Performance of multihop CSMA unicast under intermittent interference

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Abstract— **the main goal of this paper is to evaluate the effect of Wi-Fi or other forms of interference on the performance of a unicast 802.15.4 sensor network. The 802.15.4 CSMA/CA mechanism is modeled as a layered Markov Chain, taking into consideration the back off process, the protocol for packet re-transmission attempts, the number of 802.15.4 nodes and unsaturated traffic conditions. Interference is modeled as discrete time Markov Process. This allows us to evaluate end-to-end success probabilities.**

***Index Terms*—802.15.4, Coexistence, CSMA, Unicast, Interference**

I. Introduction

The IEEE 802.15.4/ZigBee has gained increased popularity as a possible low data rate and low power protocol for wireless personal area networks. IEEE 802.15.4 operates in the 2.4 GHz ISM band. However, the presence of Wi-Fi interference across the same band causes co-existence issues, leading to loss of reliability for the network or inefficient use of the radio spectrum. Most papers on co-existence focus mainly on the power differences and large differences in time constants in accessing the channel of the two protocols [1]. On the other hand, existing models for evaluation of IEEE 802.15.4 mainly focus on internal interference within the network and ignore the effect of the Wi-Fi interference [2], [3]. Therefore, this paper presents an accurate Markov chain model for evaluating the effect of Wi-Fi on a unicast multihop 802.15.4 network, focusing on the analysis of success rate and delay during the CSMA mechanism of the protocol.

The rest of the paper is structured as follows: In section *II*, we evaluate the effect of the Wi-Fi interference by assuming that it behaves as a discrete time Markov chain. In section *III*, we give a brief overview of the IEEE standard, with the aim to derive a simplified but sufficient model for our analysis. Section *IV* describes the Markov model we formulated to describe the 802.15.4 protocol operations. Firstly, we introduce the model for a single 802.15.4 node and secondly we try to extend this in order to account for a multi-node scenario. Finally, results and concluding remarks are given in sections *V* and *VI*, respectively.

II. Interference Model

Interference, for instance from Wi-Fi, can be approximated as a discrete time process $\{C[t], t = 0,1,2, \dots\}$ that is independent of the packet network [4]. This implies the assumption that the 802.15.4 network does not affect Wi-Fi devices, which is realistic for a specific distance range (region R3 in [3]). As presented in Fig.1, this binary on-off process alternates between active and idle periods, i.e., the finite state space $S = \{1,0\}$, where 1 represents the idle state and 0 the busy state.

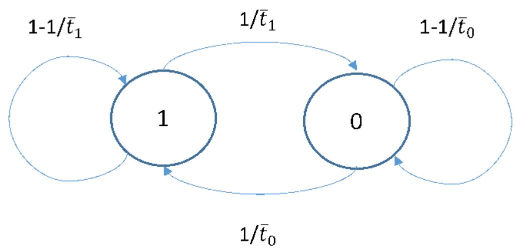


Fig. 2. Discrete time markov chain model for Interference

Measurements at a survey site, in particular extensions of [5], suggest that we can estimate the average time that the process stays in each state $(\bar{t}_1, \bar{t}_0)$. This enables us to estimate the corresponding state transition probabilities. The transition probability matrix P is given as

$$P = \begin{bmatrix} p_{0/0} & p_{0/1} \\ p_{1/0} & p_{1/1} \end{bmatrix} = \begin{bmatrix} 1 - 1/\bar{t}_0 & \bar{t}_0 \\ \bar{t}_1 & 1 - 1/\bar{t}_1 \end{bmatrix} \quad 1.$$

For that channel, we can define the clear channel rate (γ_0) as the average fraction of time that the channel is idle. That is,

$$\gamma_0 = \frac{\bar{t}_1}{\bar{t}_1 + \bar{t}_0} \quad 2.$$

The Markovian model leads to exponentially distributed packet and idle times. A comparison with measured timing distributions is outside the scope of this paper, but will be reported later [6].

