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Coexistence Technical Advisory Group

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Re:	[This is a response to a Call for Contributions, 19-04-0007-03-0000-Call-for-Submissions-Coexistence-Assurance-Methodology on 10 February.]		
Abstract	[This contribution contains a draft for a coexistence assurance methodology guide. It contains information from a tutorial, "Coexistence in the 2.4 GHz Band: Challenges and Solutions" by Nada Golmie and a presentation, "An Analytical Coexistence Assurance Model" by Steve Shellhammer.]		
Purpose	[To consider this contribution as the initial draft for the IEEE 802.19 Guide for Methodology on Evaluating Coexistence.]		
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IEEE P 802.19/D0

Date

Draft Guide for Methodology on Evaluating Coexistence.

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Introduction

(This introduction is not part of IEEE P802.19, Guide for Methodology on Evaluating Coexistence.)

See 9.3 of the *IEEE Standards 2000 Style Manual* for information on the Introduction. Use the **heading 1** style for the Introduction and the **paragraph** style for succeeding paragraphs of text. (See Clauses 1-3 in this template for information about styles.)

A working group list is included in the Introduction, with names listed in alphabetical order, first name followed by last name. Working group names should always be in the **member** style. In the example below, a lengthy list was broken into three columns. To create columns, use the Section command to break a continuous list into three columns; do **not** use tabs. Tabs will cause the order of names to change when the text is converted.

NOTE—The list may use one to four columns.

Example:

At the time this standard was completed, the working group had the following membership:

Stephen Shellhammer, *Chair*

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Ian Gifford	
Nada Golmie	
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The following members of the balloting committee voted on this standard. Balloters may have voted for approval, disapproval, or abstention. (To be provided by IEEE editor at time of publication.)

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Draft Guide for Methodology on Evaluating Coexistence

1 Overview

1.1 Scope

This Coexistence Assurance (CA) Methodology document will describe several methods for predicting the impact of mutual interference on network performance.

1.2 Purpose

The purpose of this guide is to provide a standardized method for predicting impact of mutual interference on network performance between dissimilar wireless networks.

1.3 Interference models overview

In order to predict the impact of interference it is necessary to build an interference model. Such models can be built at different levels of precision. Modeling and evaluation techniques may be described at several levels of precision. The following are examples of modeling and evaluation techniques.

Interference Model 1 – Analytical Model

This interference model utilizes analytical approximations of the wireless network physical layer (PHY) and Medium Access Control (MAC) sublayer. Since analytical approximations are used the precision of the model is potentially less than the other models; however, the model can be built in less time than the other models.

Interference Model 2 – Hybrid Analytical/Simulation Model

This interference model uses a combination of analytical and simulation techniques. Portions of the PHY and MAC models are based on analytical approximations and portions of the models are based on simulations. This interference model is more detailed than the analytical model but less detailed than the simulation model.

Interference Model 3 – Simulation Model

This interference model is based on simulations of both the PHY and MAC layers of the wireless system. This model is the most detailed model.

Interference Testing

If actual wireless network hardware is available then it is possible to perform testing and experimentation of the impact of interference on network performance. This approach to measuring network performance impact has the advantage of being very accurate; however, also the accuracy of this technique is dependent on the implementation details of the wireless network hardware being used in the testing.

These modeling and evaluation techniques will be described in more detail in later clauses.

2 Normative references

There are no normative references.

3 Definitions

Coexistence - The ability of one system to perform a task in a given shared environment where other systems have an ability to perform their tasks and may or may not be using the same set of rules. (IEEE 802.15.2-2003)

3.1 Discussion of Coexistence

The definition of coexistence defined in clause 3 is the result of countless debates, presentations, and contributions. To some this definition is still insufficient, since it is written in general terms, as is the suggested format for IEEE 802 definitions. It is for this reason that an explanation is necessary.

