IEEE 802.15.4 Throughput Analysis under IEEE 802.11 Interference

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***Abstract*— It is well known that both the IEEE 802.15.4 wireless standard for low power, low data-rate sensor networks, and the IEEE 802.11 wireless local area data networks, operate in the 2.4GHz industrial, scientific and medical (ISM) band. If the networks are in physical vicinity of each other to cause packet interference, most often, it is the 802.15.4 traffic that is adversely affected given the low operational output power of 802.15.4 nodes. In this paper, we undertake a theoretical study on the effect that 802.11 nodes have on the channel utilization capacity of an 802.15.4 network. We suggest what parameters in an 802.11 network can be adjusted dynamically so as to optimize channel/bandwidth utilization of the 802.15.4 network while at the same time minimizing interference. We also present the results of MATLAB simulations of our theoretical framework.**

I. Introduction

The IEEE 802.15.4 wireless standard addresses the medium access and physical layer (MAC/PHY) needs of low data-rate, low-power wireless sensor networks (WSN) or personal area networks (PAN). Its operational frequency includes the 2.4GHz industrial, scientific and medical (ISM) band to facilitate worldwide availability. Given the high costs of deploying and maintaining a wired infrastructure, and in contrast, the cost of IEEE 802.15.4 radio chips rapidly plummeting in recent years, WSN-based applications are becoming increasingly ubiquitous across a range of vertical market segments including building automation, industrial automation, and remote vital-sign monitoring of patients through wearable sensors. At the same time, the ISM band is also occupied by enterprise-level, wireless local area data networks (based on IEEE 802.11b/g standards, also referred to as WiFi), the numbers of which continue to explode. IEEE 802.11[1] is the de facto standard for wireless LANs in the market today with approximately 213 million WiFi chipsets shipped in 2006 [20]. Shown in Figure 1 [10] (is the channel layout of IEEE 802.11 and IEEE 802.15.4 respectively

As can be seen from Figure 1, IEEE 802.11 has 11 channels (1 through 11 between 2.401 GHz and 2.473 GHz each with a bandwidth of 5 MHz and an interchannel spacing of 5 MHz), while IEEE 802.15.4 has 16 channels (11 through 26 between 2.4 GHz and 2.4835 GHz each with a bandwidth of 2 MHz and an interchannel spacing of 5 MHz). Clearly, there is significant overlap between most of the channels offered by the two standards. Furthermore, unlike IEEE 802.15.4 networks,

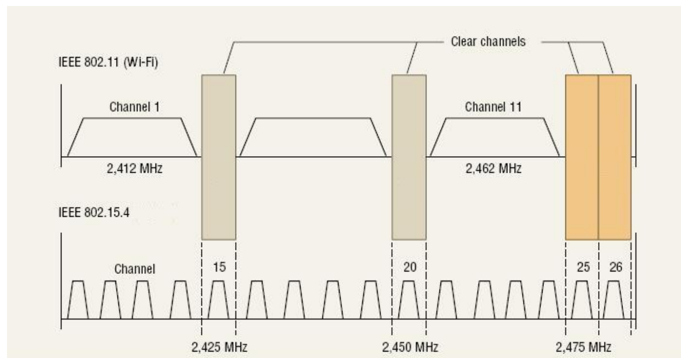

Fig. 1. Channel layout in IEEE 802.11 and IEEE 802.15.4 wireless standards.

WiFi networks involve large data-rates and high power; typical operating power of an IEEE 802.15.4 node is 0 dBm [5], [12], while that of a WiFi node is 30 dBm [1]. As a result, an 802.15.4 node operating in a channel, say channel 1, in the vicinity of an 802.11 node, will effectively be drowned out as a result of the massive disparity in operating powers. Thus, given the possible interference between 802.15.4 and 802.11 networks in close proximity of each other, the issue of managing the co-existence of these networks is crucial in order to maintain the quality of service requirements of the respective applications, particularly IEEE 802.15.4 applications given their low power output.

Most approaches to addressing this co-existence issue involve a channel utilization strategy, i.e., the networks operate on distinct channels that are spaced further apart in frequency and do not overlap. As shown in Figure 1, if the two networks operate on so called “clear channels”; channels 1, 6, and 11 for WiFi networks, and channels 15, 20, 25, 26 for 802.15.4 networks, there will be no interference. While this strategy does indeed result in co-existence, we argue in this paper that this may not be an efficient strategy in terms of available channel and bandwidth utilization, especially as the number of WSN/PAN and WiFi networks increase in the vicinity of each other. What we need is a dynamic adjustment of the IEEE 802.15.4 and IEEE 802.11b/g parameters as a function of interference in order to achieve co-existence and at the same time optimize channel and bandwidth utilization.

