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Performance of multihop CSMA unicast under intermittent interference

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Abstract
We study the effect of Wi-Fi or other forms of interference on unicast multihop 802.15.4 traffic in a sensor network, based on a layered state-driven Markov chain. The probability of a successful transmission attempt is treated as a conditional probability that depends on the state, that is, on the previous experience that the packet had with the presence of harmful interference. This allows us to evaluate end-to-end success probabilities.

1 Introduction
The increasing popularity of wireless sensor networks has led to a rapid growth in the number of devices that use the IEEE 802.15.4 standard. To allow for fast deployment, the IEEE 802.15.4 opted for the 2.4 GHz ISM band. However, the presence of other wireless technologies like Wi-Fi (IEEE 802.11) or Bluetooth (IEEE 802.15.1) across the same band potentially causes coexistence issues, leading to loss of reliability for the network or inefficient use of the radio spectrum. Wi-Fi transmitters are the more concerning since they are commonly used in office or residential environments. The co-existence of 802.15.4 and Wi-Fi has been a subject of many previous papers. Most papers focus on the power differences and the large differences in time constants between the slow 802.15.4 and the fast 802.11 in accessing the channel [1, 2]. Publications on interference within an 802.15.4 network are also relevant. In [3], the back-off state of a node has been modeled as a Markov Chain. We adopt a similar model, but with a number of differences: We include the impact of Wi-Fi interference but initially neglect interference from other ZigBee nodes. We consider a unicast multihop network, in which packets follow a particular route, that is, we extend the model to include more than one hop. The probability of sensing the channel busy is assumed in [3] to be a constant, that is, independent of the history of the packet in the network. We extend this by considering a conditional probability of sensing the channel busy, which depends on whether it has experienced idle or busy channels in the past. The rest of the paper is structured as follows. The network interference is modeled in section 2. Section 3 provides an overview of the IEEE 802.15.4 protocol with the aim to derive an accurate model for our analysis. A layered Markov model is formulated in section 4. Each-subsection includes a layer describing a different protocol operation. Finally, concluding remarks are given in section 5.

2 The Interference Model
The network interference, for instance from Wi-Fi, will be modeled as a stochastic process $C'(t)$ that is independent of the packet network. This implies the assumption that the 802.15.4 network does not affect Wi-Fi devices, which is true for a specific distance range (region R3 in [2]). We will compare two different models in the following sub-sections.
2.1 Markovian Interference Model

Here, we assume that the interference is a binary on-off process alternating between active and idle periods. Let \( \{C_{th}(t) : t \geq 0\} \) represent a stochastic process with discrete state space \( S = \{1, 0\} \), 1 representing a clear channel (idle state) and 0 the busy state. The process transitions from idle to busy state, independent of the past, according to a continuous-time Markov chain. This process can be fully described by the finite state space \( S = \{1, 0\} \), the transition matrix \( P_I(t) \) and the holding-time rates \( \alpha_k, k \in S \).

Every time that state \( k \) is visited, the chain spends on average \( t_k = \frac{1}{\alpha_k} \) units of time there before moving on. Once we choose particular \( t_1 \) and \( t_0 \), that is, the average inter-frame idle time between two consecutive IEEE 802.11 packets and the average time that the Wi-Fi traffic is on respectively, not only we fix the holding rates, but also the probability \( \gamma_0 \) is defined as \( \gamma_0 = P_r(C_{th}(t) = 1) = \frac{t_1}{t_0 + t_1} \).

The transition probabilities can be calculated by solving the Kolmogorov backward equations for the CTMC with transition matrix \( P_I(t) \). For the given two state CTMC the transition matrix are of the following form:

\[
P_I(t) = \begin{pmatrix}
    \frac{a_0 + a_1}{a_0 + a_1} & \frac{a_1}{a_0 + a_1} \\
    \frac{a_0 + a_1}{a_0 + a_1} & \frac{-a_1}{a_0 + a_1}
\end{pmatrix} + \begin{pmatrix}
    \frac{a_0 + a_1}{a_0 + a_1} & \frac{-a_1}{a_0 + a_1} \\
    \frac{a_0}{a_0 + a_1} & \frac{a_0 + a_1}{a_0 + a_1}
\end{pmatrix} e^{-(a_0 + a_1)t}
\]

2.2 Interference Traffic Model based on measured data

In this traffic model, we assume that the interference pattern is characterized by measurements at a survey site. Let \( C_m(t) \) be a stochastic process that describes the channel status at instant time \( t, t \in [0, T] \).

\[
C_m(t) = \begin{cases}
    1 & \text{if } E(t) < E_{th} \\
    0 & \text{if } E(t) \geq E_{th}
\end{cases}
\]

In the above equation, \( E(t) \) is the measured interference power level at time \( t \) and \( E_{th} \) is the threshold value above which we assume that 802.15.4 communication is disrupted. The clear channel rate \( \gamma_0 = P_r(C_m(t) = 1) \) is obtained directly from measured realizations \( c_m(t), t \in T \) of the stochastic process \( C_m(t) \) in a sampling window of length \( T \).

