IEEE 802.15.4 Low Rate –Wireless Personal Area Network Coexistence Issues

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Abstract – IEEE 802.15.4 is a proposed standard addressing the needs of low-rate wireless personal area networks or LR-WPAN with a focus on enabling wireless sensor networks. The standard is characterized by maintaining a high level of simplicity, allowing for low cost and low power implementations. Its operational frequency band includes the 2.4GHz industrial, scientific and medical band providing nearly worldwide availability; additionally, this band is also used by other IEEE 802 wireless standards. Coexistence among diverse collocated devices in the 2.4 GHz band is an important issue in order to ensure that each wireless service maintains its desired performance requirements. This paper presents a brief technical introduction of the IEEE 802.15.4 standard and analyzes the coexistence impact of an IEEE 802.15.4 network on the IEEE 802.11b devices.

I. INTRODUCTION

With the success of wireless local area networks (WLANs), the wireless networking community has been focused on enhancing WLAN capabilities and developing new approaches to meet the needs of the growing pool of applications requiring wireless devices. In addition, there is a movement towards standardized protocols and away from applications requiring inflexible wireless connectivity often based on proprietary technologies. Recently, the concept of a standardized low rate wireless personnel area network (LR-WPANs) has emerged [1-4]. Fuelled by the need to enable inexpensive wireless sensor network applications, in December 2000 Task Group 4, under the IEEE 802 Working Group 15, was formed to begin the development of a LR-WPAN standard IEEE 802.15.4. The goal of Task Group 4 is to provide a standard which has the characteristics of ultra-low complexity, low-cost and extremely low-power for wireless connectivity among inexpensive, fixed, portable and moving devices [1].

The IEEE 802.15.4 devices are proposed to operate in the 2.4 GHz industrial, scientific and medical (ISM) band. The same operational band used by other IEEE 802 wireless devices, such as IEEE 802.11b (WLAN) and IEEE 802.15.1 (Bluetooth). IEEE 802.15.4 and IEEE 802.11b standards support complimentary applications; e.g., IEEE 802.15.4 devices used to support a wireless sensor array within a home or industrial complex could be collocated with IEEE 802.11b in order to provide WLAN support. Wireless devices based on these two standards are likely to be collocated and therefore their ability to coexist needs to be evaluated. Central to the coexistence issue between wireless devices is the ability to differentiate between operational conditions which will and will not result in the communication devices failing to meet the requirements of an application.

Section II of this paper presents a technical overview of the proposed IEEE 802.15.4 standard. In Section III, an analytical model is presented to provide an approach for evaluating the coexistence between IEEE 802.15.4 and IEEE 802.11b. Conclusions are presented in Section IV.

II. TECHNICAL OVERVIEW

A summary of the high-level features of the IEEE 802.15.4 is shown in Table 1.

By favoring low-cost and low-power, IEEE 802.15.4 is enabling applications in the fields of industrial, agricultural, vehicular, residential and medical sensors and actuators. Until recently, these applications could not make use of current wireless technologies or would have to use proprietary solutions (in most cases unidirectional) [2,3].

The intent of IEEE 802.15.4 is to address applications where existing WPAN solutions are too expensive and the performance of a technology such as Bluetooth^{TM} is not required. IEEE 802.15.4 LR-WPANs complement other WPAN technologies by providing very low power consumption capabilities at very low cost, thus enabling applications that were previously impractical. Table 2 illustrates a basic comparison between IEEE 802.15.4 and other IEEE 802 wireless networking standards.

The IEEE 802.15.4 standard is being designed to be used in a wide variety of applications which require simple wireless communications over short-range distances with limited

Table 1: IEEE 802.15.4 High Level Characteristics

Frequency Band	Two PHYs	Low-Band (BPSK)	868 MHz	1 channel - 20 kb/s
			915 MHz	10 channels - 40 kb/s
		High-Band (O-QPSK)	2.4 GHz	16 channels - 250 kb/s
Channel Access	CSMA-CA and slotted CSMA-CA			
Range	10 to 20m			
Addressing	Short 8 bit or 64-bit IEEE			

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power and relaxed throughput needs. IEEE 802.15.4 facilitates Wireless Sensor Networks (WSNs) with the goal of reducing the installation cost of sensors and actuators while enabling sensor-rich environments.