II. IEEE 802.15.4 Standard Overview

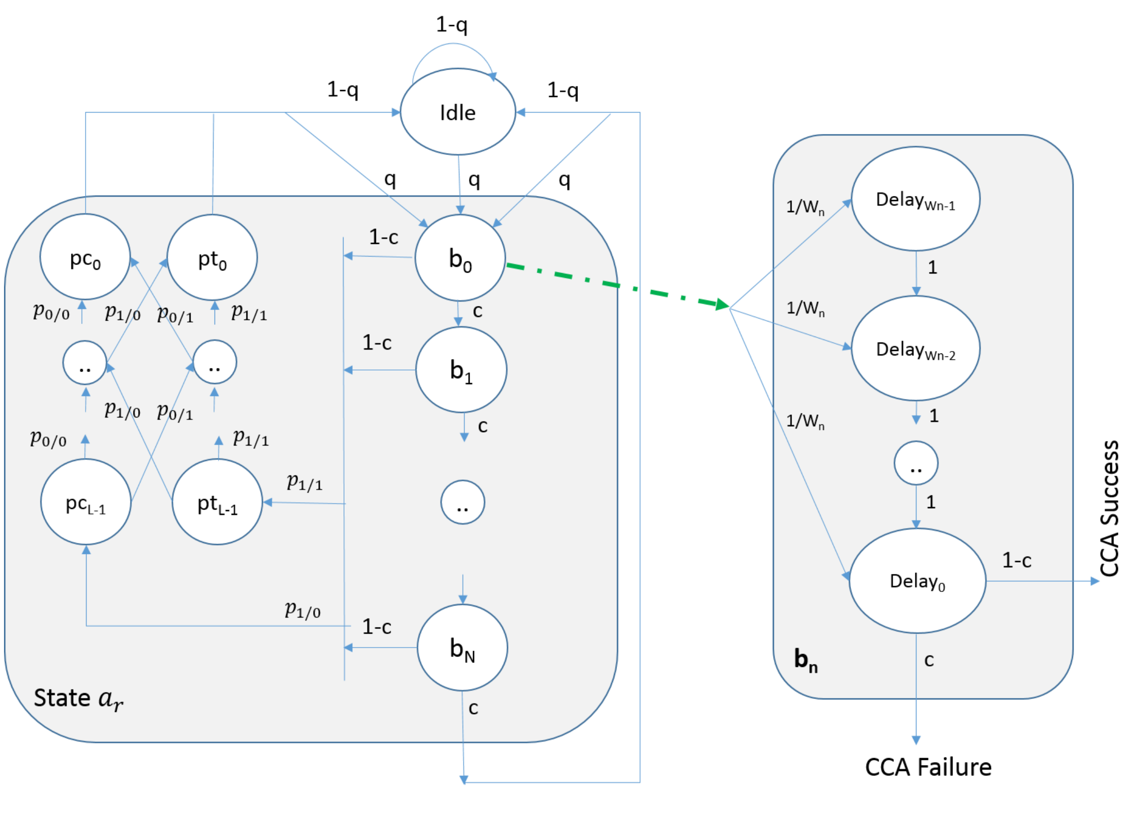
In this section, we review the IEEE 802.15.4 protocol in order to derive a simplified but sufficiently accurate model for our needs. IEEE 802.15.4 employs CSMA/CA for medium access control. To simplify our analysis, we consider a slotted version of the CSMA algorithm: all nodes are synchronized and transmissions can only begin at the boundaries of time units called backoff slots (each slot lasts for T_{bs} = 0.32 msec). When a node has a packet to transmit, it first backs off for a random number of backoff slots chosen uniformly between 0 and $2^{BE} - 1$, where the backoff exponent *BE* is initially set to 3. After finishing the backoff, the IEEE 802.15.4 station checks the channel using a clear channel assessment (CCA). When another ZigBee node is transmitting or an external interference source occupies the ZigBee channel, the CCA on the ZigBee device will fail. The random back off is intended to reduce the probability of collisions among contending nodes. If the channel is sensed idle, the node starts to transmit its current packet after a short turnaround time from receiving to transmitting (t_x). These transmissions may be successful or run into a collision, for instance because Wi-Fi is ignorant of the ZigBee traffic and starts a packet transmission. These transmission failures are remedied by a positive acknowledgement scheme (ACK), i.e. retransmitting the packet if no acknowledgement from the receiver is heard by the transmitter. If the current re-transmission attempt exceeds the maximum number *R*, the protocol terminates with a communications failure. By default, $R = 4$ (one initial attempt and up to 3 retries). On the other hand, if the channel is found to be busy, the backoff exponent is incremented by one until BE reaches the default value of 5 (*BE* is frozen when this value is reached) and the node waits for a new random number of back off slots until the channel can be sensed again. This procedure continues until a maximum number of *N* back-offs is reached. If the current back off state (n) exceeds the maximum number *N*, the protocol terminates with a channel access failure). By default, $N = 4$.