As a first step towards achieving this goal, in this paper, we analytically study the effect WiFi nodes have on the channel utilization capacity of an 802.15.4 network. We then suggest what parameters in an 802.11 network be adjusted dynamically so as to optimize channel/bandwidth utilization of the 802.15.4 network while at the same time minimizing interference. We also present the results of MATLAB simulations of our theoretical framework.

The rest of this document is organized as follows: In Section II, we report on the related works. In Section III, we give background information on IEEE 802.15.4 and IEEE 802.11 internal mechanisms. In Section IV, we illustrate our throughput analysis and in Section V, we present our numerical results simulated. And, finally, in Section VI, we convey possible future work directions.

II. Related Work

802.15.4 has been analyzed before for throughput performance. [16] analyzes the slotted-CSMA version using the Markovian chains as the authors in [3] perform for 802.11. Similarly, [17] focuses on the unslotted-CSMA version. Yet, unslotted-CSMA has been analyzed before in the seminal work [15] which assumed aggregate Poisson arrival of packets. In our work, also, we use this model for our analysis.

Even though the number of works in this area is not significant, WLAN-WPAN coexistence issues has been addressed before. [7], [13] study the WLAN effect on Bluetooth links. [11] determines the best 802.11 channels to use in order to minimize the 802.11 effect on 802.15.4 traffic. WLAN performance under WPAN traffic is analyzed for Bluetooth traffic [8] and for 802.15.4 [9].

802.15.4 performance under 802.11 traffic is analyzed in [18] from packet error rate perspective only. In [19], it is shown experimentally that in case of overlapping channels, more than 92% of WPAN frames are destroyed by WLAN traffic. Similar results are obtained in [6].

III. Background

A. IEEE 802.15.4

IEEE 802.15.4 is the wireless standard developed for ultra-low power, low rate wireless personal area networks (WPANs). IEEE 802.15.4 standard defines the physical and medium access control layer characteristics for WPANs and leaves the other layer details to the users. In addition, as the ZigBee [22] effort that is supported by the industry for standardizing the infrastructure for low-power applications adopted the 802.15.4 standard for their physical and medium access layers, the importance of 802.15.4 standard is escalated. In this section, we give a brief introduction to the 802.15.4 standard, for more information please see [4] and [23].

IEEE 802.15.4 physical layer defines two different options for communication: 2.4 GHz and 868/915 MHz. 868 MHz band is available in Europe whereas 915 MHz is available in the United States; 2.4 GHz is available worldwide. Both of these choices use Direct Sequence Spread Spectrum for modulation. Table I summarizes features of different physical layer choices. Notice that the lower data rate physical choice has better receiver sensitivity because of its lower bit rates.

IEEE 802.15.4 medium access mechanism utilizes the very well known CSMA/CA algorithm very similar to 802.11 MAC layer but without the RTS/CTS support because of the low data rate requirement for WPANs. There are two modes defined by MAC protocol:

- *Beacon-enabled Mode* In this mode, the coordinator periodically transmits beacons in order to synchronize the wireless nodes and identify the PANs. Two subsequent beacons define a beacon superframe during which the wireless nodes can transmit. A superframe is divided into two parts: *Contention Access Period*, during which the sensors nodes content to access the channel, and the *Inactive Period*, during which the transmissions are not allowed and the wireless nodes are expected to stay idle and they can execute sleep states. In this mode, wireless stations use slotted CSMA/CA.
- *Beaconless Mode* In this mode, there is no synchronization among nodes and the devices use the simple unslotted CSMA/CA method.

In the rest of this document, we use the terms 802.15.4 and IEEE 802.15.4 interchangeably.

B. IEEE 802.11

Data Rate	**Code Length**	**Modulation**	**Symbol Rate**	**Bits/ Symbol**
1 Mbps	11(BarkerSeq.)	BPSK	1 MSps	1
2 Mbps	11(BarkerSeq.)	QPSK	1 MSps	2
5.5 Mbps	8 CCK	QPSK	1.375 MSps	4
11 Mbps	8 CCK	QPSK	1.375 MSps	8

TABLE II
IEEE 802.11B Data Rate choices.

IEEE 802.11 is the standard specification defined for wireless connectivity for fixed, portable, and moving stations within a local area. Similar to its low-power counterpart IEEE 802.15.4 mentioned in the previous section, IEEE 802.11 also defines the PHY and MAC layers for communication. Unlike 802.15.4, however, 802.11 focuses on higher data rate communication as this is more common in local area networks (LANs). Even though there are variations of 802.11 for different purposes, in this document, we focus on the 802.11b as it is the first widely accepted standard. However, our analysis is easily extendible for other variations as well. In the rest of this document, we use the terms 802.11 and IEEE 802.11b interchangeably.