3 IEEE 802.15.4 Standard Overview

We review the IEEE 802.15.4 protocol in order to derive a simplified but sufficiently accurate model. IEEE 802.15.4 employs CSMA/CA for medium access control. When a node has a packet to transmit, it backs off for a random number of backoff slots (each slot lasts for \( T_{bs} = 0.32 \) msec) chosen uniformly between 0 and \( 2^{BE} - 1 \). After the backoff, the channel is checked using a clear channel assessment (CCA). If the channel is sensed idle, the node starts transmitting its packet. This transmission can be successful or run into a collision, for instance because Wi-Fi is ignorant of 802.15.4 traffic. These transmission failures can be remedied by a positive acknowledgment scheme (ACK), that is, the packet is retransmitted up to a maximum number of retries \( R \), if no acknowledgment packet is received. If the the maximum number \( R \) is exceeded, the protocol terminates with a communications failure. On the other hand, if the channel is found to be busy, the backoff exponent (BE) is incremented by one and the node waits for a new random number of back off slots until the channel can be sensed again. This procedure continues up to a maximum number \( N \) of allowed back-offs and the protocol terminates with a channel access failure.
4 Formulation of the protocol model

The protocol operations, as described in section 3, are modeled in the form of a layered Markov Chain presented in Fig. 1. A detailed description of each layer is provided in the following sub-sections.

4.1 The Random Delay Mechanism

The random delay mechanism in CSMA/CA can be approximated by means of a discrete-time transition chain as shown in Fig. 1a. The random back off period before attempting a CCA is represented by a transition to one of the $\text{Delay}_{d}$ states, $d \in [0, 2^{BE} - 1]$. We assume that the conditional idle probability $P_r(C|D = d)$ for a clear channel assessment depends on previous observations and the observation delay $\tau = dT_{bs}$, i.e., on how long ago these previous observation have been done. In this paper, we are not (yet) interested in latency. Thus we have no need to consider time-driven Markov chains and we will further collapse this into an event-based Markov chain. We use the model of Fig. 1a to calculate the probability of sensing the channel idle during CCA.

$$P_r(C) = \sum_{d=0}^{2^{BE} - 1} P_r(C|D = d)P_r(D = d) = \frac{1}{2^{BE}} \sum_{d=0}^{2^{BE} - 1} P_r(C|D = d)$$

We can distinguish two different cases:

*Initial back-off: No evidence about channel status*

In the case of the first attempt to access the channel, we have no previous knowledge about the channel status. Thus, the probability $P_r(C|D = d))$ to sense the channel
idle after the backoff time $\tau = dT_{bs}$ is assumed independent on time $\tau$ and equal to the clear channel rate for both interference models.

$$Pr(C) = \frac{1}{2^{BE}-1} \sum_{d=0}^{2^{BE}-1} Pr(C|D = d) = \frac{1}{2^{BE}} \sum_{d=0}^{2^{BE}-1} \gamma_0 = \gamma_0 \forall d \in [0, 2^{BE} - 1] \quad (4)$$

**Channel assessment following a busy detection**

When a node is attempting to access the channel given that it was sensed busy in the previous attempt, we know that there was an on-going Wi-Fi transmission in the medium. We assume that probability $Pr(C|D = d)$ to sense the channel idle given a previous busy detection after the back off waiting time $\tau = dT_{bs}$ depends on the result of the previous CCA attempt. This probability will be estimated for the two traffic models:

i. Markovian Interference traffic model

The probability to sense the channel idle (state 1) after time $\tau = dT_{bs}$ given that now is in state 0 is given by the (2, 1) entry of the transition matrix $P_I(\tau)$. Thus according to Eq.3:

$$Pr(C) = \frac{1}{2^{BE}} \sum_{d=0}^{2^{BE}-1} Pr(C|D = d) = \frac{1}{2^{BE}} \sum_{d=0}^{2^{BE}-1} P_{I(\tau)}(dT_{bs}), d \in [0, 2^{BE} - 1] \quad (5)$$

ii. Interference traffic model based on measured data:

Similarly, we are interested in the conditional probability of an idle channel assessment at time $t + \tau$ given that the previous CCA at time $t$ indicated a busy channel.