Table 2: IEEE 802.15.4 High Level Characteristics

	802.11b WLAN	802.15.1 WPAN	802.15.4 LR-WPAN
Range	~100 m	~10 - 100 m	10 m
Raw Data Rate	11 Mbps	1 Mbps	<= 0.25 Mbps
Power Consumption	medium	low	**ultra low**

A. *LR-WPAN Design*

A main design consideration for LR-WPANs is low power consumption, thereby maximizing battery life. To achieve low average power consumption, IEEE 802.15.4 assumes that the amount of data transmitted is short and that it is transmitted infrequently in order to keep a low duty-cycle. In addition, the packet structure was designed to add minimal overhead over the transported payload.

The standard allows the formation of two possible network topologies: the star topology or the peer-to-peer topology, Figure 1. In the star topology, the communication is performed between network devices and a single central controller, called the PAN coordinator. A network device is either the initiation point or the termination point for network communications. The PAN coordinator is in charge of managing all the star PAN functionality. In the peer-to-peer topology, every network device can communicate with any other within its range. This topology also contains a PAN coordinator, which acts as the root of the network. Peer-to-peer topology allows more complex network formations to be implemented; e.g. ad hoc and self-configuring networks. The routing mechanisms required for multi-hopping are part of the network layer and are therefore, not in the scope of IEEE 802.15.4.

An IEEE 802.15.4 LR-WPAN device is composed of a physical (PHY) layer and a medium access control (MAC) sublayer that provides access to the physical channel for all types of transfer and ensures the reliable transfer of frames.

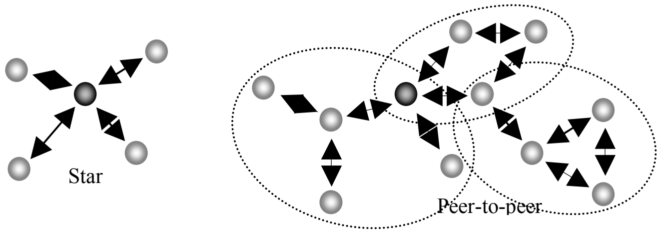

Figure 1: Star and peer-to-peer topology (organized as a clustered network)

B. *PHY Layer*

IEEE 802.15.4 was designed to support two PHY options based on direct sequence spread spectrum (DSSS); this characteristic allows the use of low-cost digital IC realizations. Both PHYs make use of the same basic packet structure for low-duty-cycle low-power operation. The primary difference between the two PHYs is the frequency band. The 868/915 MHz PHY (also called low-band) is specified for operation in the 868 MHz band in Europe offering one channel with a raw data rate of 20 kb/s and the 915 MHz ISM band in North America offering 10 channels with a raw data rate of 40 kb/s. The low-band uses binary phase shift key (BPSK) modulation.

The 2.4 GHz PHY (also called high-band) specifies operation in the 2.4 GHz ISM band, with nearly worldwide availability. This band spans from 2.4 to 2.483 GHz and offers 16 channels with channel spacing of 5 MHz, operating with a raw data rate of 250 kb/s using offset quadrature phase shift key (O-QPSK) modulation.

The IEEE 802.15.4 standard specifies a receiver sensitivity of -85 dBm for the 2.4 GHz band and -92 dBm for the 868/915 MHz band. Practical implementations are expected to improve this requirement. The standard specifies a transmit power capability of 1 mW, although it can vary within governmental regulatory bounds.

Both PHY layers use a common packet structure, enabling the definition of a common MAC interface. Each packet, or PHY protocol data unit (PPDU), contains a preamble, a start of packet delimiter, a packet length, and a payload field, or PHY service data unit (PSDU). The 32-bit preamble is designed for acquisition of symbol and chip timing. The IEEE 802.15.4 payload length can vary from 2 to 127 bytes. This structure is shown in Figure 2.

PHY protocol data unit (PPDU)			
Preamble	Start of packet delimiter	Length Field	PHY layer payload PHY service data unit (PSDU)
4 bytes	1 byte	1 byte	2-127 bytes

Figure 2: IEEE 802.15.4 Packet Structure

C. *MAC sublayer*

The IEEE 802 project divides the data link layer (DLL) in to two sublayers, the MAC and logical link control (LLC) sublayers. The LLC is standardized in IEEE 802.2 and is common among the IEEE 802 standards.