802.11 defines four different data rates with different physical characteristics for diverse environments. Table II summarizes these four different PHY choices. Notice that all PHY choices defined in 802.11 operate on 2.4 GHz band and share this band with other traffic such as 802.15.4 and Bluetooth traffic and with devices such as microwave ovens.

PHY	Band	Data Parameters			Channels	Receiver Sensitivity
		Bit Rate (kb/s)	Symbol Rate (kbaud)	Modulation		
868 MHz	868.0-868.6 MHz	20	20	BPSK	1	$-92dBm$
915 MHz	902.0 - 928.0 MHz	40	40	BPSK	10	$-92dBm$
2.4 GHz	2.4 - 2.4835 GHz	250	62.5	16-ary orthogonal	16	$-85dBm$

TABLE I
IEEE 802.15.4 PHY CHARACTERISTICS.

802.11 MAC layer defines two different access schemas: mandatory contention-based *Distributed Coordination Function* (DCF) for distributed access and optional *Point Coordination Function* (PCF) which provides contention-free access to support applications that require real-time service. As PCF is not widely implemented in the commercial products today, in this document, we focus on the DCF functionality.

DCF operates as follows: any wireless station ready to transmit, first, senses the channel to avoid collisions. If the medium is not idle, the station defers the transmission employing a binary exponential backoff schema. If the medium has been idle for longer than the DIFS (DCF interframe space) amount of time, the transmission can start immediately, otherwise the station picks a random number from the interval $[0, W-1]$ and waits this number of idle slots to appear on the medium where W is the window size and defined as a configuration parameter (IEEE 802.11b default is 32). If transmission attempt is unsuccessful, the window size is doubled until a predefined maximum (IEEE 802.11bs default is 1024) and the process is repeated until the maximum retry count is reached, after which the upper layers are reported about bad channel conditions. In order to avoid channel capture, each successful transmission is followed by a backoff operation.

In 802.11, each transmission packet is acknowledged by the receiver after SIFS (short interframe space) amount of time. In order to give higher priority to acknowledgement packets, SIFS is smaller than DIFS.

IV. THROUGHPUT ANALYSIS

Figure 2 illustrates the deployment schema we are assuming in this document. In this deployment, there is a wireless sensor network using 802.15.4 as its communication schema with constant mean packet arrival rate and there is a WiFi node which transmits 802.11 packets according to a packet arrival rate with constant mean. In order to model this deployment, we considered the distance between the 802.11 node and the center of the sensor network. Indeed, for large number of sensors deployed densely in a region, intuitively, the average interference amount can be calculated using the distance between the interferer and the center of interference region.

A. Interference Analysis

The interference analysis based on extensive field trials of IEEE 802.15.4 network operation in the presence of 802.11 traffic have been reported in literature [14], [10]. In these trials, different 802.15.4 channels were chosen and the resulting performance (measured in terms of packet delivery success rate and percentage of duplicate packets) in the presence of 802.11 nodes were examined.

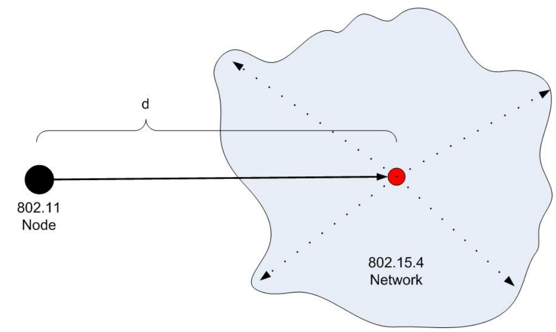

Fig. 2. Heteregenous Networks deployment schema.

The packet delivery rates clearly show that when the 802.15.4 and 802.11 channels overlap, packet delivery rate of 802.15.4 nodes is reduced from 100

Thus, as pointed out in the Introduction, the results in [14], [10] do confirm that the interference 802.11 nodes in close proximity have on an 802.15.4 network is minimal or non-existent when the networks operate on non-overlapping channels, or when the physical distance between two networks is large.

B. Channel Utilization

Let G_{11} denote the arrival rate of packets belonging to 802.11 traffic, including the retransmissions for this class; and similarly let G_{15} denote packet arrival rate of 802.15.4 users. Packet lengths of 802.11 and 802.15.4 are denoted as τ_{11} and τ_{15} respectively.

If we assume that the packet generation is close to exponential distribution, then, the probability that, for instance, an 802.11 packet does not arrive for T amount of time can be approximated as $P_{idle,11}(T) = e^{-G_{11}T}$.

The transmission schema can be analyzed through five different events as shown in Figure 3:

1) $T_1 =$A successful 802.15.4 transmission.
2) $T_2 =$A successful 802.11 transmission.
3) $T_3 =$An 802.15.4 packet collided with an 802.11 packet.
4) $T_4 =$An 802.15.4 packet collided with another 802.15.4 packet.
5) $T_5 =$Idle time spent between two 802.15.4 packets.

