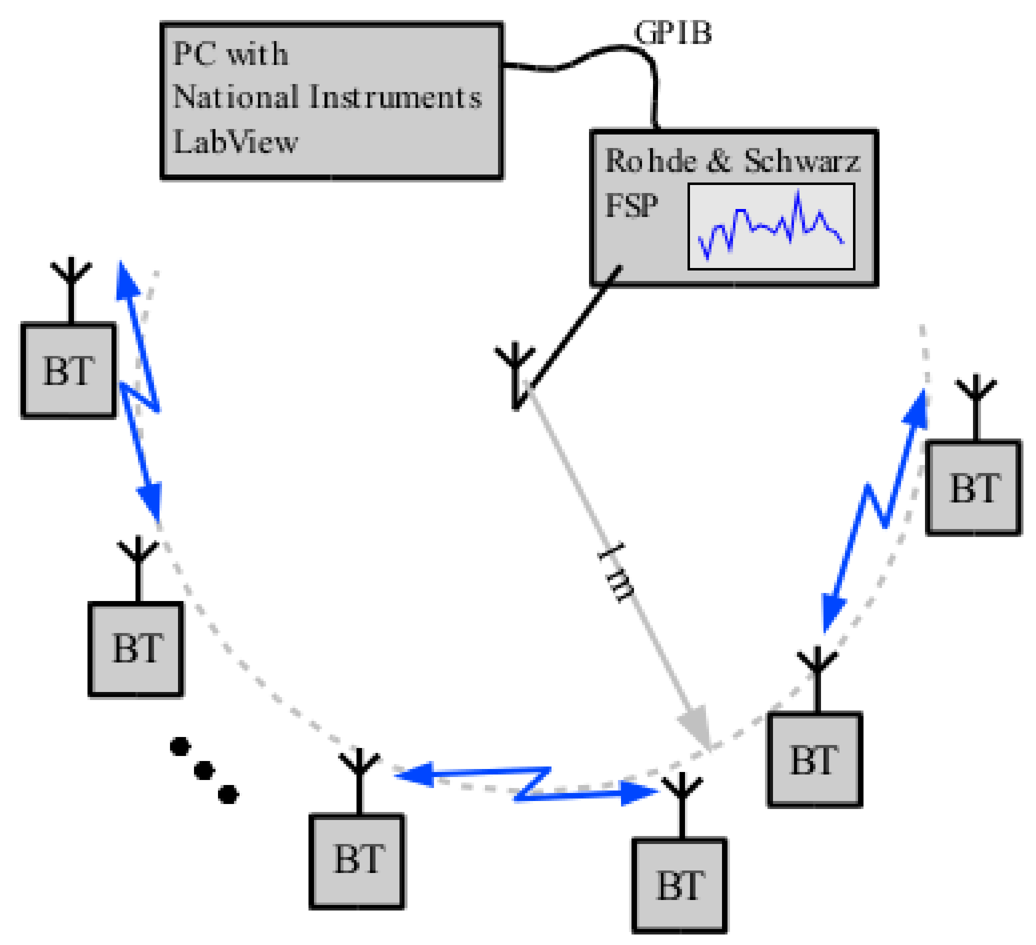

Figure 1: Measurement setup for measuring the CDFs of the received interfering energy from multiple Bluetooth networks.

retically calculated CDFs of received interference with CDFs based on measurements of interfering Bluetooth networks.

The measurement setup is presented in Section II., along with an analysis of the properties of the calculated and the measured CDFs. The CDF measurements are described in Section III. where the results are compared with the corresponding CDFs calculated from the closed form analytical expressions. Finally, in Section IV., some concluding remarks are given.

II. Interfering Energy Distribution

In this section we will discuss the measurement setup used when measuring the distribution of instantaneous interfering energy received per packet and the restrictions we have made to limit the number of measurement series. In order to compare the measured interference data with the theoretical distribution results from [18] we also need to modify the theoretical results slightly. Fluctuations due to transmitted data will be present in the measurements, while these fluctuations are marginalized in the theoretical results. We therefore expand the model from [18] to also include a stochastic variable representing the data in the interfering packets.

A. Measurement Setup

To measure the distributions of the received energy from interfering Bluetooth networks, the measurement setup illustrated in Figure 1 has been used. The CDFs of the received interfering energy from the Bluetooth transmissions are measured using a Rohde & Schwarz FSP spectrum analyzer connected to an antenna, around which the Bluetooth units are placed at a distance of 1 meter.

