Analytic Modeling of the Coexistence of IEEE 802.15.4 and IEEE 802.11 in Saturation Conditions

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***Abstract*—With the increasing deployment of smart wireless devices using different technologies such as IEEE 802.15.4 and IEEE 802.11 which operate in the same frequency band, it becomes urgent to deeply understand the impact of this coexistence on the performance of the involved networks. We present in this letter an analytic framework based on Markov chains that captures accurately the behavior of channel access mechanisms in IEEE 802.11 DCF and the unslotted IEEE 802.15.4 when both technologies are coexisting together. The model allows the derivation of metrics such as the probability of successful transmissions, the probability of collision, and the fraction of time that the channel is idle, or experiences successful transmissions for both 802.11 and 802.15.4 nodes. Through extensive simulations of diverse coexistence scenarios, we validate the accuracy of the proposed model, and we analyze the performance of both 802.11 networks and 802.15.4 networks in saturation conditions.**

***Index Terms*—802.11, 802.15.4, coexistence, Markov chain.**

I. Introduction

In recent years, there has been a tremendous increase in the deployment of smart wireless devices such as smartphones and tablets for ubiquitous Internet access, or sensors and actuators at home for automation or health monitoring [1]. Because of the lack of available spectrum, the technologies used by these devices (IEEE 802.11 for smartphones and tablets, and IEEE 802.15.4 for sensors and actuators) operate in the same 2.4 GHz unlicensed industrial, scientific, and medical (ISM) bands. However, these technologies were not designed with the coexistence issue in mind; for instance, devices using IEEE 802.11, and those using IEEE 802.15.4 use different and incompatible channel access mechanisms and PHY parameters, making Cross Technology Interference (CTI) problems more exacerbated.

Lately, new standards for WiFi such as IEEE 802.11n [2] or IEEE 802.11ac [3] exploit the 5 GHz frequency band. However, the market migration to the 5 GHz band has not been complete. In fact, the 2.4 GHz band remains the most used unlicensed band in the world making it a technology candidate for wireless connectivity for the Internet of Things (IoT) paradigm [4]. Hence, IEEE 802.11 and IEEE 802.15.4 CTI problems remain unsolved.

In general, techniques proposed in the literature to improve the coexistence of IEEE 802.11 and IEEE 802.15.4 in the 2.4 GHz ISM band basically depend on several aspects such as the type of modulation, the transmission power, the spread spectrum, the load, packet size, the geographical distribution of the interacting nodes, etc. However, many of these techniques [5]–[8] reflect on experiments whose generalisation depends on the data and environments considered.

In order to bring about solutions to mitigate or solve CTI interference between 802.11 and 802.15.4, an accurate analytic model of their coexistence needs to be performed. Some recent works [9], pursued such direction, but used an 802.11 model which is not completely accurate, (it does not differentiate the busy slots in which nodes successfully transmit [10], [11]), and used a simplified model of the slotted 802.15.4 (BoX-MAC).

In this letter, we propose a different and more systematic approach to study the coexistence of IEEE 802.15.4 and IEEE 802.11. Our approach relies on an analytical framework based on accurate Markov chains; the advantage of such approach is that it captures the steady state behavior of the system, and allows the derivation of metrics such as the throughput, the probability of successful and failed transmissions, etc.

Our contribution can be summarized as follows:

- We propose an analytical framework based on Markov chains that accurately models the coexistence of IEEE 802.11 and the unslotted IEEE 802.15.4 in saturation conditions.
- We derive the expressions of the probability of successful transmissions, the probability of failed transmissions, and the saturation throughput for both the 802.11 and 802.15.4 nodes.
- Through extensive simulations, we analyze the performance of the coexistence of 802.11 and the unslotted IEEE 802.15.4.

The rest of the letter is organized as follows. In Section II, we present the system model with the main assumptions considered, and we detail the analytical model for the coexistence of the 802.11 and 802.15.4 nodes. In Section III, we present some numerical results, and we discuss the performance of both 802.11 and 802.15.4 nodes. Finally, we conclude this work while highlighting some future directions in Section IV.

II. System Model, Assumptions, and Analytical Model of the Coexistence of 802.11 and 802.15.4

We consider an 802.11-based network co-located with an 802.15.4-based network, and sharing the same spectrum band. The size of the global network is constant, only the proportion of 802.11 nodes versus 802.15.4 nodes varies. For our analysis, we use the following assumptions: 802.11 nodes (resp. 802.15.4

Manuscript received May 3, 2015; revised June 8, 2015; accepted June 15, 2015. Date of publication June 24, 2015; date of current version November 9, 2015. The associate editor coordinating the review of this paper and approving it for publication was D. Qiao.