Then, the channel utilization for 802.15.4 traffic can be represented as

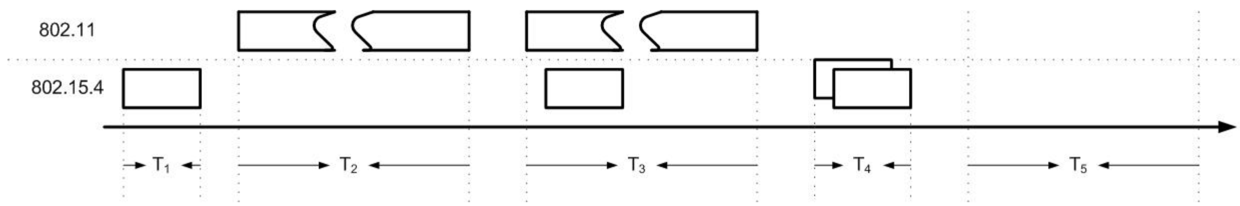

Fig. 3. Possible events that might occur on the medium.

$$S = \frac{T_1}{T_1 + T_2 + T_3 + T_4 + T_5} \quad (1)$$

If a is the propagation delay, then a successful 802.15.4 transmission depends on the fact that, no other 802.15.4 nodes sample the medium for a amount of time and no 802.11 traffic is generated during the transmission. First probability is $e^{-aG_{15}}$ and the second probability is $e^{-G_{11}\tau_{15}}$, then

$$T_1 = \tau_{15} \times G_{15} \times e^{-aG_{15}} \times e^{-G_{11}\tau_{15}} \quad (2)$$

802.11 successful transmission time can be calculated by using the packet generation rate directly. Notice that regardless of the collision probability, if a 802.11 packet is on the medium, the channel medium is wasted from 802.15.4 perspective. Hence, we can merge the second and third events as a 802.11 overall transmission. This value can be directly calculated using the packet 802.11 arrival rate.

$$T_2 + T_3 = G_{11} \times \tau_{11} \quad (3)$$

Fourth event represents the cases where two 802.15.4 packets collide. Notice that a similar analysis for unslotted, nonpersistent CSMA analysis already made in [15] which is based on the assumptions undertaken in [2]. However, as the 802.11 traffic already considered in the second and third evets, we should exclude it here. Hence, the average duration of 802.15.4 collision is

$$\begin{aligned} T_4 \quad = \quad & G_{15} \times (1 - e^{-aG_{15}}) \times e^{-(\tau_{15}+a)G_{11}} \times \\ & \left[\tau_{15} + a + \frac{1}{G_{15}} \times \left(a - \frac{1}{G_{15}}(1 - e^{-aG_{15}})\right)\right] \end{aligned}$$

Finally, the average amount of time that the medium is idle is $\frac{1}{G_{15}}$ in case of 802.15.4 traffic only. If there is 802.11 traffic present at this moment, it counts towards the second event, hence, these cases should be ignored. Then,

$$T_5 = (\frac{1}{G_{15}} - \tau_{15}) \times \alpha \times e^{-G_{11}\alpha(\frac{1}{G_{15}} - \tau_{15})} \quad (4)$$

where α is the normalization factor for changing values of G_{15}.

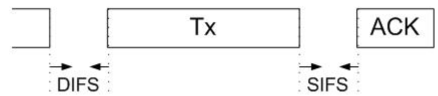

Fig. 4. 802.11 Packet exchange schema.

C. Channel Access Times

A typical 802.11 transmission schema consists of a packet transmission and a corresponding acknowledgement and SIFS amount of time between these two as seen in Figure 4. The user also waits the medium to be idle for DIFS amount of time. However, from our perspective 802.11 traffic occupies the medium during the transmissions only, i.e. for a duration of packet and acknowledgement transmissions. For the sake of simplicity, we will assume that during a 802.11 transmission, channel will look busy even during the SIFS amount of time mentioned above. Hence,

$$\tau_{11} = T_x + T_{ACK} + SIFS \quad (5)$$

ACK size for 802.11b is 38 bytes and SIFS is $10\mu s$. If the packet size for 802.11 traffic is L_{11} bits and the 1 Mb/s data rate is assumed then,

$$\tau_{11} = (L_{11} + 38 + 10) = (L_{11} + 48)\mu s \quad (6)$$

If TCP/IP default value of 1500 bytes is used, $\tau_{11} = 12048\mu s$.

In order to calculate τ_{15}, we should consider only the packet transmission time itself with the assumption that acknowledgement option is turned off. As 802.15.4 data rate is 250 kb/s, if the TinyOS [21] default value of 38 bytes is used, $\tau_{15} = \frac{38*8}{250} = 1216\mu s$.