For convenience, the FSP spectrum analyzer is controlled by a National Instruments LabVIEW software application on a PC using a GPIB interface cable. The LabVIEW application configures the spectrum analyzer for zero-span measurements, which means that the IF-filter of the analyzer is not swept but instead locked to a specified center frequency, f_0, with a specified bandwidth, B. The application makes the analyzer measure the power received as a function of time during a specified time interval T, and then stores the measurement result on the PC. One such measurement of length T is referred to as a snapshot.

Table 1: Outline of the 16 measurement series with Bluetooth networks as interferers.

Number of interferers	Packet lengths Interf.	Ref.
1,2,3,4	Short	Short
1,2,3,4	Long	Short
1,2,3,4	Short	Long
1,2,3,4	Long	Long

For a specific T, a specific B, and for a specific center frequency f_0, an estimate of the CDF of the interfering energy is obtained by performing a large number of snapshot measurements with random time intervals in-between. Since Bluetooth is under consideration, these measurements must be performed on all 79, $B = 1$ MHz wide, channels in the ISM-band at 2.4 GHz used for frequency hopping by the Bluetooth units (2402–2480 MHz).

Bluetooth uses three principal lengths of transmitted packets; 1, 3 or 5 time slots, where a time slot is 625 μs. Included in these packet lengths there is a guard interval of about 270 μs, allowing the network to change frequency channel before the next transmission. Bluetooth networks will in general use all three principal packet lengths and these packets do not need to be completely filled with data. To limit the amount of measurements required we have chosen to only consider two of the three packet lengths, namely 1 and 5 time slots, and always use such packets which are completely filled with data. This means that we have two packet types, which we will refer to as *short* and *long* packets. *Short* packets have an active interval (header+payload) of length $T = 355$ μs and *long* packets have an active interval of length of $T = 2855$ μs. In Bluetooth terminology our *short* packets are fully loaded DH1/DM1 packets and our *long* packets are fully loaded DH5/DM5 packets.

The measurements with Bluetooth networks as interferers used in this investigation are outlined in Table 1. In each of the measurements we take 99 snapshots on each of the 79 frequency channels and these snapshots are stored on the PC. The 7821 snapshots stored per measurement contain the average interference power in mW over the active interval length used by the reference network (short or long). If the instantaneous interfering energy $E_{I,\text{inst}}$ for a certain snapshot is required, the average interference power can be multiplied by this active interval length.

B. Theoretical Energy Distributions

In the work on per-packet link budget analysis of interfering networks in [18], it is assumed that the individual contributions from interfering packets are independent. It is also assumed that the relative time and frequency offsets between interfering packets and the reference packet are independent from the transmitted data. This leads to a model of the instantaneous received interfering energy

$$E_{I,\text{inst}} = E_{I,\text{tot}} \times X, \tag{2}$$

where $E_{I,\text{tot}}$ and X are independent. The first stochastic variable $E_{I,\text{tot}}$ models the expected interfering energy (due to random time/frequency locations of the interfering packets) while the second X models the additional fluctuations depending on transmitted data. The non-trivial calculation of the distribution $f_{E_{I,\text{tot}}}(e)$ of $E_{I,\text{tot}}$ is treated in detail in [18], since it forms the basis of the per-packet link-budget analysis introduced therein. While the instantaneous fluctuations due to transmitted data was beyond the scope of that paper, they become important when comparing the theoretical distribution $f_{E_{I,\text{tot}}}(e)$ with our measured data. The measurement setup in Figure 1 will deliver measurements of instantaneous energy levels ($E_{I,\text{inst}}$) and we cannot separate variations due to random locations of interfering packets ($E_{I,\text{tot}}$) from variations due to transmitted data (X) in these packets.

To overcome this problem with separation of $E_{I,\text{tot}}$ from X in our measurements, we compare the theoretical distributions from [18] with our measurement data through the model in (2). To do this we need a distribution of X and make the standard assumption that the interference contributions from different packets are independent and each have a zero-mean complex Gaussian distribution. This leads to a total interference with zero-mean complex Gaussian distribution and a corresponding exponential distribution of its energy, i.e.,

$$f_X(x) = \begin{cases} \exp(-x) & x \geq 0 \\ 0 & \text{otherwise} \end{cases} .$$

Now when we have a complete theoretical model of the instantaneous received interfering energy $E_{I,\text{inst}}$, we can compare our theoretical model against the measurement data.