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Digital Object Identifier 10.1109/LCOMM.2015.2449298

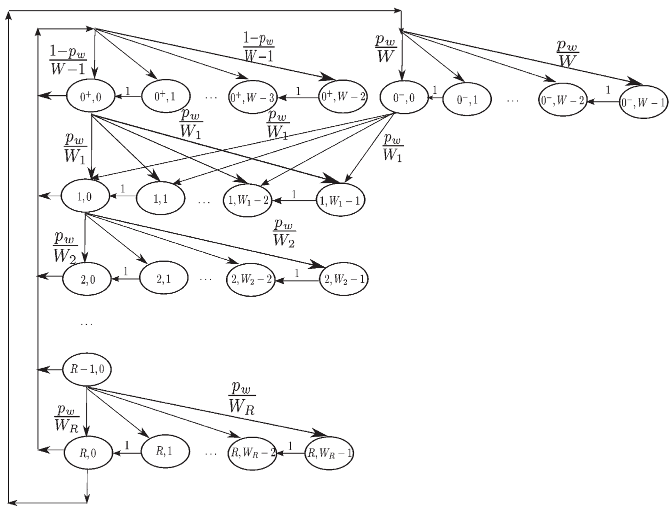

Fig. 1. Markov chain model of 802.11 transmitting node [11].

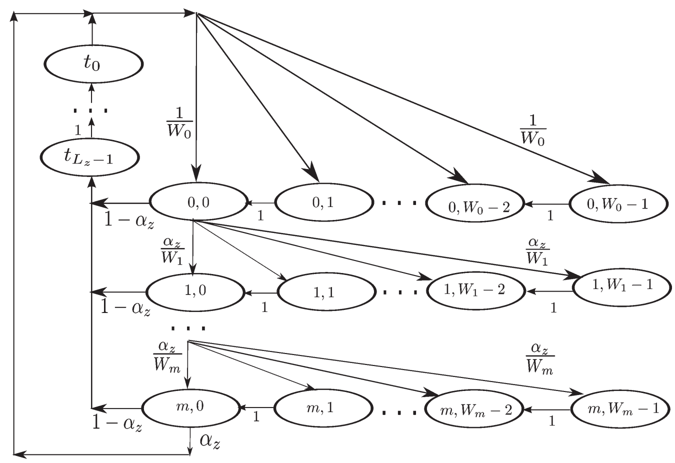

Fig. 2. Markov chain model of the transmitting node for the unslotted IEEE 802.15.4 CSMA/CA.

nodes) can detect each other transmission if they are in their detecting range. We assume ideal channel conditions, i.e., a failed transmission occurs only upon collisions. The packets of 802.15.4 nodes are of the same size, and 802.11 packets are also of the same size, this assumption is consistent with the previous literature.

Let us determine the probabilities of successful transmissions and collisions, and the normalized throughput of the 802.11 nodes and the 802.15.4 nodes. Let us first consider the two-dimensional Markov chain presented in Fig. 1 [11] which accurately models the backoff procedure with frozen states of the 802.11 nodes. For convenience, we adopt the following notation: $W = \mathrm{CW}_{\min} + 1$, and $W_j = 2^j W, j = 0, \dots, R$. Let us denote by $b(t)$ and $s(t)$ the random processes representing the value of the backoff counter, and the backoff stage $j(j = 0, 1, \dots, R)$, at model time slot t, respectively. We assume that the backoff counter is decremented at the end of each time slot.The state of each 802.11 node is described by the couple (j, k) in which j stands for the backoff stage, and $k(k = 0, \dots, W_j)$ stands for the backoff delay. A node proceeds to the transmission when the backoff counter reaches the value $k = 0$. After a successful transmission, the node switches into state $(0^+, k)_{0\le k\le W-2}$ with probability $\frac{1-p_w}{W-1}$, p_w being the probability that an 802.11 node's frame collides. If a collision occurs the node enters into state $(1, k)_{0\le k\le W-1}$ with probability $\frac{p_w}{W_1}$, and proceeds to the backoff counter decrementation based on the 802.11 decrementation policy. This process is repeated until the packet is either successfully transmitted or dropped. The packet is dropped if after reaching the maximum backoff stage, the transmission is unsuccessful. Note that each state referring to backoff stage 0 is represented either by state 0^+ (after a successful transmission) or by state 0^- (after a packet drop). Due to lack of space, we do not present the tansition probabilities in this letter. However, interested readers can find them in [11].