“The ability of one system to perform a task” is general enough so that it can cover a vast area of abilities, systems, and tasks. “The ability” may be as simple as the ability to send data. “One system” may be viewed as a single layer, a group of layers, or all layers of an implementation. For the IEEE 802 the system will most likely be the physical (PHY) layer and the Medium Access Control (MAC) sublayer. “Perform a task” may be defined to be to send data or to request and receive a connection. All of this would not be of any concern for one system or another if it were not for the fact that this is being done “in a given shared environment.” What this means is that if two systems are not sharing any limited resource, then coexistence is not applicable. However, for example, if a particular environment has two systems using the same radio frequency band (same time, same effective area), then coexistence now becomes an important consideration. “Where other systems have an ability to perform their tasks” means that this is not a one way definition but rather a two way (or possibly multi-way) definition. That is it is not enough to show that one system can perform its task in the presence of another system, but that the other system must be able to perform its task also. Finally, “may or may not be using the same set of rules” covers the various cases for similar and dissimilar systems to operate each according to their prescribed protocols (set of rules).

4 Background

As more and more heterogeneous wireless systems use the limited resources, means other than international or national regulations and laws are needed to permit current and future usage in an unmanaged, unregulated, wireless world.

Coexistence is a lot more complicated than the simple regulatory issues on power emissions (Electro Magnetic Interference (EMI)) and radio frequency allocations (licensed and unlicensed). These are the brute force and simple methods to avoid coexistence, which are only possible when regulated and enforced. If each system is given a different radio frequency to operate in, then no two systems would ever cause interference of another system because neither would be sharing the same resource. If all other systems must limit their radio emissions below a certain level, then none of these systems would cause interference to the claimed system because the initial system would have been designed to perform in an environment with a level of interference no higher than that stated. However we are all painfully aware that there are not enough radio frequency bands so that every system has its own dedicated band, nor can we limit the radio emissions so that every system is ranked by an emission level.

Even the known methods for measuring and ensuring the above two characteristics are becoming outdated as new methods and applications are carried via wireless means. For example, bit error rate (BER) is a classic measurement that gives information that can be used to develop and improve protocols and systems. However, a BER alone is insufficient when it comes to coexistence. A certain BER may be detrimental to a particular application, but not be for another. Voice data is an example of this. Voice data can be sampled

and distributed under the pulse code modulation (PCM), adaptive pulse code modulation (ADPCM), code excited linear prediction (CELP), or any of the other standards or proprietary codings. Each of these will perform differently, some not at all, given certain BERs.

Also because most systems now support multiple applications, the use of a single BER for the system may or may not satisfy all applications. Specifying the worst BER for the application that is most effected by BER, may be over kill, if that application is not the most commonly used application.

4.1 Past and present methods for interference reduction or coexistence avoidance

Previous simple solutions to reduced interference or coexistence avoidance were through national and international regulations.

Frequency band allocations were used to divide the limited radio frequency spectrum, thus avoiding coexistence.

Transmitter power was and still is a regulated form of interference reduction and coexistence improvement.

Time division access permits sharing of a limited resource.

Frequency hopping and direct sequence spread spectrum methods are used to reduce interference and to improve coexistence.

Most of these regulations and techniques consider only the electromagnetic interference from a radio spectrum point of view. This is just the beginning of other methods and techniques for coexistence, since these radio effects eventually affect the MAC sublayer and other higher layer protocols.

4.2 Steps to consider for evaluating coexistence

The follow describes briefly the steps necessary for evaluating coexistence.

The first step in evaluating coexistence starts by identifying at least two systems that you want to examine.

Once at least two systems are identified, then one needs to identify what resource is being shared. In most cases this is the wireless resource. If the two systems do not share a resource, then no further examination is needed.

After two systems, which share a common resource, have been identified, one must select the performance metrics that will be used in the further evaluations. Some performance metrics are bit error rate, packet loss, access delay, and throughput. Once the performance metrics are agreed to, then one must determine in which manner these performance metrics will be used. This should be one of the methods described here, so that results may be more easily be compared. Defining usage scenarios and “typical” applications to use needs to be defined next. Some suggestions are topology, transmission power, and traffic distribution. Given all this one can begin to generate results and to quantify the impact of mutual interference on the protocol’s performance.