We will perform our comparisons of theory and measurements using cumulative distributions in the dB domain. For that purpose we write (2) as

$$E_{I,\text{inst,dB}} = E_{I,\text{tot,dB}} + X_{\text{dB}}, \tag{3}$$

where the PDF of $E_{I,\text{inst,dB}}$ can be written as a convolution between the PDF of $E_{I,\text{tot,dB}}$, and the PDF of X_{dB}. The PDF of $E_{I,\text{tot,dB}}$ can be calculated using the expressions from [18], while the PDF of X_{dB} is

$$f_{X_{\text{dB}}}(x_{dB}) = \frac{\ln 10}{10} 10^{x_{\text{dB}}/10} \exp\left(-10^{x_{\text{dB}}/10}\right).$$

III. BLUETOOTH INTERFERERS

In this section we will concentrate on the theoretical model of interference (3) and its relation to the measurements in Table 1. First we illustrate the importance of including ACI in the theoretical model to obtain the correct energy distribution. Secondly, we compare the four measurements with only one Bluetooth interferer to the corresponding theoretical distributions. The cases with more than one Bluetooth interferer is treated at the end, where we have selected three measurements with 1, 2 and 4 interferers using the same long packets in both interferers and reference network. These three energy distributions are compared to their theoretical counterparts. The levels of the interference, expressed in terms of average interference power over the reference packet in mW/dBm, are the correct ones for the measurements while the theoretical CDF curves are calculated for a nominal propagation loss of 0 dB and shifted along the dB axis to the same range as the measurements.

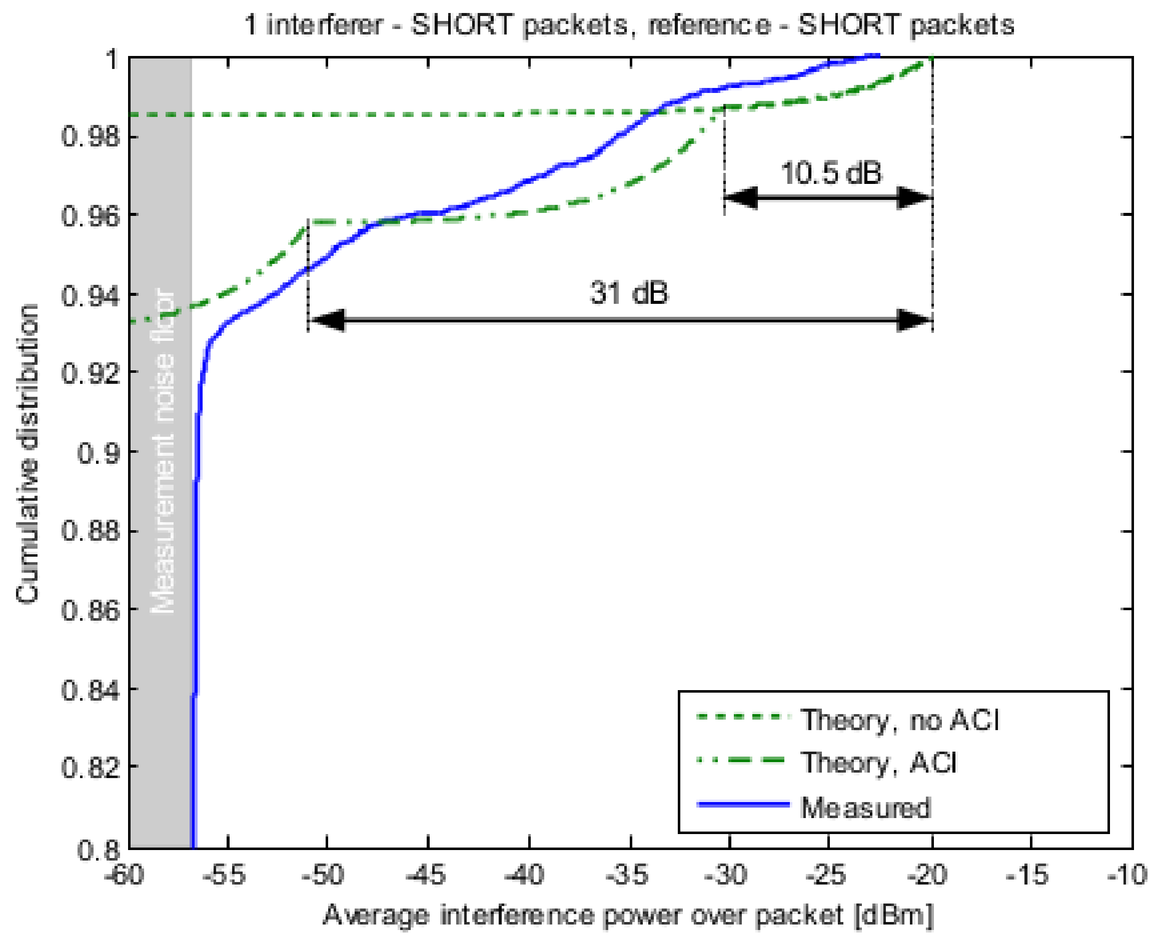

Figure 2: Short packet CDFs for the case where a single interfering Bluetooth network transmits short packets. The dashed curve shows theoretical results without taking ACI into account, and the dash-dotted curve includes ACI.