$$Pr(C) = \frac{1}{2^{BE}} \sum_{d=0}^{2^{BE}-1} Pr\{C_m(t + dT_{bs}) = 1|C_m(t) = 0\} \quad (6)$$

Fig.2 shows the probability $Pr(C)$ of a channel idle assessment after backoff time $\tau$ given a previous busy channel detection for the two interference models. The calculations in

![Figure 2: Probability $Pr(C)$ of a channel idle assessment given a previous busy channel detection](image)

(a) Markovian Interference traffic model  (b) Measured data traffic model
Fig. 2b are based on measured data collected from a survey site in an office environment in Shanghai [4]. In both models, we can observe that the previous busy channel detection provides us with information about the consequent channel assessment, i.e., the probability to sense the channel idle is lower than the unconditional probability \( \gamma_0 \) (red line). The green dots in Fig. 2b present the results from the Markovian interference model assuming the same average busy time \( \bar{t}_0 \).

### 4.2 Back-off state Markov Model

Extending the backoff state \( b_n \) as proposed in Fig. 1b, a Markov Chain is constructed. We start from the first attempt to access the channel, till either the channel is sensed idle and the packet is transmitted or the maximum number of back-off stages \( N \) has been reached and the protocol terminates. We use the following notation: \( b_n \) denotes the \( n^{th} \) back-off attempt, \( n \in [1, \ldots, N] \), \( pt \) a packet transmission and the CAF state denotes protocol termination with a channel access failure. Finally, \( B(t) \) represents a stochastic process such that:

\[
B(t) = \{ b_n, pt, CAF \}, n \in [1, \ldots, N] \tag{7}
\]

Let \( P_B \) be the transition matrix of the Markov chain with transition probabilities\(^*:\)

\[
P_B(b_n|b_{n+1}) = 1 - c_n \tag{8}
\]

\[
P_B(b_n|pt) = c_n \tag{9}
\]

\[
P_B(b_N|CAF) = 1 - c_N \tag{10}
\]

The transition probabilities \( c_n \) are the idle probabilities \( P_i(C) \) as calculated in the previous sub-section (\( c_1 \) from Eq. 4 and \( c_n \) from Eq. 5-6). Filling in the transition matrix \( P_B \), enables us to determine the overall probability \( f \) to terminate the protocol with a channel access failure (reach CAF state in Fig. 1b). This probability is presented in Fig. 3, for a different number of allowed backoff attempts \( N \). The dashed lines present probability \( f \) in the case that we do not consider conditional probabilities. That is, the probability to sense the channel idle \( (c_n) \) given a previous busy detection does not depend on history and is considered equal to the clear channel rate.

![Figure 3: Probability \( f \) to terminate the protocol with a channel access failure](image1)

(a) Markovian Interference traffic model

![Figure 3: Probability \( f \) to terminate the protocol with a channel access failure](image2)

(b) Measured data traffic model

Figure 3: Probability \( f \) to terminate the protocol with a channel access failure

\(^*\)For sake of notational simplicity, we shorten \( P_B(B(t) = a)|B(t + 1) = b) \) as \( P_B(a|b) \).
4.3 Single Hop Markov Model

In order to model the packet re-transmission attempts, we extend the backoff state $a_r$ as proposed in Fig.1c, starting from the first transmission attempt, till either the packet has been successfully transmitted to the next hop or the maximum number of allowed retries has been reached. At any point in time, a packet is in one of the following states: state $a_r$, during which a node is contending to access the channel, state $pt_r$, where a packet is being transmitted in the current retry, the $s$ state denoting a successful packet transmission or in the CAF or CF states that denote a channel access failure or a communications failure respectively. Finally $A(t)$ represents a stochastic process such that:

$$A(t) = \{a_r, pt_r, s, CF, CAF\}, r \in [1, \ldots, R]$$ (11)

Let $P_A$ be the transition matrix of the Markov chain with probabilities:

$$P_A(a_r|pt_r) = 1 - f$$ (12)
$$P_A(a_r|CAF) = f$$ (13)
$$P_A(pt_r|s = s_r)$$ (14)
$$P_A(pt_r|a_r+1) = 1 - s_r$$ (15)
$$P_A(pt_R|CF) = 1 - s_R$$ (16)

Filling in the transition matrix $P_A$, enables us to determine the probabilities $f_{CAF}$ (reach CAF state in Fig.1c) and $f_{CF}$ (reach CF state in Fig.1c). Transition probabilities $f$ are calculated as in sub-section 4.2 and probability $s_r$ (successful packet transmission after a clear CCA) will be estimated in the following sub-sections:

i. Markovian Interference traffic model

In this case, a lossless channel is assumed, i.e., we do not take into account any form of packet losses that may occur during the transmission ($s_r = 1$). Since a packet is always transmitted successfully, for the Markovian interference, we do not model the ACK packets and we do not consider any packet retransmissions ($R = 1$). Thus, the overall probability to fail to transmit the packet in a single hop is as presented in Fig.3a.