V. Numerical Analysis

In order to understand the effects of 802.11 traffic on 802.15.4 throughput, we numerically simulated the above functions in MatLab. In this section, we report our findings.

A. Performance Analysis of Heterogeneous Networks

In our first experiment, we report on the effects of 802.11 packet generation rate on the performance. In Figure 5, we see that as the packet generation rate of 802.11 increases, as expected, the channel utilization of 802.15.4 decreases greatly. Notice that. as the packet generation rate of 802.15.4 increases, this diminising effect becomes more and more acute.

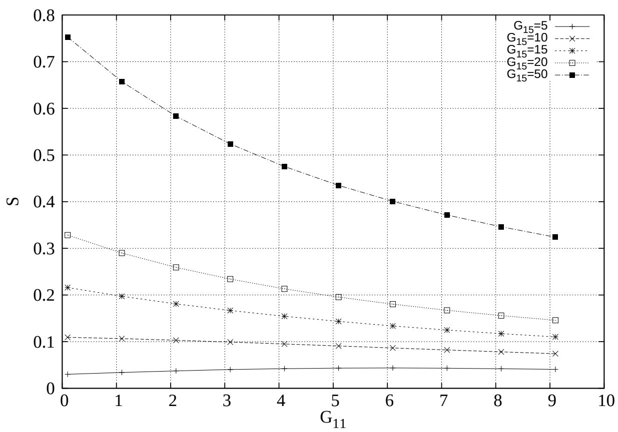

Fig. 5. G_{11} effect on S. $a = 1$.

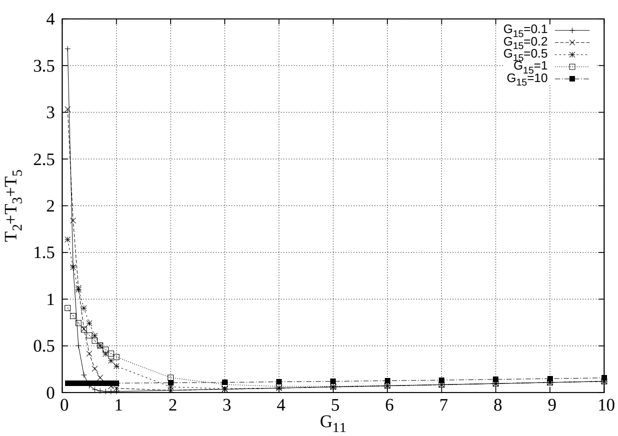

Fig. 6. Cost behavior for changing 802.11 traffic.

One interesting result is that when the packet generation rate of 802.15.4 nodes is too low, increasing 802.11 packet generation rate, surprisingly, increases the channel utilization factor. This anomaly occurs because of the low 802.15.4 traffic rate and can be explained easily by the fact that the channel idle time decreases greatly when the 802.11 traffic increases. Indeed, as can be seen in Figure 6, increasing the 802.11 traffic decreases the sum of 802.11 medium access time and the idle time for low G_{15}. Under normal conditions, this would not affect the 802.15.4 channel utilization as 802.15.4 traffic generation rate is kept constant. However, when traffic rate of 802.15.4 stations is very low, the anomaly explained in Figure 8 happens.

Lets say that the top packet generation schema happens when the 802.11 traffic rate is low where the window size is t and increasing this rate decreases the window size of consideration as shown in Figure 6. In this case, the new window size becomes t' where $t' = t - \Delta$. Notice that since G_{15} is very small $G_{15} \times \Delta \simeq 0$ and the number of packets received in the intervals $[0, t]$ and $[0, t']$ are the same. Hence, the amount of throughput received per second in the latter case

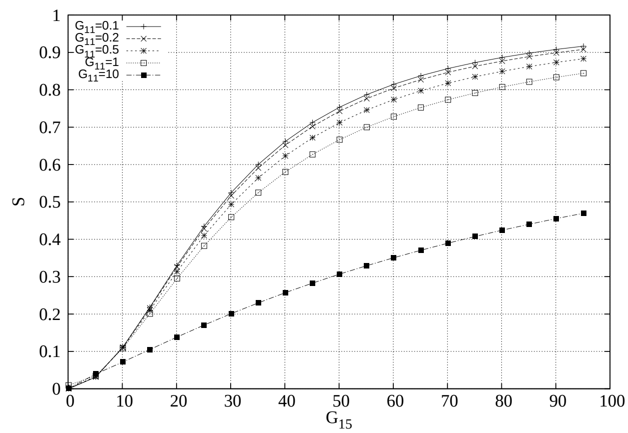

Fig. 7. G_{15} effect on S. $a = 1$.