The transmission probability τ_w for 802.11 nodes is [11]

$$\tau_w = \frac{1}{1+\frac{1-p_w}{2\left(1-p_w^{R+1}\right)}\left[\sum_{j=1}^{R} p_w^j\left(2^j W-1\right)-\left(1-p_w^{R+1}\right)\right]}. \quad (1)$$

Assuming ideal channel conditions, and given that a successful transmission may occur when neither an 802.15.4 node nor an 802.11 node is transmitting, we can express the conditional collision probability of 802.11 nodes as

$$p_w = 1 - (1-\tau_w)^{M-1} \sum_{v=0}^{N} \binom{v}{N} (1-\tau_z)^{N-v} \tau_z^v \alpha_z^v. \quad (2)$$

In (2), τ_z is the probability that an 802.15.4 node starts performing a CCA in a generic time slot, and α_z is the probability that an 802.15.4 node sees the channel busy when performing the CCA.

In order to derive τ_z and α_z, let us consider the Markov chain depicted in Fig. 2 by which we modelled the channel access procedure for 802.15.4 nodes.

Let $W_j = \max(2^{\mathrm{BE}_{\max}}, 2^{\mathrm{BE}_{\min}+j})$, with $j = 0, \dots, m$ (m being the maximum number of backoffs), be the maximum duration of the backoff stage j, and let $s(t)$ and $b(t)$ be random processes representing the number of backoff and the backoff counter at time t respectively. Owing the chain regularities, we derive the following steady state probabilities:

$$b_{0,0} = \frac{1}{\sum_{j=0}^{m} \alpha_z^j \frac{W_j+1}{2} + L_z\left(1-\alpha_z^{m+1}\right)} \quad (3)$$

$$b_{i,0} = b_{0,0}\alpha_z^i, \quad \text{for } i = 0, 1, 2, \dots, m. \quad (4)$$

Considering that the CCA is performed when the backoff counter reaches zero, we have

$$\tau_z = \sum_{i=0}^{m} b_{i,0} = \frac{1-\alpha_z^{m+1}}{1-\alpha_z}\left[\sum_{j=0}^{m} \alpha_z^j \frac{W_j+1}{2} + L_z\left(1-\alpha_z^{m+1}\right)\right]^{-1}. \quad (5)$$

The probability α_z that an 802.15.4 node sees the channel busy can be defined as the probability that there is at least one ongoing transmission from either 802.15.4 nodes, or 802.11

nodes, or both. Let L_w and L_z be the packet length in time duration of 802.11 nodes and 802.15.4 nodes respectively, and

$$L_{\max} = \begin{cases} L_z, & \text{if} \quad u = 0 \\ \max\{L_w, L_z\}, & \text{otherwise.} \end{cases} \tag{6}$$

The probability that an 802.11 node transmits in a randomly chosen time slot depends on the conditional probability p_w that a transmitted packet encounters a collision. Therefore,

$$\alpha_z = L_{\max} \sum_{u=0}^{M} \binom{u}{M} (1-\tau_w)^{M-u} \tau_w^u \sum_{v=1}^{N} \binom{v}{N} (1-\tau_z)^{N-v} \times \tau_z^v (1-\alpha_z)^v + L_w \sum_{u=1}^{M} \binom{u}{M} (1-\tau_w)^{M-u} \tau_w^u \times \sum_{v=1}^{N} \binom{v}{N} (1-\tau_z)^{N-v} \tau_z^v \alpha_z^v. \tag{7}$$

The probabilities τ_z, τ_w, α_z, and p_w are therefore obtained by numerically solving the system of nonlinear equations (1), (2), (5), and (7).

For conformity of notation, let P_{S_w} (resp. P_{S_z}) be the probability that an 802.11 node (resp. 802.15.4 node) successfully transmits, and P_{C_w} (resp. P_{C_z}) be the probability that there is a collision after an 802.11 node (resp. 802.15.4 node) transmission. Let $P_{I_{(m_w,n_z)}}$ be the probability that m_w 802.11 nodes and n_z 802.15.4 nodes do not transmit, we have

$$P_{I_{(m_w,n_z)}} = (1-\tau_w)^{m_w} \sum_{v=1}^{n_z} \binom{v}{n_z} (1-\tau_z)^{n_z-v} \tau_z^v \alpha_z^v. \tag{8}$$