First we consider the measured CDF for short reference packets ($T = 355\ \mu s$) when a single interfering Bluetooth network transmits short packets, shown as the solid curve in Figure 2. For the purpose of visibility of the impact of ACI, we have chosen to present the theoretical CDFs from [18] without the modification introduced in Section B.. The theoretical CDF without ACI is quite far from the measured CDF, while the introduction of ACI makes the correspondence much clearer. The levels of ACI used to calculate the theoretical CDF are -10.5 dB and -31 dB, for interferers on channels at 1 and 2 MHz offset from the reference packet, respectively. These values are also used in [18] and are derived from minimum requirements in the Bluetooth specification [21]. In the figure we can see that these ACI levels are not entirely correct and better comparison results can be obtained by selecting ACI levels for the theoretical CDFs that fit our measurement data. This, however, introduces a risk of fitting our model to the measurements rather than evaluating its capacity to predict the interference distributions in different scenarios. We will therefore use the ACI levels derived from the Bluetooth specification throughout this paper, even if our "reference network" is a spectrum analyzer with a different receiver chain than a standard Bluetooth unit.

After concluding that it is important to include ACI in the theoretical model of interference, we proceed with four comparisons of theory and measurements for single Bluetooth networks as interferers. These comparisons are shown in figures 3 to 6, where each plot shows the measured CDF (solid) and the theoretical CDFs both with (dash dotted) and without (dotted) data variations included. In all four cases, the theoretical model seem to give a reasonably good prediction of the measured interference distribution. Significant features, like the changes in curvature and the over all slope of the curves show good resemblance between theory and measurements in all four cases. The comparison becomes a bit difficult for low interference levels, close to the measurement noise floor at about -57 dBm. The noise floor pulls down the measured CDF for low dBm values, as compared to the noise-free theoretical CDFs.