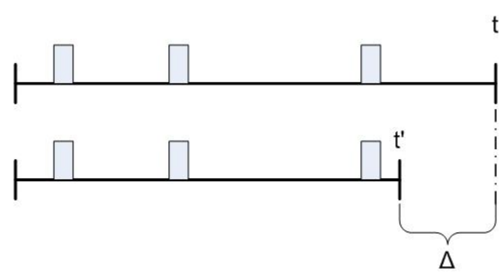

Fig. 8. Channel utilization anomaly.

is $\frac{G_{15} \times t}{t'}$. Then,

$$\begin{aligned} \frac{G_{15} \times t}{t'} &= G_{15} \times \frac{t' + \Delta}{t'} \\ &= G_{15} \times \left(1 + \frac{\Delta}{t'}\right) \end{aligned}$$

which greatly depends on the $\frac{\Delta}{t'}$ factor and as t' gets smaller, this factor starts to get bigger.

In a similar analysis, we looked at 802.15.4 packet generation effect on channel utilization as presented in Figure 7. As the graph suggests, 802.11 traffic rate has indeed a huge effect on channel utilization. As the packet generation rate of 802.11 increases, the channel utilization drop becomes sharper.

As the equations defined above depend on the propagation delay parameter a, we conducted experiments in order to see the effect of a on the channel utilization. In Figure 9, we see this effect for very large propagation delays. Of course, such numbers are not realistic but this figure confirms the intuition that as the propagation delay increases, the channel utilization decreases causing more number of collisions. However, Figure 10 illustrates that for small values of propagation delay (which is at the microseconds level for wireless communication), the channel utilization is independent of the propagation delay.

Notice that the equations defined in the previous sections rely on packet generation patterns as well as channel occupa-

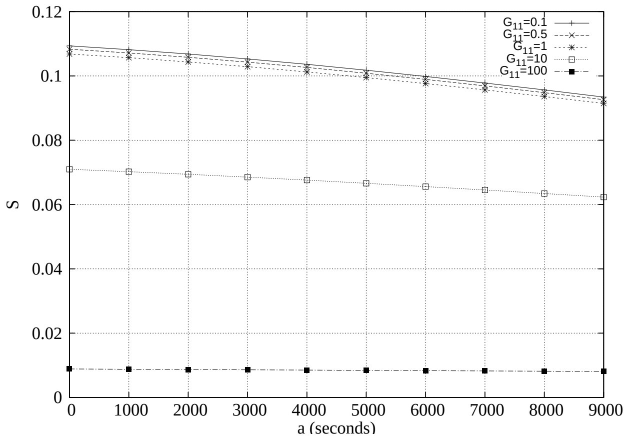

Fig. 9. a effect on S. $G_{15} = 10$.

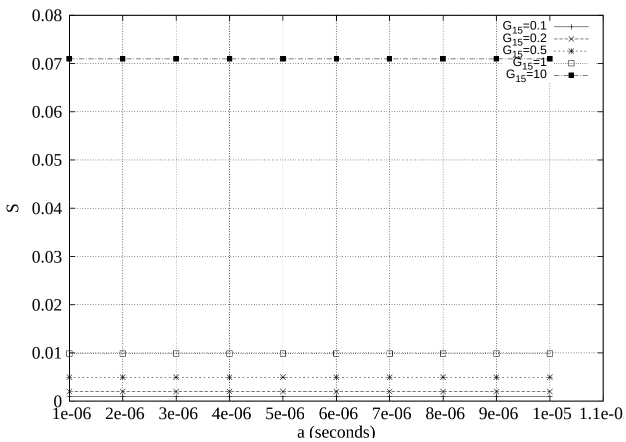

Fig. 10. a effect on S. $G_{11} = 10$.

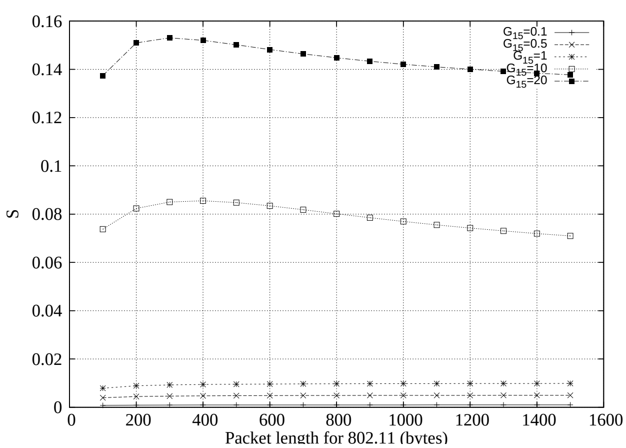

Fig. 11. 802.11 Packet length effect on S. G_{11} normalized according to default value $G_{11} = 10$ for packet length of 1500 bytes.