The IEEE 802.15.4 medium access control (MAC) sublayer controls the access to the radio channel employing the CSMA-CA mechanism. If upper layers detect that the communications throughput has been degraded below a determined threshold, the MAC will be instructed to perform an energy detection scan through the available channels. Based on the detected energy, the upper layers will switch to the channel with the lowest energy. The IEEE 802.15.4 performs the energy scan by the use of a clear channel assessment procedure. This can be performed by following either a simple in-band energy detection above a threshold, or an IEEE 802.15.4 carrier detection or a combination of both.

The 802.15.4 MAC is also responsible for flow control via acknowledged frame delivery, frame validations as well as maintaining network synchronization, controlling the association, administering device security and scheming the guaranteed time slot mechanism.

The MAC sublayer provides two services to higher layers: the MAC data service accessed through the MAC common part sublayer (MCPS-SAP) containing three primitives and the MAC management service accessed through the MAC layer management entity (MLME-SAP) containing 28 primitives.

The LR-WPAN standard allows the optional use of a superframe structure for applications requiring dedicated bandwidth to guarantee communication latency. The format of the superframe is defined by the PAN coordinator, by using the network beacons which bound the superframe structure. The superframe is composed of 16 equally sized time slots grouped in two sections: the contention access period (CAP) and the contention free period (CFP). The time slots assigned for the CFP are called guaranteed time slots (GTS) and are administered by the PAN coordinator. A pictorial of the superframe structure is shown in Figure 3.

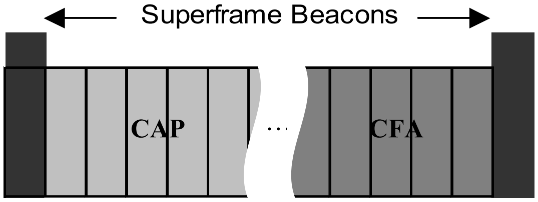

Figure 3: Superframe structure

III. COEXISTENCE WITH IEEE 802.11B

Coexistence between 2.4 GHz band wireless devices has become an important issue in order to ensure each collocated wireless service maintains its desired performance requirements. As discussed above, the IEEE 802.15.4 was designed to meet the communication needs of certain applications. It also represents a new device which might impact the operation of current 2.4 GHz ISM band devices such as the IEEE 802.11b WLAN. In this section, the impact of the IEEE 802.15.4 on the IEEE 802.11b is evaluated.

Coexistence is evaluated in terms of the factors influencing the IEEE 802.11b's performance. These factors involve the operational environment, including the interference environment and the signal propagation characteristics. Due to the multiplicity and the uncertainty of these factors, a stochastic model of the underlying process is well suited for coexistence evaluation. The IEEE 802.11b protocol is based on packet transmission with a packet acknowledgement. Packet collision is therefore the underlying process determining coexistence. A formal definition of a packet collision, C, is the event where one or more IEEE 802.15.4 signals corrupts an IEEE 802.11b packet transmission such that the retransmission of the IEEE 802.11b packet is required. Using this definition, the probability of collision, $\Pr[C]$, can be evaluated in terms of the operational environment. The IEEE 802.11b performance can then be evaluated by evaluating a standard measure of performance, such as packet error rate (PER), in terms of $\Pr[C]$.

In developing the analytical model, the IEEE 802.15.4 network is assumed to be based on a group of clusters as depicted Figure 4. Only the downlink signal between the IEEE 802.11b access point (AP) and the IEEE 802.11b station (STA) is assumed to be impacted by IEEE 802.15.4 network activity. This assumes there is sufficient separation between the AP and the IEEE 802.15.4 devices, such that interference on the uplink is less likely. The AP and STA are separated by a distance d_S and based on the typical IEEE 802.11b transmit power of 20 dBm, the maximum coverage range is $d_S \approx 20m$.