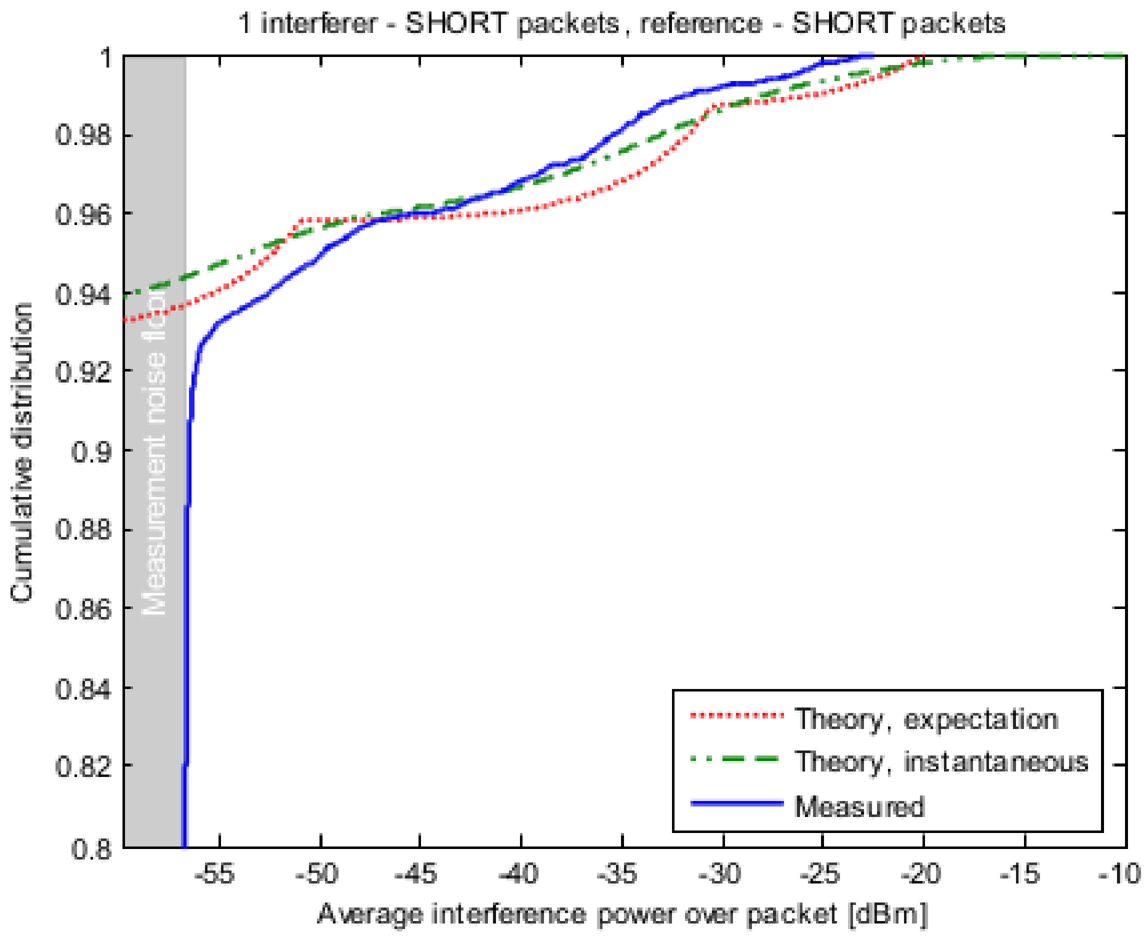

Figure 3: Short packet CDFs for the case where a single interfering Bluetooth network transmits short packets.

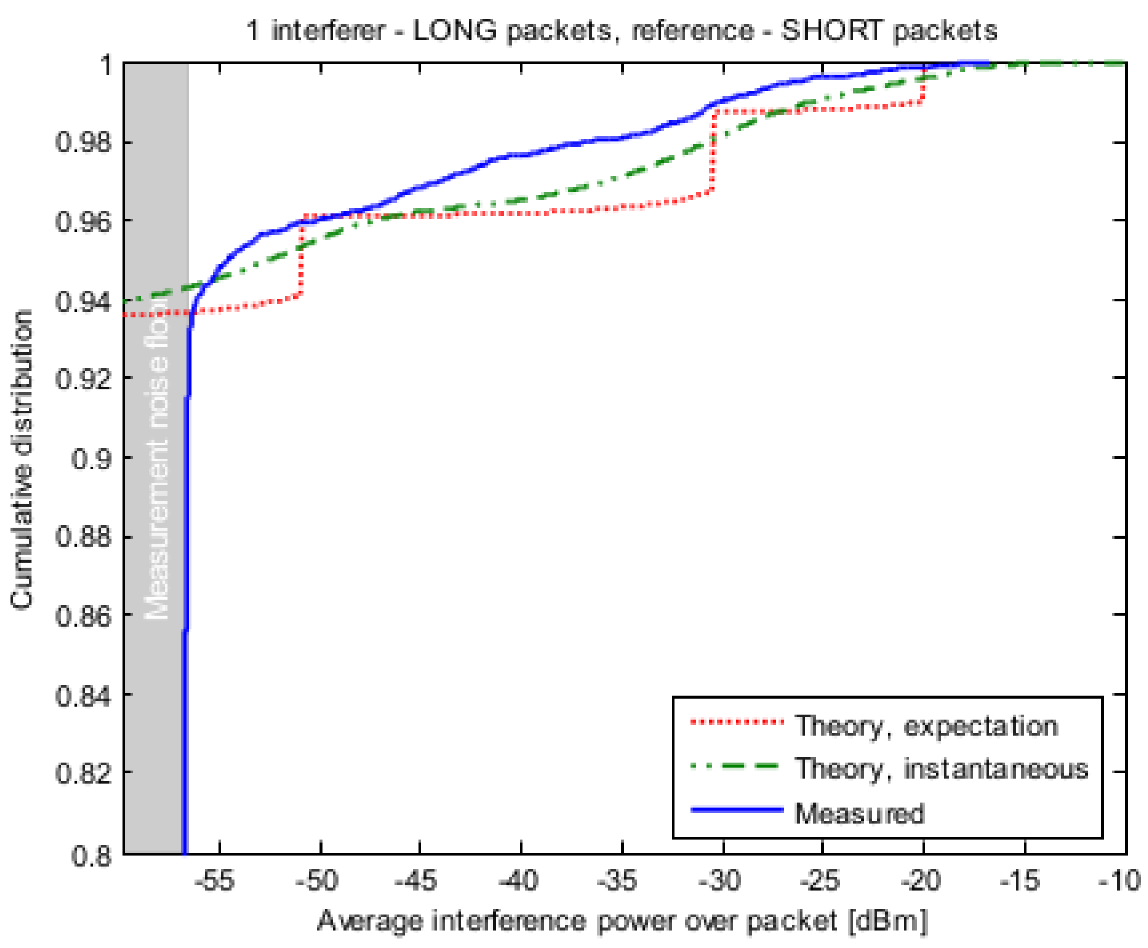

Figure 4: Short packet CDFs for the case where a single interfering Bluetooth network transmits long packets.