III. Interference Model

We desire to build an analytical model for evaluating the performance of an IEEE 802.15.4 network under Wi-Fi interference. Our objective is to estimate for each node in the network (k), the probability that a packet is successfully transmitted denoted as $P_{suc}^{(k)}$. We will do this in a three stage approach. First we use a Markov chain model for the CSMA backoff mechanism of a single node. This model will give us an expression for the probability of a single node being in a transmitting state. In the second modelling stage, we estimate the probability of a channel busy assessment based on the transmission probabilities of its neighboring nodes. Finally, in order to obtain the end to end success probability, a Markov chain is used to model the packet re-transmission mechanism.

A. *Single Node Model-Backoff mechanism*

The back off procedure, as described in section *III*, is modeled in the form of a Markov Chain as presented in Fig.2a. In [4], we suggested a similar model for unicast transmissions. However, we re-formulated it in such a way to account for internal 802.15.4 interference also. We study the performance of unsaturated traffic, that is, a single node has a packet available for transmission in each time unit with probability q. We do not consider any packets generation during the random back off states or during transmissions. We start from an initial state, which is the first attempt to access the channel (denoted with b_0), till either the channel is sensed idle during CCA and the packet is transmitted or the maximum number of allowed back-off stages *N* (which equals to 4 in IEEE 802.15.4) has been reached and the protocol terminates with a channel access failure. During transmission, Wi-Fi, that is ignorant of 802.15.4 traffic, may initiate a transmission causing the 802.15.4 packet to be corrupted. This is the reason we introduced two packet



a b

Fig. 2. Single node Markov model describing 802.15.4 CSMA/CA backoff mechanism

transmission paths in Fig.2a. States pt represent packet transmission while the channel is in state 1 (Wi-Fi interference is off), while the pc states represent transmissions while the channel state is 0 (Wi-Fi interference is on). Transitions between Wi-Fi on and off states during 802.15.4 packet transmission are given according to the Wi-Fi Markov chain model. A single node can only be in one of the following states: the idle state, where the node is waiting for a new packet, a back off state b_n that denotes the n^{th} back-off attempt, $n \in \{0, \dots, N\}$, in the packet transmission states pt_l and packet collision states pc_l, where $l \in \{0, \dots, L\}$ represents the current packet slot transmitted and L is the ZigBee packet length in slots. Each back off state b_n is extracted as in Fig.2b. As explained, when a node has a packet to transmit, it waits for a random back off period before attempting a CCA. This is represented by a transition to one of the $Delay_d$ states, each with probability $W_n = 1/2^{BE_n}$ and $d \in [0, W_n - 1]$.

Finally, $B(t)$ represents a stochastic process such that

$$B(t) = \begin{cases} \mathrm{b}_n \\ \mathrm{pt}_l \\ \mathrm{pc}_l \\ \mathrm{idle} \end{cases} n \in \{1, \dots, N\}, l \in \{0, \dots, L\} \quad 3.$$

Let P_B be the transition matrix of the Markov chain. For sake of notational simplicity, we shorten

$$P_B(B(t) = a | B(t+1) = b)$$

as $P_B(a|b)$.
The following transition probabilities are defined:

$$P_B(\mathrm{b}_n | \mathrm{b}_{n+1}) = c \quad 4.$$
$$P_B(\mathrm{b}_n | \mathrm{pt}_{L-1}) = (1-c)\left(p_{1/1}\right) \quad 5.$$
$$P_B(\mathrm{b}_n | \mathrm{pt}_{L-1}) = (1-c)\left(p_{1/0}\right) \quad 6.$$
$$P_B(pt_l | pt_{l+1}) = p_{1/1} \quad 7.$$
$$P_B(pt_l | pc_{l+1}) = p_{1/0} \quad 8.$$
$$P_B(pc_l | pc_{l+1}) = p_{0/0} \quad 9.$$
$$P_B(pc_l | pt_{l+1}) = p_{0/1} \quad 10.$$
$$P_B(b_N | \mathrm{idle}) = (1-q)c \quad 11.$$
$$P_B(pt_0 | \mathrm{idle}) = 1-q \quad 12.$$
$$P_B(\mathrm{idle} | \mathrm{idle}) = 1-q \quad 13.$$
$$P_B(pt_0 | \mathrm{b}_0) = q \quad 14.$$