Since both the IEEE 802.11b and IEEE 802.15.4 operate on fixed carrier frequencies, the $\Pr[C]$ is based on the IEEE 802.15.4 nodes' probability of activity and whether or not an active node has sufficient power to cause interference at the STA. The probability of activity within a single cluster is given by $\Pr[A_C]$ and, within the cluster, there are N_{T_C} nodes. By modeling the activity at each of the cluster's nodes as independent and identically distributed (iid), then the probability of activity at a given node is $\Pr[A_C]/N_{T\_C}$. Next, if N_{I_C} nodes within a cluster have sufficient power to cause a collision at the station, then the collision probability for a single cluster is

$$\Pr[\mathrm{C}] = 1 - \left(1 - \frac{\Pr[A_C]}{N_{T\_C}}\right)^{N_{I\_C}} . \tag{1}$$

The result given in (1) can be extended to a network of IEEE 802.15.4 clusters. Given the network has N_C clusters and modeling the activity within each cluster as independent,

$$\Pr[\mathrm{C}] = 1 - \prod_{i=1}^{N_C}\left(1 - \frac{\Pr\left[A_C^{(i)}\right]}{N_{T\_C}^{(i)}}\right)^{N_{I\_C}^{(i)}} \tag{2}$$

where the superscript (i) is used to denote the i^{th} cluster.

The expression in (2) can be simplified under the following two assumptions. First, assume the probability of activity at

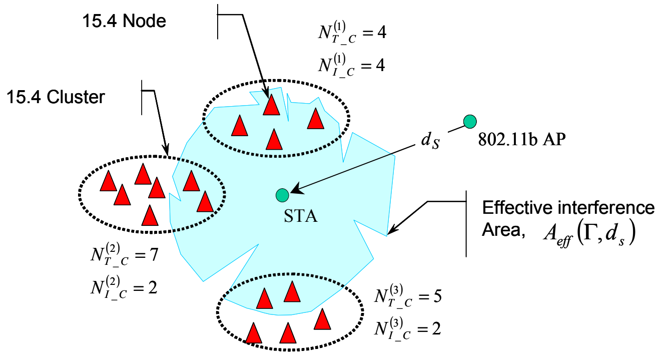

Figure 4: Geometry for deriving analytical model.

all nodes in the network is iid and $\Pr[A_C] \equiv \Pr[A_C^{(i)}] \quad \forall i \in 1,\ldots,N_C$. Next, by examining the Taylor Series expansion of the second term in (2)

$$\left(1-\frac{\Pr[A_C]}{N_{T\_C}^{(i)}}\right)^{N_{I\_C}^{(i)}} = 1-\frac{N_{I\_C}^{(i)}}{N_{T\_C}^{(i)}}\Pr[A_C] + \frac{N_{I\_C}^{(i)}\left(N_{I\_C}^{(i)}-1\right)}{2!\left(N_{T\_C}^{(i)}\right)^2}(\Pr[A_C])^2+\ldots \tag{3}$$

and comparing it with the Taylor Series expansion of

$$(1-\Pr[A_C])^{N_{I\_C}^{(i)}/N_{T\_C}^{(i)}} = 1-\frac{N_{I\_C}^{(i)}}{N_{T\_C}^{(i)}}\Pr[A_C]+ \frac{N_{I\_C}^{(i)}\left(N_{I\_C}^{(i)}-N_{T\_C}^{(i)}\right)}{2!\left(N_{T\_C}^{(i)}\right)^2}(\Pr[A_C])^2+\ldots \tag{4}$$

to a first order approximation (3) and (4) are the same. The error between the two expressions is $\sim O\left((\Pr[A_C])^2\right)$ and for many IEEE 802.15.4 applications $\Pr[A_C] < 0.1$. Therefore, the second assumption is to use (4) to approximate (3). Hence, using these two assumptions, (2) can be approximated by

$$\Pr[\mathrm{C}] \approx 1-(1-\Pr[A_C])^{N_0} \tag{5}$$

where

$$N_0 = \sum_{i=1}^{N_C} N_{I\_C}^{(i)} \big/ N_{T\_C}^{(i)}\,. \tag{6}$$

A. Estimating Number of Clusters

Estimating the number of clusters N_0 is presented in this section. In order for a IEEE 802.15.4 node to cause a collision at the STA, the interference to signal power $\Omega_{I/S}$ must exceed a power threshold $\gamma(f_{0ffset})$; i.e., $\Omega_{I/S} \geq \gamma(f_{0ffset})$ where $\gamma(f_{0ffset})$ is dependent on the frequency separation, f_{offset}, between the IEEE 802.11b's carrier frequency and the IEEE 802.15.4's carrier frequency. Therefore, the estimate of N_0, $\hat{N}_0$, is based on determining the effective area of interference, $A_{eff}(\Gamma, d_S)$ where Γ is the normalized interference to signal power ratio threshold,