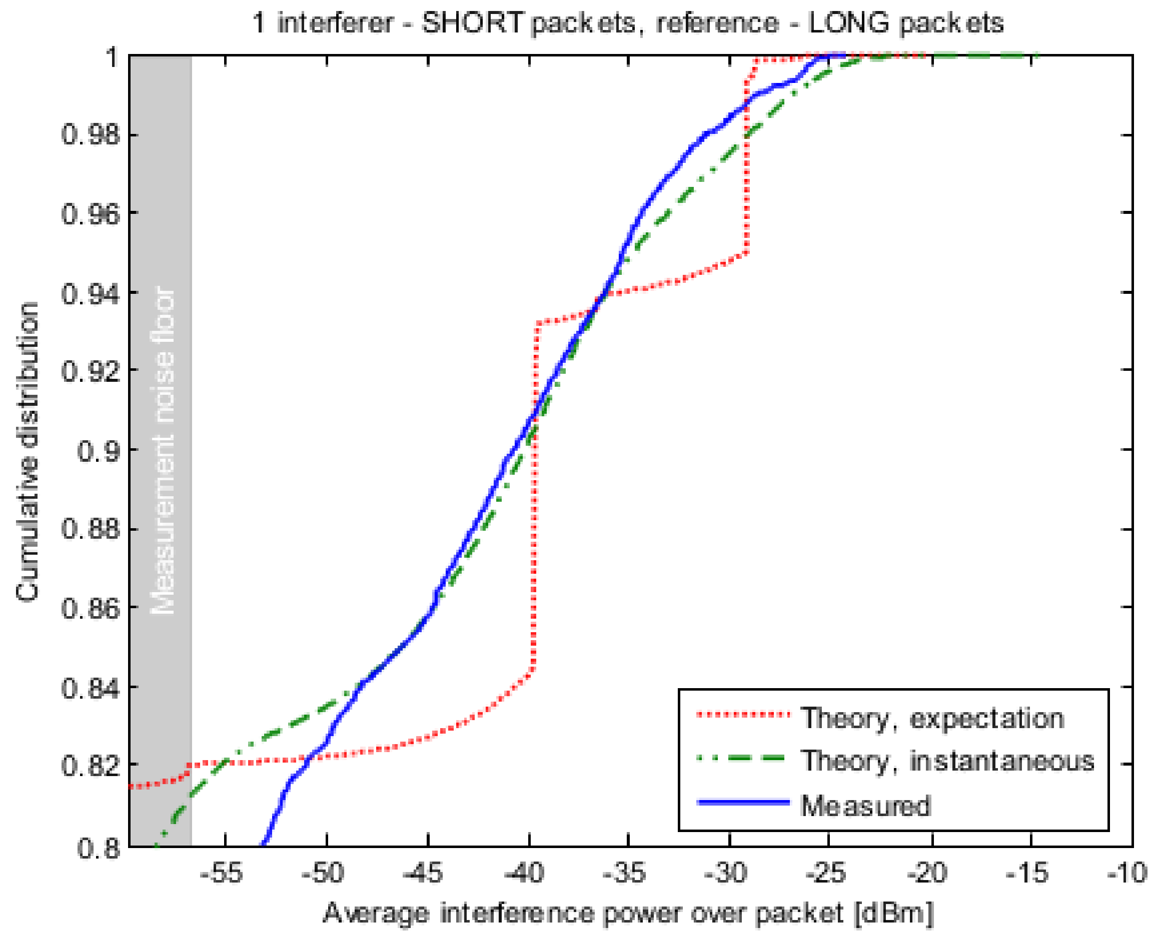

Figure 5: Long packet CDFs for the case where a single interfering Bluetooth network transmits short packets.