Equation (4) denotes the transition between consecutive back-off stages after a busy channel assessment. Equations (5-6) denote the start of a packet transmission. We consider the turnaround time almost equal to a time unit. Equations (7-8-9-10) represent the transmission of a packet in back off slot units. This transmission may encounter a Wi-Fi collision or not. Equations (11-12-13) represent the transition to an idle state that can happen either a failure, after the end of a packet transmission or from a previous idle state, if there are no packets available for transmission. Finally, (14) indicates the start of the backoff procedure if there is a packet available for transmission. We define the state probability vector π containing all steady state probabilities

$$\pi_j = \lim_{t \to \infty} P[B(t) = j], j \in b_n, pt_l, idle.$$

It follows that [7]

$$\pi = \pi P_B \quad 15.$$

and due to the law of total probability

$$1 = \sum_j \pi_j \quad 16.$$

That is,

$$1 = \sum_{n=0}^{N} \pi_{b_n} + \sum_{l=0}^{L-1} \pi_{pt_l} + \sum_{l=0}^{L-1} \pi_{pc_l} + \pi_{idle} \quad 17.$$

The above equations give as a system of linear equations that π_j must satisfy. Thus, the steady state probabilities π_{b_n} can be calculated using the above mentioned set of equations (15-16-17). Finally, we derive the probability $v^{(k)}$ that node k is in a transmitting state as:

$$v^{(k)} = \sum_{l=0}^{L-1} \pi_{pt_l} + \sum_{l=0}^{L-1} \pi_{pc_l} \quad 18.$$
$$v^{(k)} = L \sum_{n=0}^{N} (1 - c_n) \pi_{b_n} \quad 19.$$

This probability depends on the traffic characteristics and on the probability of a channel busy assessment. In the second modeling stage, we will try to define an estimate for that probability based on the neighboring nodes probability of being in a transmitting state.

B. Extension to more nodes-channel busy assessment

We consider a multihop network with N nodes. For simplicity, we assume that every node has the same view of the network. That is, all nodes are in the sensing range of each other, thus we do not consider packet collisions with other 802.15.4 packets. The event of a busy channel assessment is a sum of three contributions: Another 802.15.4 node is engaged into a transmission and Wi-Fi channel is off, an 802.15.4 node is transmitting and the Wi-Fi channel is on or only due to Wi-Fi interference. Thus:

$$c^{(k)} = c_z^{(k)} + c_w^{(k)}\left(1 - c_z^{(k)}\right) \quad 20.$$

where $c_z^{(k)}$ is the probability that node k finds the channel occupied by another 802.15.4 packet transmission (collided with Wi-Fi or not), whereas $c_w^{(k)}$ is the probability to find the channel busy due to a Wi-Fi packet transmission.
The probability that a node senses the channel busy due to another 802.15.4 node's packet transmission can be given as

$$c_z^{(k)} = P\left\{\bigcup_{k\in\Omega_k} T_k\right\} \quad 21.$$

where T_k represents the event of a packet being transmitted by node k and Ω_k is the set of neighboring nodes. Ignoring the case that nodes can start sensing in the same time,

$$c_z^{(k)} = \sum_{k\in\Omega_k} v^{(k)} \quad 22.$$

Regarding the probability to sense the channel busy due to Wi-Fi interference, we assume that given no previous knowledge about the channel status, it is related to the clear channel rate according to

$$c_w^{(k)} = 1 - \gamma_0 \quad 23.$$

C. *Success probability*

To complete the analysis, we need to derive an expression of the success probability for each link of the network. Fig.3 presents the third layer in our model, describing the number of packet re-transmission attempts. As described in section *III*, a packet is discarded due to two reasons: Channel access failure or retry limits.

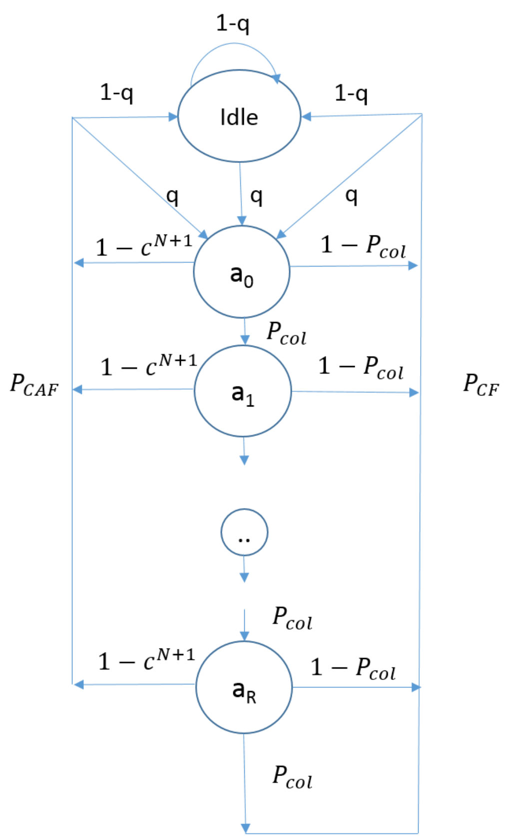


Fig. 3. Markov chain model of the CSMA/CA algorithm including packet re-transmission attempts for 802.15.4 MAC.