Therefore,

$$P_{S_w} = M\tau_w P_{I_{(M-1,N)}}, P_{C_w} = M\tau_w \left(1 - P_{I_{(M-1,N)}}\right) \tag{9}$$
$$P_{S_z} = N\tau_z(1-\alpha_z) P_{I_{(M,N-1)}}, \tag{10}$$
$$P_{C_z} = N\tau_z(1-\alpha_z) \left[1 - P_{I_{(M,N-1)}}\right]. \tag{11}$$

Let S_w (resp. S_z) be the normalized throughput, i.e., the fraction of time the channel experiences successful transmissions of 802.11 (resp. 802.15.4) nodes payload bits. We have

$$S_w = \frac{P_{S_w} L_w}{D}, \quad S_z = \frac{P_{S_z} L_z}{D} \tag{12}$$

with

$$D = P_{I_{(M,N)}} + \left[P_{S_w} T_{S_w} + P_{S_z} T_{S_z}\right] + \left[P_{C_w} T_{C_w} + P_{C_z} T_{C_z} + P_{C_{w,z}} T_{C_{w,z}}\right].$$

T_{S_w} (resp. T_{S_z}) is the time required for a successful 802.11 node (resp. 802.15.4 node) frame transmission, and T_{C_w} (resp. T_{C_z}) is the time required before reattempting a transmission after a collision; they are defined by the standards [12], [13].

III. Model Validation and Performance Analysis of the Coexistence Between 802.11 and 802.15.4

A. Simulation Scenario

For any given scenario, we considered a network of a fixed number N of 802.15.4 nodes and a fixed number M of 802.11 nodes. The positions of the nodes within the network do not change during the simulation. We considered scenarios were the hidden node problem is not present, and where the nodes of the same type have the same "view" of the network (i.e., they are in the same neighborhood). In the simulations, both 802.11 nodes and 802.15.4 nodes can detect each other's transmissions. We set the total number of nodes to 20, and the number of 802.15.4 nodes (resp. 802.11 nodes) takes values $N = 1, 5, 10, 15, 19$ (resp. $M = 19, 15, 10, 5, 1$), and for each case, we varied the ratio L_z/L_w of the 802.15.4 packet duration (L_z) to the 802.11 packet duration (L_w).

For each case, we analyzed the probability of successful transmission, the probability of collision, and the saturation throughput (the fraction of time that the channel experiences successful transmissions for 802.11 and 802.15.4 nodes.)

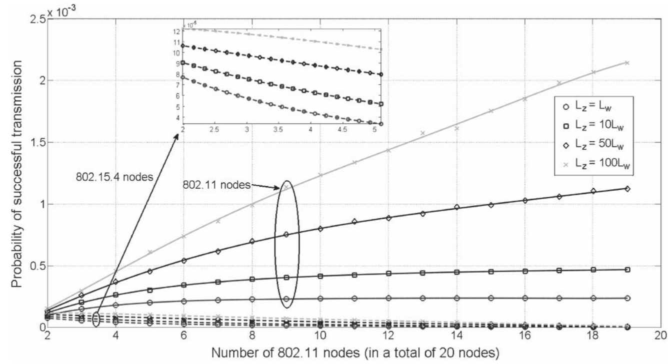

Fig. 3. Probability of successful transmission in the cases $L_z = L_w$, $L_z = 10L_w$, $L_z = 50L_w$, and $L_z = 100L_w$.

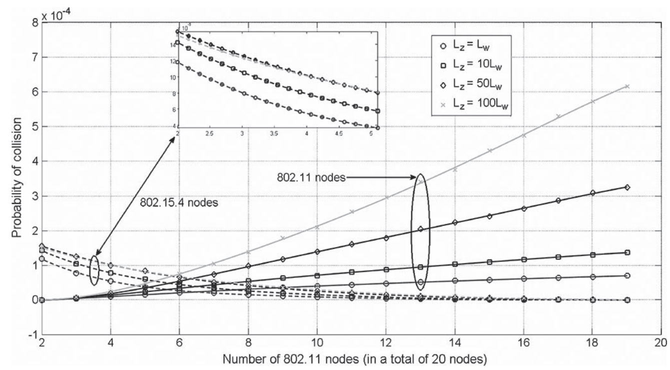

Fig. 4. Probability of collision in the cases $L_z = L_w$, $L_z = 10L_w$, $L_z = 50L_w$, and $L_z = 100L_w$.

B. Performance Analysis

In Figs. 3 and 4 we present both the probability of successful transmission, and the probability of collision with respect to the number of 802.11 nodes in the network. The total number of nodes in the network is 20, and the results are presented for different ratios of 802.11, and 802.15.4 packet lengths. For both 802.15.4 nodes and 802.11 nodes, we observe that both the probability of successful transmission, and the probability of collision for a given type of node decrease as the number of nodes of the other type increases.