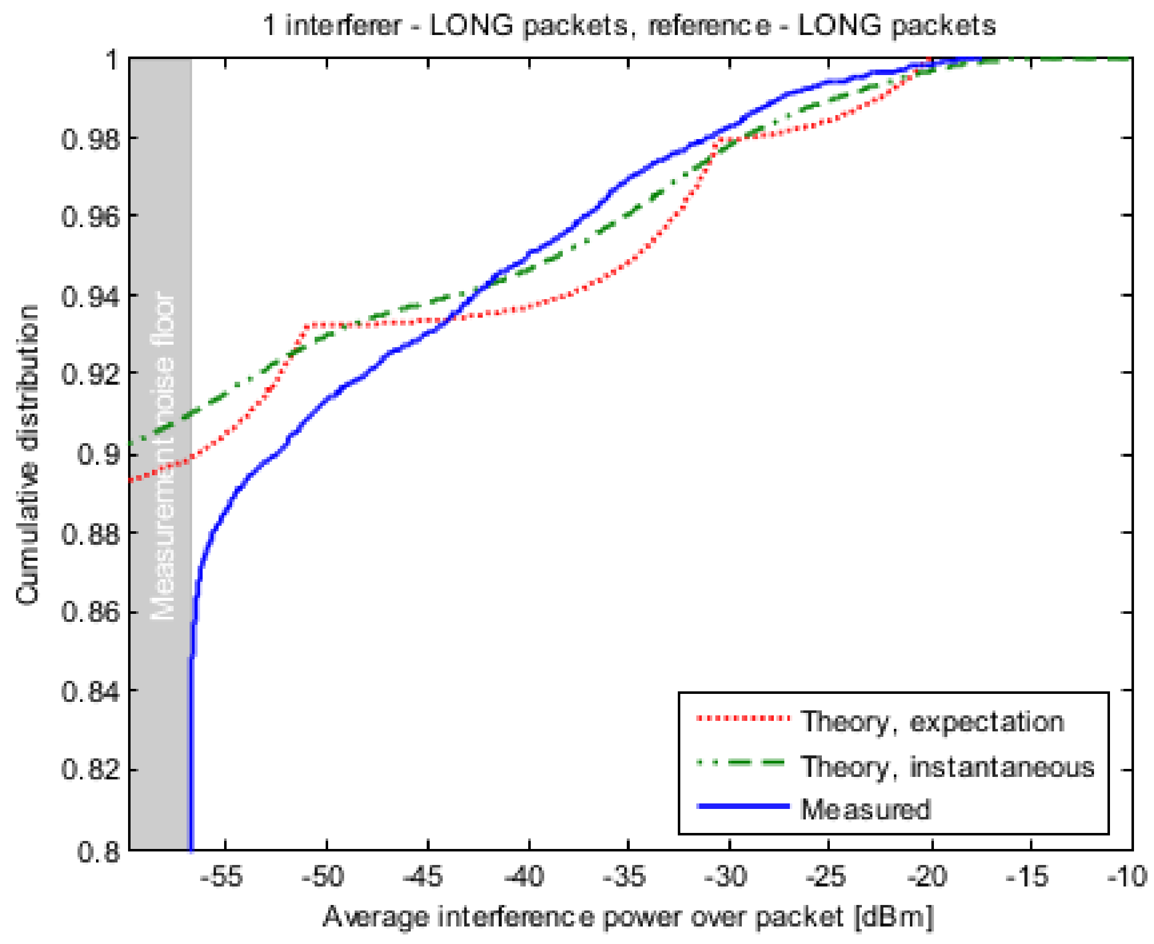

Figure 6: Long packet CDFs for the case where a single interfering Bluetooth network transmits long packets.

Having concluded that the theoretical interference model seems to follow measured interference levels reasonably well in four cases with single Bluetooth networks as interferers, we continue with the case when we have more than one interferer. There are four different settings with different interferer and reference packet lengths in our measurements. Each packet length setting contains measurements with 1, 2, 3, and 4 interferers. After inspecting comparisons of all these cases, finding that they show very similar behavior, we have chosen to present only one in this paper and, for visibility, with only 1, 2 and 4 interferers included in the figure. A comparison of theoretical and measured CDFs for long packets in both interferers and reference network is shown in Figure 7. The curves representing 1 interferer are the same as in Figure 6, while the curves for 2 and 4 interferers are new. The theoretical and measured CDFs seem to agree well in shape for high dBm values, while the measurement noise floor limits the possibility to make good comparisons for low dBm values.