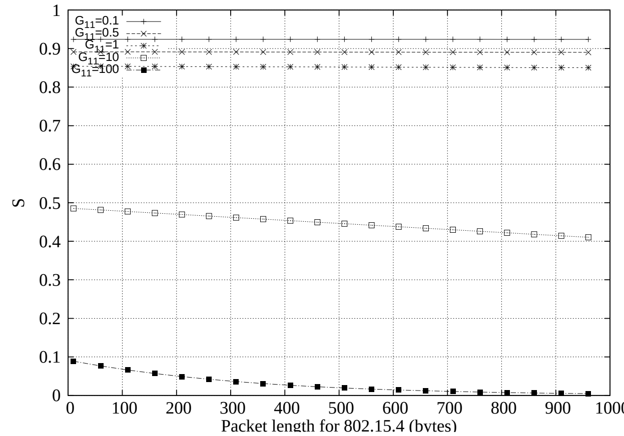

Fig. 12. 802.15.4 Packet length effect on S. G_{15} normalized according to default value $G_{15} = 10$ for packet length of 38 bytes.

tion times. Hence, for a given traffic pattern, we investigated the effect of changing the packet length on the channel utilization. Note that changing the packet length has an indirect effect on the packet generation rate also. For instance, for a given traffic pattern G and channel access time τ, if changing the packet length drops the channel access time to $\tau/2$, this, essentially means that the traffic pattern also increases roughly to $2G$.

Investigation of the 802.11 packet length variation is illustrated in Figure 11. This figure suggests that, initially, as the packet length increases for 802.11 traffic, channel utilization increases since this essentially means to decrease the packet generation rate of 802.11. However, after some point, this increase starts to have detrimental effect on the channel utilization as using larger blocks of accesses yield to larger but more infrequent gaps for 802.15.4 traffic even though the cumulative duration of gaps is the same for both scenarios.

Figure 12 demonstrates a similar analysis for 802.15.4 packet length. Even though this figure suggests using smaller packet lengths in order to maximize channel utilization, since lowering the packet length essentially means to increase the packet generation rate, this modification is not feasible for wireless sensor network which, generally, have very strict duty cycle requirements. Hence, we do not consider packet length adjustment procedures for 802.15.4 in this paper.

IEEE 802.11b standard provides four different modulation techniques to choose from for backward compatibility. Namely, these modulation techniques support 1 Mb/s, 2 Mb/s, 5.5 Mb/s and 11 Mb/s traffic. The decision for the modulation technique is solely left to the user and the standard does not provide a mechanism for this decision. We experimented with different modulation techniques in order to see the level of their effects on 802.15.4 channel utilization. As Figure 13 suggests, using the higher data rate modulations increase the channel utilization as this yields to shorter medium occupancies for 802.11 packets.

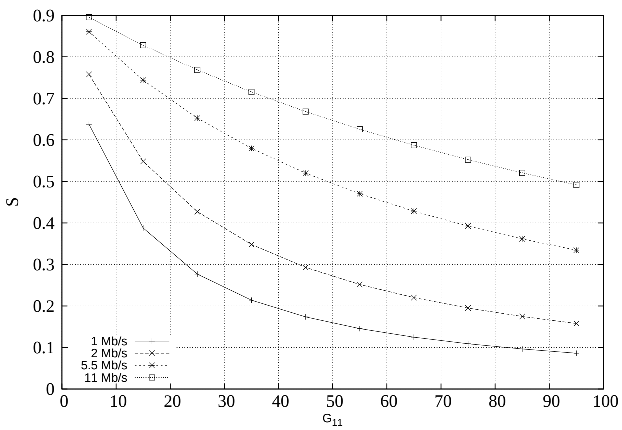

Fig. 13. Physical modulation effect on S. $G_{15} = 100$, $a = 1$, packet lengths are 1500 and 38 bytes for 802.11 and 802.15.4 respectively..

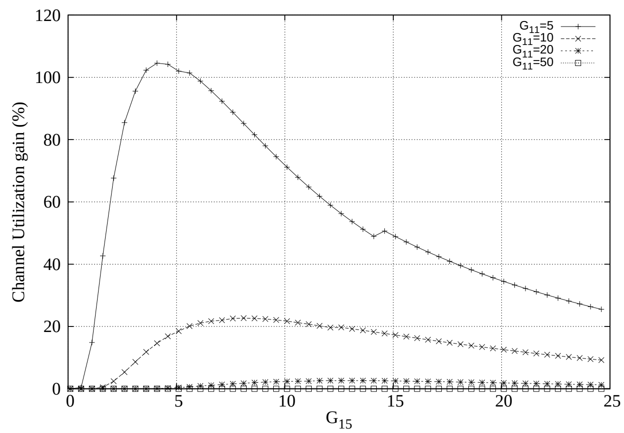

Fig. 15. Channel utilization gain using optimal packet length for 802.11 traffic.Packet length for 802.15.4 is 38 bytes, $a = 1$.