ii. Interference traffic model based on measured data:

We adopt a similar approach to [5], in order to consider a packet failure after a clear CCA. Let $S(t)$ be a stochastic process denoting the availability of the channel for a transmission of duration $t_p$ starting at instant $t$, $t \in \{0, T - t_p\}$.

$$S(t) = \begin{cases} 
1, & \text{if } \int_t^{t + t_p} C_m(t) d\tau = t_p \\
0, & \text{if } \int_t^{t + t_p} C_m(t) d\tau < t_p 
\end{cases}$$ (17)

where $t_p$ denotes the time duration that the channel needs to be free of interference. The clear channel rate $\gamma_{t_p}$ is defined as $\gamma_{t_p} = P_r\{S(t) = 1\}$.

Surprisingly, experiments in [4] revealed that the probability to find a clear time slot for a successful packet transmission is virtually not correlated with the outcome of the preceding CCA. Using this as an approximation, the probability of a channel clear assessment and the probability of a successful packet transmission become independent. Thus the probability for a successful packet transmission ($s_r$) is equal to the clear channel rate $\gamma_{t_p}$. 

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Figure 4: Estimated failure rate of the 802.15.4 32-byte packet transmission in a single hop under Wi-Fi interference.

Fig. 4 shows the overall probability to fail to transmit the packet in a single hop ($f_{CAF} + f_{CF}$). A number of repetitive re-transmission attempts significantly reduces the failure rate. The circles in Fig. 4a present measured failure rates from a lab test in Shanghai [4]. Our theoretical estimation of the failure rate in a single hop is very close to the fitted curve of the above mentioned measured rates, denoting the accuracy of the model. From Fig. 4b we can observe that at low clear channel rate the protocol mostly fails during CCA. However, as the clear channel rate increases transmissions fail even if CCA denoted a clear channel.

4.4 MultiHop Markov Model

At the highest layer of abstraction, a Markov chain is constructed that follows the packet as it passes over multiple hops. At any point in time, a packet is in one of the following states: state $m_h$, including the channel access mechanism and the packet transmission in the current hop $h$, the $s$ state denoting a successful transmission or in the CAF or CF states that denote a channel access failure or a communications failure respectively. $M(t)$ represents a stochastic process such that:

$$M(t) = \{m_h, s, CF, CAF\}, h \in [1, \ldots, H]$$

(18)

Let $P_M$ be the transition matrix of the Markov chain with transition probabilities:

$$P_M(m_h|m_{h+1}) = 1 - (f_{CAF} + f_{CF})$$

(19)

$$P_M(m_m|CAF) = f_{CAF}$$

(20)

$$P_M(m_h|CF) = f_{CF}$$

(21)

$$P_M(m_h|s = 1 - (f_{CAF} + f_{CF})$$

(22)

Filling in the transition matrix $P_M$, enables us to calculate the end to end probability of a successful packet transmission in all hops as presented in Fig. 5. As expected, as the number of hops a packet has to pass through to reach the final destination increases, the probability of a successful transmission decreases. The difference in the two models is due to the fact that in the case of the Markovian Interference, we assume that the 802.15.4 packets are always transmitted successfully ($s_r = 1$).
5 Conclusions

Our model was motivated by a need to analyze and predict the performance of IEEE 802.15.4 under IEEE 802.11 (Wi-Fi) interference. We adapted and extended a Markov Chain analysis to account for Wi-Fi interference to a unicast multihop CSMA/CA network. The main strength and novelty of this model is that it accounts for a changing conditional probability of successful transmission, as the node makes successive attempts, given the history of earlier transmission attempts. Preliminary results in a single hop, showed good agreement with the measured failure rates, indicating that the model can be used in a multiple hops scenario. Results revealed that when the channel is very busy ($\gamma_{tp} < 0.4$) the failure rate increases dramatically. Increasing the re-transmission attempts $R$ is not recommended, as most transmissions fail during CCA. Other measures, like frequency agility, should be performed. At high $\gamma_{tp}$ values, transmissions fail even after a clear CCA, indicating that the channel should be free of interference for a gap length at least equal to the 802.15.4 packet for a successful transmission. Packet re-transmissions are now essential, however, increasing $R$ too much does not have a huge impact (recommended value between 3-5).

![Figure 5: End-to-end failure rate of the 802.15.4 packet transmission in many hops for $N=5$ allowed back off attempts and $R=4$ packet re-transmissions](image)

References