After comparing a set of measurements with the corresponding theoretical model in [18], we conclude that the theoretical

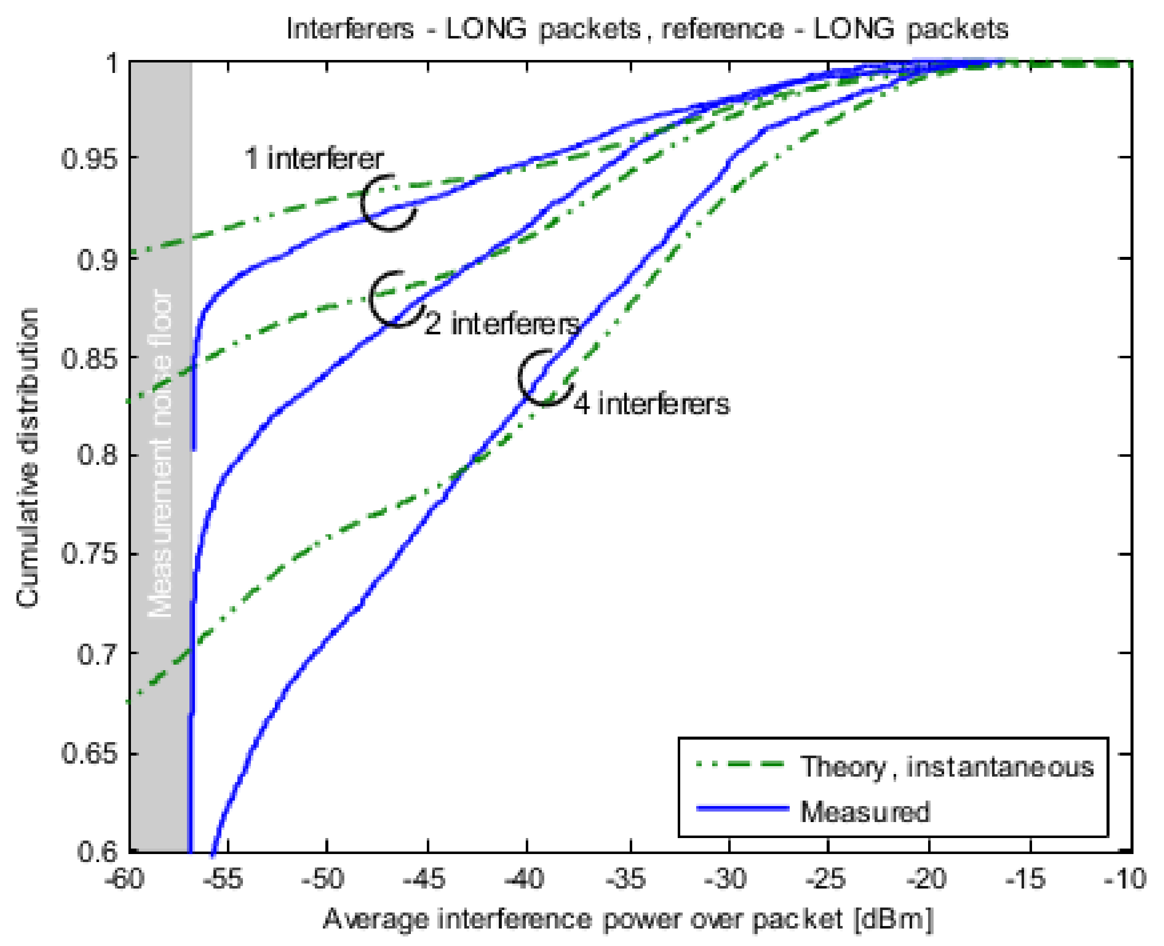

Figure 7: Long packet CDFs for the cases where one, two and four interfering Bluetooth networks transmit long packets.

model shows a reasonably good agreement with measurements, even if the correspondence between the measurement setup and the scenario modeled is not perfect. The biggest difference being that a spectrum analyzer is used as a receiver in the measurements while the model is based on the assumption of a Bluetooth receiver, leading to differences in ACI levels clearly visible in the comparisons. Even though we have only performed measurements on, and made comparisons with, a small subset of the possible interference scenarios, we feel confident that the model in [18] gives a good representation of the real interference in a wide range of Bluetooth scenarios, as long as ACI is properly included.

IV. Conclusions

There are several advantages of using analytical methods compared to using complex simulation setups when analyzing interference in heterogeneous radio networks, e.g., the ability to describe the generic properties of a system and the applicability of an analytical model on a large variety of system setups. In this paper we present measurement results providing experimental support for parts of the analytical framework in [18]. It is shown that for the investigated scenarios, calculated interference CDFs from Bluetooth networks are in good agreement with corresponding measured CDFs, indicating that the closed form expressions for the CDFs of the received interfering energy in [18] capture important mechanisms in real Bluetooth networks. This leads us to believe that the analytical model in [18] is useful, not only when analyzing the performance of interfering Bluetooth networks, but also in more general analyses of wider classes of interfering radio networks.

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