$$\Gamma = \gamma(f_{offset}) + (\Omega_S)_{Tx} - (\Omega_I)_{Tx}\ (\mathrm{dB}) \tag{7}$$

where $(\Omega_S)_{Tx} = 20dBm$ and $(\Omega_I)_{Tx} = 0dBm$ are the transmit powers at the AP and the IEEE 802.15.4 interferer, respectively. Using the effective area of interference, the number of interferers satisfying $\Omega_{I/S} > \gamma(f_{offset})$ is

$$\hat{N}_0 = A_{eff}(\Gamma, d_S)\, D_I \tag{8}$$

where D_I is the IEEE 802.15.4 cluster density and (8) assumes the IEEE 802.15.4 nodes are uniformly distributed.

As derived by the author in [5], the effective interference area can be determined by

$$A_{eff}(\Gamma, d_S) = \pi\,(d_S)^2\, \exp\left[\frac{2\left(\sigma_{I/S}^2 - 10n\Gamma\log_{10}(e)\right)}{(10n\log_{10}(e))^2}\right]. \tag{9}$$

In (9), the signal propagation is based on a lognormal shadowing model with exponential path loss where *n* is the path loss exponent and $\sigma_{I/S}$ is the combined signal path lognormal shadowing standard deviation, i.e., $\sigma_{I/S} = \sqrt{\sigma_I^2 + \sigma_S^2}$.

An analytical model of $\gamma_{I/S}(f_{offset})$ is given by

$$\gamma_{I/S}(f_{offset}) = \gamma_{I/S}(0) - J_S(f_{offset})\ (\mathrm{dB}) \tag{10}$$

where $J_S(f_{offset})$ is the normalized jamming suppression of the IEEE 802.11b in the presence of a IEEE 802.15.4 signal and $\gamma_{I/S}(0)$ is the power threshold at $f_{offset} = 0Hz$. The jamming suppression, $J_S(f_{offset})$, was analytically derived based on

$$J_S(f_{offset}) = \Phi_{vv}(f_{offset}) * J_{CW}(f_{offset})(\mathrm{dB}) \tag{11}$$

where $J_{CW}(f_{offset})$ is the normalized jamming suppression of the IEEE 802.11b in the presence of a continuous wave (CW) tone derived in [5,6] and $\Phi_{vv}(f_{offset})$ is an estimate of the power spectral density (PSD) for a IEEE 802.15.4 signal. For the analysis presented in this paper the PSD for an MSK signal was used to approximate $\Phi_{vv}(f_{offset})$, i.e.,

$$\Phi_{vv}(f) = \frac{16A^2T}{\pi^2}\left(\frac{\cos 2\pi fT}{1-16f^2T^2}\right)^2 \tag{12}$$

where $T = 0.5\mu s$. Also, for this initial study $\gamma_{I/S}(0) = -10dB$ which corresponds to the value obtained from an empirical study involving Bluetooth and IEEE 802.11b [6,7]. In Figure 5, a graph of $\gamma_{I/S}(f_{offset})$ versus f_{offset} is given.

In order to evaluate the probability of collision, the range of $\hat{N}_0$ needs to be evaluated. From (8) and (9), the parameters influencing $\hat{N}_0$ are $D_I, n, \sigma_{I/S}, d_s, f_{offset}$. Graphs of normalized $\hat{N}_0$ versus d_S are given in Figures 6 and 7, using typical ranges for propagation parameters n and $\sigma_{I/S}$. In Figure 6, the IEEE 802.15.4 nodes and IEEE 802.11b are assumed to be cochannel, i.e., $f_{offset} = 0Hz$ ($\Gamma = 10dB$) and in Figure 7, $f_{offset} = 12MHz$ ($\Gamma = 45dB$).

From the results depicted in Figures 6 and 7, the following two observations can be made concerning environmental factors influencing the number of interferers, N_0:

1. Separation between the AP and STA, d_S, plays a major role regardless of the other environmental factors.

2. Factors influencing signal propagation, n and $\sigma_{I/S}$ become more significant as the carrier frequency offset increases, i.e., increasing f_{offset}.