However, we observe a considerable degradation of the probability to transmit (successfully or unsuccessfully) of 802.15.4

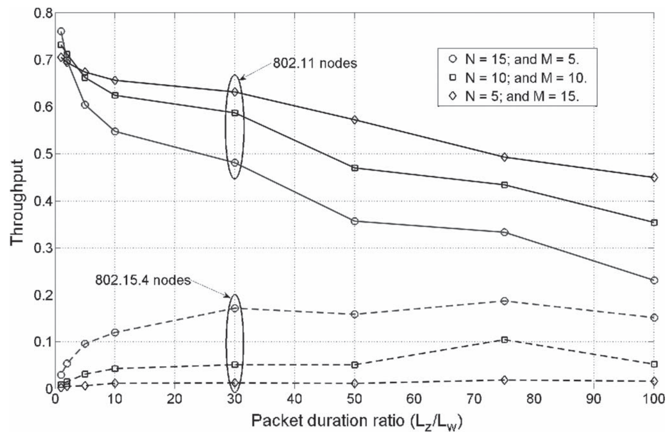

Fig. 5. Throughput in the cases ($N = 15$, $M = 5$), ($N = 10$, $M = 10$), and ($N = 5$, $M = 15$).

nodes as the number of 802.11 nodes increases in the network. One reason for this is the significant difference between the CCA length of 802.15.4 nodes and the duration of the last sensing of 802.11 nodes before transmission. The CCA of 802.15.4 nodes is more than 10 times higher than the last sensing duration of 802.11 nodes [12], [13].

Another reason for this performance degradation of 802.15.4 nodes is the larger time slot in 802.15.4 compared to 802.11, which has as consequence to force 802.15.4 nodes to permanently backoff with an increase in their contention window.

In Fig. 5, we present the saturation throughput (the fraction of time that the channel spends in the *"success"* state) for different number of 802.11 nodes and 802.15.4 nodes in the network. We distinguish the case where the channel experiences successful transmissions from 802.11 nodes, and the case of successful transmissions from 802.15.4 nodes. We observe that as opposed to the case of successful transmissions from only 802.11 nodes, the throughput of 802.15.4 nodes decreases as the ratio of 802.11, and 802.15.4 packet length increases. That is, as the packet length of 802.11 nodes tends to the 802.15.4's one, the channel experiences successful transmissions from 802.11 nodes longer than successful transmissions from 802.15.4 nodes because of the higher probability of successful transmission of 802.11 nodes compared to 802.15.4.

IV. Conclusion

In this letter, we presented an analytical framework based on Markov chains that models the coexistence between 802.11 networks and 802.15.4 networks. The model allows the derivation of metrics such as the probability of successful transmissions, the probability of collision, and the fraction of time that the channel experiences successful transmissions for both 802.11 nodes and 802.15.4 nodes. Through extensive simulations of coexistence scenarios, we validated the accuracy of the proposed model, and we analyzed the performance of both 802.11 networks and 802.15.4 networks in saturation conditions. The model confirmed a considerable degradation of the probability of transmission of 802.15.4 nodes as the number of 802.11 nodes increases in the network due to the fact that there is a significant difference between the CCA duration of 802.15.4 nodes, and the duration of the last sensing of 802.11 nodes. Another reason for this performance degradation for 802.15.4 nodes is the larger time slot in 802.15.4 compared to 802.11 time slot, which has as consequence to force 802.15.4 nodes to permanently backoff with an increase in their contention window. In this work, we assumed ideal channel conditions and homogeneous nodes. As future directions, we will extend the model to erroneous channels and heterogeneous nodes.

Also, the model assumes there is no hidden terminal problem. The hidden terminal problem is a critical issue in wireless communications. It is commonly accepted that the use of Request To Send/Clear To Send (RTS/CTS) mechanism in CSMA/CA-based homogenous networks may avoid the hidden terminal problem. However, the RTS/CTS mechanism introduces both the exposed terminal problem in which nodes unnecessarily refrain from transmission, and additional message exchange in the network. In a coexistence scenario between 802.15.4 nodes and 802.11 nodes, this could lead to a severe degradation of 802.15.4 node's performance since each time an 802.15.4 node refrains from transmission, it is much likely to experience larger backoff delay. If RTS/CTS mechanism is not used interference will increase instead. As a future work, we will consider the impact of the hidden terminal problem in the context of coexistence between 802.15.4 and 802.11.

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