4.3 Summary

By now one should see that coexistence is neither simple to describe nor easy to measure at a high level, rather it is a matter for details and specifics. This brings us to the need for such a guideline. In the following clause we introduce four models and techniques that may be used to evaluate coexistence between and among systems.

Please note that this document does not provide nor is it intended to provide levels or values that will determine whether something is coexistent or not. Only the methods for obtaining the data, which can be used to make such determinations, are described herein.

5 Interference Models

In order to predict the impact of interference it is necessary to build an interference model. Such models can be built at different levels of precision. Described in the following clauses are several modeling and evaluation techniques at several levels of precision. A table containing a summary of the advantages and disadvantages of each type is presented at the end of this clause.

5.1 Interference Model 1 – Analytical Model

This interference model utilizes analytical approximations of the wireless network physical layers and MAC sublayers. Since analytical approximations are used, the precision of the model is potentially less than the other models; however, the model can be built in less time than the other models.

Availability of vendor fact sheets or theoretical results describing radio receivers in terms of bit error versus signal to interference ratio

Based on probability of packet collisions in time and frequency.

Provides a back of the envelope approximation.

5.1.1 Interference Model 1 – Analytical Model – step by step

To be included

5.1.1.1 Step one- model the interferer

There may be two interferer models needed. One is for a baseline, when no interference other than Additive White Gaussian Noise (AWGN), or thermal noise, is assumed (N_0) and the second is for characterizing the interference (N_{eff}) caused by the system under consideration. When modeling the interferer a pulse is used, which is modeled in the frequency domain as band-limited white noise of power, P_T

Distribution of pulse durations

Distribution of spacing between pulses

5.1.1.2 Step two – use of path loss model

Select a path loss model and clearly state it, so that others may use it. This gives E_b

5.1.1.3 Step three – define a topology

To be included

5.1.1.4 Step four – create receiver model

Suggest modeling the receiver filter as an ideal brick wall filter, as far as interference goes. This permits only the portion of the interfering signal to get passed through undisturbed. The remainder of the interfering signal is eliminated entirely.

5.1.1.5 Step five – what to measure

Select the performance metric(s). Most likely this is the bit error rate (BER). This then becomes a calculation of the BER for two periods. One period is the duration of a received packet when there is no interference. The other period is the duration of a received packet when there is interference.

A choice should be made as to whether the AWGN, or thermal noise, is significant enough to consider further or not. If one wants to consider AWGN, then pick an AWGN level that would give an equivalent power after the receiver filter.

5.1.1.6 Step six – summary

One now has a model and method to calculate the BER when there is (N_{eff}) and there is not interference (N_0) along with the E_b obtained by the path loss model.

5.1.1.7 Step seven – calculate packet error rate

One can now continue by applying the BER to examine another performance metric, packet error rate.

5.1.1.7.1 Packet error rate steps

Calculate PER for a fixed value of T.

Average over all values of T using the previously calculated probability density function (PDF) for T

If necessary, average over packet duration, T_D , assuming it is variable.

5.1.1.8 Step eight – calculate other metrics

Calculate other metrics (such as throughput, latency, or packet loss rate) based on the PER and necessary approximations (e.g., independence).

5.1.1.9 Step nine – write-up

Document the work for presentation.

5.2 Interference Model 2 – Hybrid Analytical/Simulation Model

This interference model uses a combination of analytical and simulation techniques. Portions of the PHY and MAC models are based on analytical approximations and portions of the models are based on simulations. This interference model is more detailed than the analytical model but less detailed than the simulation model.

5.2.1 Interference Model 2 – Hybrid Analytical/Simulation Model – step by step

To be included

5.2.1.1 Step one

To be included

5.2.1.2 Step two

To be included

5.3 Interference Model 3 – Simulation Model

This interference model is based on simulations of both the PHY and MAC layers of the wireless system. This model is the most detailed model. This model contains both physical layer and MAC sublayer protocol behavior details. This model is used to study a number of “what if” scenarios. Under these “what if” scenarios, one can analyze the effects of mutual interference under various accuracy ranges.