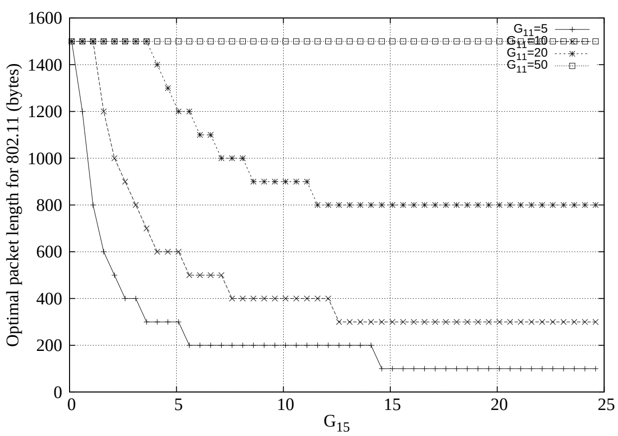

Fig. 14. Optimal packet length to use for 802.11 traffic for different 802.15.4 traffic.Packet length for 802.15.4 is 38 bytes, $a = 1$.

B. Optimal 802.11 Packet Length Calculation

Notice that in Figure 11 the 802.11 packet length change effect on channel utilization is a parabolic shape suggesting there is a point in the function which maximizes the output function, in this case the channel utilization. This shape suggests that there is an optimal 802.11 packet size choice which maximizes the channel utilization for given traffic patterns. In order to see the effect of 802.11 packet size, we further developed another experiment. For this experiment, we looked at all the 802.11 packet size possibilities for a given packet generation pair, and calculated the packet size which maximizes the channel utilization. For instance, in Figure 11 for $G_{15} = 20$ and $G_{11} = 10$, the packet length that maximizes S is around 300. We plotted this function in Figure 14.

Figure 14 suggests that if the packet generation rate of 802.11 is too large than the packet length does not have any effect on the channel utilization whatsoever, which is reasonable since the 802.11 traffic would be very dominant on the medium in such a case. However, for reasonable 802.11 packet generation rates, we see that according to the 802.15.4 traffic, the optimal 802.11 packet size changes. As can be seen from Figure 14, as the 802.15.4 traffic increases, it is always better to use smaller and smaller packets. This, in fact, is meaningful since the channel would be captured by the 802.11 traffic for long times if the 802.11 packet lengths are big. Under these circumstances, it is always better to use smaller packets and increase the packet generation rates for 802.11 traffic.

Figure 15 presents the channel utilization that is gained using the optimal packet length found in Figure 14. The gain calculation is simply

$$Gain = \frac{S_{opt} - S_{norm}}{S_{norm}} \times 100 \tag{7}$$

where S_{opt} is the channel utilization observed using optimal 802.11 packet length whereas S_{norm} is the channel utilization observed using the standard packet length of 1500 bytes.

Notice that for low 802.11 traffic, using optimal packet length has a huge effect on 802.15.4 performance, and the channel utilization is doubled for some 802.15.4 traffic patterns. As the 802.11 traffic rate increases, the medium is captured mostly by this traffic and the outcome of using optimal 802.11 packet length starts to lose its importance. In addition, as the packet generation rate of 802.15.4 increases, the effect of optimal packet length also decreases since, then, it is not enough to partition the 802.11 access on the medium.

VI. Conclusions and Future Work

In this paper we studied one of the most important and challenging wireless issues of our time, namely, the coexistence of 802.11 and 802.15.4 networks beyond a channel separation strategy. This problem is of particular importance given the rapid growth of both 802.15.4-based wireless sensing applications, as well as 802.11-based computer networks; both operating within an enterprise in close proximity of each other. The first goal we set out to achieve is to mathematically characterize the effect that interfering 802.11 nodes have on the performance (channel/bandwidth utilization) of an 802.15.4 network. Our analysis shows that indeed there are parameters of an 802.11 network that could be dynamically configured so as to optimize the performance of an 802.15.4 network without compromising on the performance of the 802.11 network. The key contribution of this paper was to show that for moderate 802.11 traffic, there is an optimal 802.11 packet length for which the channel utilization of any 802.15.4 network in its proximity doubles when compared with what it would be for normal 802.11 packet length of 1500 bytes. While this result may have some practical utility, our future work involves the extension of the theoretical analysis presented in here so as to study the performance of an 802.15.4 network as a function of several configurable parameters of both 802.15.4 and 802.11 networks. Such an analysis will surely facilitate a robust planning strategy while deploying such networks with large numbers of nodes in the future where just a channel separation plan will clearly not suffice.

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