Even though the first observation is expected, the magnitude of the impact is important to note. As is evident from both the graphs and (9), $N_0 \propto d_S^2$. The second observation is more subtle. From the argument of the exponential in (9), if $10n\Gamma\log_{10}(e) >> \sigma_{I/S}^2$, then the impact of the channel signal propagation parameters n and $\sigma_{I/S}$ are negligible. This is more likely to occur when the carrier frequencies are cochannel or nearly cochannel; see Figure 5 and (7). Conversely, when $f_{offset} >> 0Hz$, then n and $\sigma_{I/S}$ can have a more substantial impact on N_0, given $\sigma_{I/S} > 0dB$. This is evident from Figure 7.

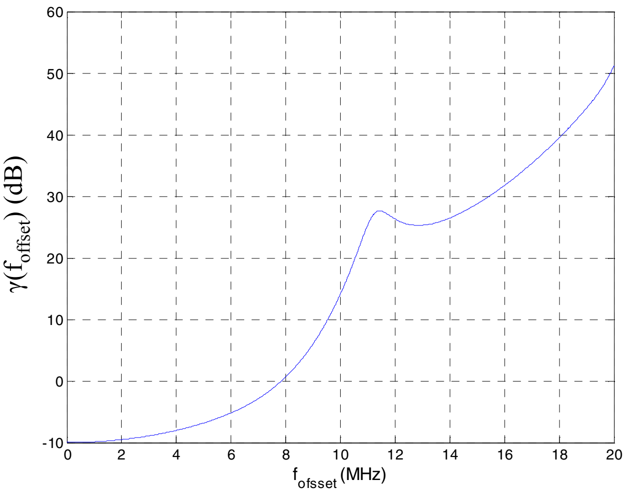

Figure 5: Power threshold versus carrier frequency offset.

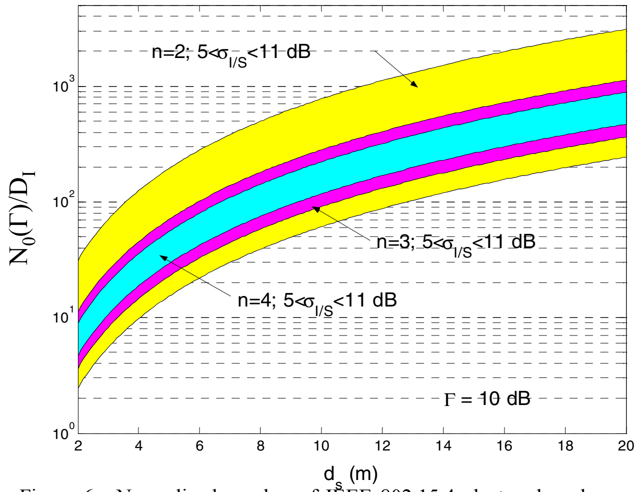

Figure 6: Normalized number of IEEE 802.15.4 clusters based on the interference and IEEE 802.11b signals being cochannel.

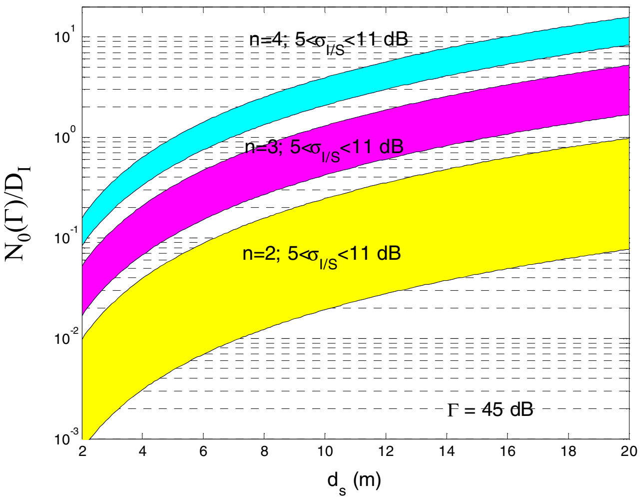

Figure 7: Normalized number of IEEE 802.15.4 clusters based on the interference and IEEE 802.11b signals' carrier frequencies being offset by 12 MHz.

B. *Coexistence Evaluation*

Coexistence issues between IEEE 802.15.4 and IEEE 802.11b can be evaluated by estimating $\Pr[C]$ by using (5), over meaningful ranges for $\hat{N}_0$ and $\Pr[A_C]$. In Figure 8, contours of equal $\Pr[C]$ are given on a log-log scale of $\hat{N}_0$ and $\Pr[A_C]$. These results for $\Pr[C]$ can then be related to expected IEEE 802.11b packet error rate, $E[PER]$, by using results derived in [5], $E[PER] = \Pr[C]$.