5.3.1 Interference Model 3 – Simulation Model – step by step

This clause contains a step by step approach to creating, modeling, measuring, and gathering information for the simulation model for interference evaluation and performance data collection.

5.3.1.1 Step one – consider homogeneous set-up

Create a model of the Radio Frequency, Physical layer, and MAC sublayer for the system. Other items to include are models of the expected or designed for traffic and the expected interference models. The expected interference model may be based on experimental measurements or analysis.

All of this is used to create an environment for two communicating systems that is used to measure performance of homogeneous systems. After this is done a baseline is now available for proceeding to the next step.

5.3.1.2 Step two – consider a heterogeneous set-up

In this step the model created from step one is added to a model from another system. In its simplest form there will be two systems communicating using one model and two other systems communicating using another model. The interference model from step one is now a combined model, which permits in this case, both communications that will act upon each other, possibly as interference.

5.3.1.3 Step three – write-up

Document the work done and the results collected. See performance analysis clause (6) and format for the presentation of results clause (7) for more information.

5.4 Interference Testing

If actual wireless network hardware is available, then it is possible to perform testing and experimentation of the impact of interference on network performance. This approach to measuring network performance impact has the advantage of being very accurate; however, also the accuracy of this technique is dependent on the implementation details of the wireless network hardware being used in the testing. This type of testing is vendor implementation specific and there is difficulty tying results to protocol options and parameters, rather than to implementation decisions.

5.4.1 Interference testing – step by step

To be included

5.4.1.1 Step one

To be included

5.4.1.2 Step two

To be included

5.5 Comparison of the models

Below is a table that lists some of the advantages and disadvantages of the described models.

Model	Advantages	Disadvantages
Model 1 -Analytical	Simple, uses approximations, Predicts relative impact of interference in a timely manner, Intended as a first-order approximation.	Not detailed.
Model 2 – Hybrid Analytical/Simulation	Faster than simulation alone, Better results than analytical alone.	Not as accurate as simulation alone, More time needed than analytical alone.
Model 3 - Simulation	Lots of possibilities, The more detailed the model the better the results.	Lots of possibilities, Results are only as good as what is modeled, Resource intensive.
Interference testing	“Real” results.	Results not available until products are developed, Difficult to tie results to protocol options and parameters, Results are vender specific.

6 Performance Analysis

In order to study or evaluate coexistence, performance needs to be defined. That is what items are going to determine whether the system is functioning correctly.

6.1 What to measure

Performance metrics must be defined. Some examples of performance metrics are described in the following:

Bit error rate (BER) - number of bits received in error divided by the total number of bits received.

Residual errors – number of bits that remain in error after applying an error correction code (a theoretical value)

Packet error rate - number of packets received in error divided by the total number of packets received.

Packet loss – number of packets lost due to errors divided by the number of packets successfully received.

Access delay – the time it takes to transmit a packet from the time it is passed to the MAC sublayer until it is successfully received at the destination. Generally this accounts for queuing and retransmission(s) delays.

Average access delay – sum of all access delays divided by the number of samples.

Coefficient of delay variance – access delay standard deviation divided by the average access delay.

Access delay probability distribution function (i.e., 95th, 99th percentiles)

End-to-end delay - the time it takes to transmit an “application” layer packet.

Average end-to-end delay – sum of all end-to-end delays divided by the number of samples.

Coefficient of end-to-end delay variance – end-to-end delay standard deviation divided by the average end-to-end delay

End-to-end delay probability distribution function (i.e., 95th, 99th percentiles)

Throughput – the number of bits successfully received divided by the time it took to transmit them over the medium.

Average throughput – total number of bits received at the destination divided by the simulation time.

Goodput – the number of successful packets received at the receiver’s “application” layer divided by the number of “application” layer packets that could be transmitted over the medium.

Average goodput – total number of information bits received at the destination divided by the simulation time.