Channel access failure when the channel is sensed busy in any of the allowed back off attempts *N*. Following the Markov chain in Fig.3, the probability that the packet is discarded due to channel access failure in any of the retries *r* is:

$$P_{CAF}{}^{(k)} = c^{N+1}\left[\sum_{r=1}^{R+1}\left((1-c^{N+1})P_{col}\right)^{r-1}\right] \quad 24.$$

A packet is successfully transmitted if the channel is sensed idle during CCA and remains idle during the whole packet transmission. The probability that the channel remains in the idle state for exactly L time units (the packet length) or more is $\left(p_{1/1}\right)^L$. Thus the probability of collision is:

$$P_{col} = 1 - \left(p_{1/1}\right)^L \quad 25.$$

The probability that a packet is discarded due to a retry limit, the probability that the packet fails to be transmitted successfully in any of the packet re-transmission attempts *r*. That is:

$$P_{CF}{}^{(k)} = [(1-c^{N+1})P_{col}]^{R+1} \quad 26.$$

Thus, the link probability of success is:

$$P_{SUC}{}^{(k)} = 1 - P_{CF}{}^{(k)} - P_{CAF}{}^{(k)} \quad 27.$$

The expressions for the single node probability to be in a transmitting state (19), the channel busy probability (20) and the link probability of success (27), form a system of non-linear equations that can be solved numerically enabling us to derive a unique solution for the success probability for each link in the network.

IV. RESULTS

In this section, we present the performance estimation of an 802.15.4 network for homogenous traffic conditions and several numbers of neighboring nodes. We used the default MAC values of protocol parameters (*N* = 4, *R* = 4) and the traffic rate was set to 20 pkts/sec. Results are based on our theoretical model and real measured collected Wi-Fi RSSI data from a survey site in an office environment in Shanghai.

Fig.4 presents the probability of a single node to successfully transmit a packet as a function of the Wi-Fi channel clear channel rate. Results are shown for different network sizes (*K* = 8, 24 and 64 neighboring nodes). The star points in Fig.4 present the success probability when no Wi-Fi interference is considered.

As expected, as the number of the neighboring nodes increases, the success probability decreases. We can observe that in a highly Wi-Fi loaded network, $\gamma_0 < 0.3$, the success probabilities are equally low independent on the network size. However, the network size has a significant influence in the performance, as we move towards lighter Wi-Fi traffic.

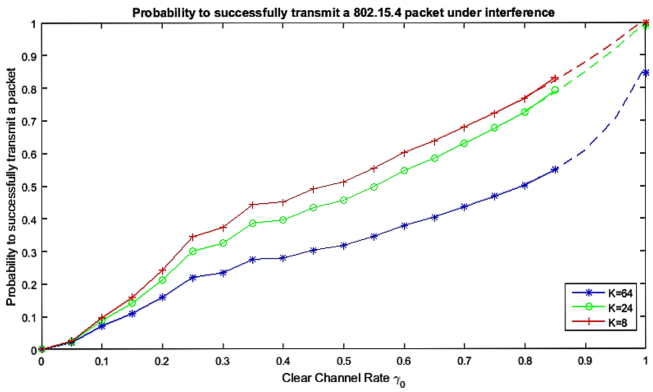


Fig. 4. Probability to successfully transmit a 802.15.4 packet under interference as a function of the clear channel rate for different nework sizes. For packet size L=32 byte, N = 4 backoff attempts and R = 3 retranmsmission attempts.

V. CONCLUSIONS

As the IEEE 802.15.4 standard becomes more and more popular in many applications, the issue of cross technology interference is consequently becoming more important. This paper addresses the effect of Wi-Fi or other forms of interference on unicast 802.15.4 transmissions. We used a Markov chain model to predict success rate of unsaturated 802.15.4 networks under interference. Our results indicate a strong influence of Wi-Fi interference on network performance. In cases of heavy Wi-Fi interference, even a network with a few nodes will not be able to operate satisfactory. Even in relatively idle Wi-Fi channels, $\gamma_0 > 0.8$, we can observe a significant drop in the network performance (15% drop for a network with 24 nodes and almost 40% for a 64 node network).

Our results extent previous results on co-existence that focused Wi-Fi interference, initially neglecting internal interference from 802.15.4 nodes. For severe traffic (low γ_0), ignoring internal interference, does not influence the estimation results. However, at low clear channel rate values, interference from other 802.15.4 nodes has a considerable influence in the network performance.

VI. REFERENCES

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