To illustrate the utility of the analysis tool presented in this paper, consider the following example. The IEEE 802.15.4 nodes operate at a $f_{offset} \geq 12MHz$; i.e., the carrier frequencies of the IEEE 802.11b and IEEE 802.15.4 are separated by at least 12MHz. This implies frequency management between the two wireless networks where the carrier frequencies are intentionally selected to reduce interference between the two networks. The density of the IEEE 802.15.4 clusters is 1 cluster in a 5x5 meter square, i.e., $D_I = 1/25\ clusters/m^2$. If $f_{offset} = 12MHz$ is assumed, then based on the RF environments evaluated, using graphs in Figure 7 and (8), $\hat{N}_0 < 0.6 clusters$. For illustration purposes, the goal is to ensure the IEEE 802.11b PER does not increase by more than 8% due to the presence of the IEEE 802.15.4 network. For a number of WLAN applications, an 8% increase in the PER would, at most, provide a mild decrease in the WLAN's performance. Then, by using either (5) or approximating the answer based on Figure 8, to maintain $E[PER] \leq 0.08$, the activity level within the IEEE 802.15.4 clusters must be less than 13%, i.e., $\Pr[A_C] \leq 0.13$. Based on [2, 3], typical IEEE 802.15.4 node activity will fall in the range of 0.1% to 1% (typically <1%) depending on the application. Combining this with the results obtained for $\Pr[A_C]$, the number of nodes in a cluster would need to be ≤ 13 for a 1% node activity rate up to ≤ 130 for a 0.1% node activity rate. Note, based on the graph depicted in Figure 5, by increasing f_{offset} either the impact on the IEEE 802.11b could be further reduced or the density and activity within an IEEE 802.15.4 network could be increased.

To summarize, for scenarios where frequency management is employed, it is reasonable to conclude that the IEEE 802.15.4 network will typically have little to no impact on the IEEE 802.11b's performance. This result should hold unless the STA is located near an IEEE 802.15.4 cluster with a high aggregate activity level.

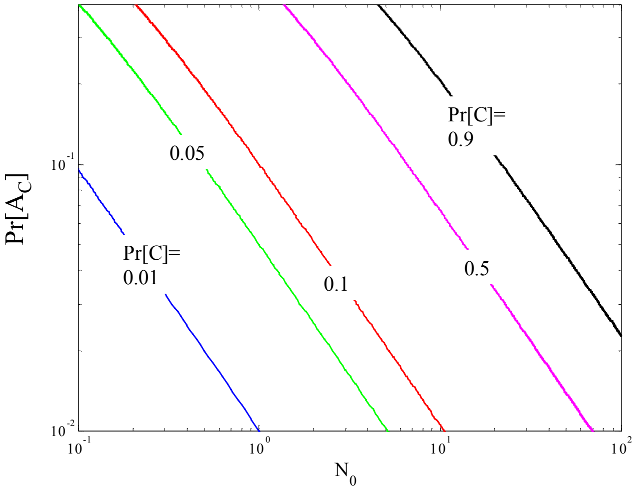

Figure 8: Pr[C] contours on log-log scale.

IV. CONCLUSION

IEEE 802.15.4 is a proposed standard addressing the needs of LR-WPAN, with a focus on enabling wireless sensor networks. The standard is characterized by maintaining a high level of simplicity, allowing low cost and low power implementations. One of its physical layers operates in the 2.4GHz industrial, scientific and medical band with nearly worldwide availability; this band is also used by other IEEE 802 wireless standards. Coexistence among diverse collocated devices in the 2.4 GHz band is an important issue in order to ensure that each wireless service maintains its desired performance requirements. A method for analyzing the coexistence impact of an IEEE 802.15.4 network on the IEEE 802.11b STA is derived. Analysis based on the model suggests the following general conclusion: assuming either automated or manual frequency management is employed, it is reasonable to conclude that the IEEE 802.15.4 network will typically have little to no impact on the IEEE 802.11b's performance. This result should hold unless the STA is located near an IEEE 802.15.4 cluster with a high aggregate activity level.

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