The term, application layer, may or may not be referring to the application layer as described in the International Organization for Standardization (ISO) Open Systems Interconnection Basic Reference Model (ISO/IEC 7498-1:1994). Instead it is used here as a generic term for a layer higher than then layers under evaluation. For example if the system model only consists of the MAC sublayer, Physical layer, and RF, then the application layer is that layer above the MAC sublayer. On the other hand if the system model consists of those and is using the TCP/IP networking and transport function, then the application layer may be the TCP layer or the layer above. The application layer may mean the application layer (ISO/IEC) when the system model contains all of the intermediary layers. This is further described under the where to measure subclause.

6.2 Where to measure?

Given the performance metrics, now one needs to determine where these metrics will be measured. For example for BER most believe this to be relevant only to the physical layer, however there is no requirement that the BER cannot be at a higher layer. It is just by convention that at a higher layer the terms, frame and packet are more convenient.

Since this is IEEE 802, some measurement points are at the physical layer receiver, the physical layer, the interface between the physical layer and the MAC sublayer, at the MAC sublayer, between the MAC

sublayer and the nearest upper layer. For IEEE 802.15.1 there are various possible measurement points within the MAC sublayer due to multiple layering within the MAC sublayer.

The more measurement points embedded into the models, then the more useful is data collected. However there is a trade-off because more information means more time to process.

7 Format for the presentation of results

To easily compare results it is suggest that the results are presented in a consistent format. The following are suggested.

Map parameters to relevant coordinate axis:

For Physical layer: use SNR on the x-axis and plot on the y-axis BER.

For MAC sublayer: use either the offered load or the BER on the x-axis and plot on the y-axis one of the following:

- i) access delay
- ii) throughput
- iii) goodput
- iv) packet loss
- v) coefficient of delay variation

8 Examples

This clause lists a number of examples that are the basis for the methodologies described.

IEEE 802.15.2 Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Bands – 2003 shows the results from using the three models (analytical, hybrid, and simulation) as applied to the two wireless technologies: IEEE 802.11 and IEEE 802.15.1.

Annex C of IEEE 802.15.3 Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) – 2003 shows the results from using an analytical (calculations) model.

Annex E of IEEE 802.15.4 Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs) –2003 shows the results from using a hybrid approach.

Annex C of IEEE 802.16.2 Recommended Practice Coexistence of Fixed Broadband Wireless Access Systems – 2001 shows the results from a simulation model.

9 Bibliography

IEEE 802.11 Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications –1999 [Reaffirmed 2003]

IEEE 802.15.1 Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Wireless Personal Area Networks (WPANs) - 2002

IEEE 802.15.2 Recommended Practice Coexistence of Wireless Personal Area Networks with Other Wireless Devices Operating in Unlicensed Frequency Bands –2003

IEEE 802.15.3 Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for High Rate Wireless Personal Area Networks (WPANs) – 2003

IEEE 802.15.4 Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (LR-WPANs) – 2003

IEEE 802.16 Air Interface for Fixed Broadband Wireless Access Systems – 2001

IEEE 802.16.2 Recommended Practice Coexistence of Fixed Broadband Wireless Access Systems – 2001

ISO/IEC 7498-1:1994 Information technology -- Open Systems Interconnection -- Basic Reference Model: The Basic Model.

Annex A Coexistence Evaluation Form

This annex contains a cover sheet that should be used to show the initial considerations for evaluating coexistence assurance.

The target system is the system that is currently under investigation. For example: a system under standard development.

The potential interfering system(s) is(are) that(those) system(s) that share a resource that may cause interference to the target system or that the target system may cause interference to.

The interference item is the resource that is shared between the target and potential systems. It is also the resource that is not shared between the target system and the excluded system.

The excluded system(s) is(are) that(those) system(s) that do not share a resource and for this reason will not be considered any further for determining coexistence.

Methodology used:	Analytical	Hybrid	Simulation	Testing	Other
Target system:					
Potential interfering system(s):		Interference item: (shared resource)			
Excluded system(s):		Reason(s):			
Performance metrics to be collected:					
What to measure?					
Where to measure?					
Describe useage scenario(s)					
“typical” applications					