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REGULAR PAPER

Network throughput analysis of IEEE 802.15.4 enabled wireless sensor networks with FEC coding under external interference

Tallal Elshabrawy *

Faculty of IET, The German University in Cairo, New Cairo City, Main Entrance El Tagamoa El Khames, Cairo 11835, Egypt

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ABSTRACT

IEEE 802.15.4 enabled wireless sensor networks are often impacted by the coexistence of different sources of external interference sharing the ISM band. Such external interference may significantly deteriorate achievable wireless sensor network throughputs due to uncontrollable collisions of interference transmissions with IEEE 802.15.4 packets. Forward error correction may be considered as a mechanism to alleviate the resiliency of IEEE 802.15.4 packets against partial collisions due to interference. In this paper, theoretical analysis of network throughput of IEEE 802.15.4 enabled wireless sensor networks under external interference with deployment of FEC will be presented. The throughput performance of IEEE 802.15.4 network under FEC deployment is governed by the percentage of collided bits within IEEE 802.15.4 coded payloads that the FEC code can withstand. The analysis in this paper considers convolutional codes as FEC candidate codes for IEEE 802.15.4 networks and proceeds to theoretically derive collision percentage thresholds that convolutional codes may tolerate under Viterbi decoding. Numerical results indicate that an optimal FEC coding rate exists for a given IEEE 802.15.4 and external interference configuration. The optimal coding rate introduces enough resiliency for the IEEE 802.15.4 transmissions to withstand external interference. Any additional redundancy bits for more robust codes would render unneeded protection that unnecessarily reduces the goodput of IEEE 802.15.4 networks.

1. Introduction

The last decade has witnessed the proliferation of IEEE 802.15.4 enabled wireless sensor networks into a multitude of home, medical as well as industrial applications and services [1–3]. In light of the global and diverse application prospects for IEEE 802.15.4 governed sensors, the Industrial, Scientific, and Medical (ISM) radio bands have been selected for IEEE 802.15.4 operation. As a result, IEEE 802.15.4 applications performance is occasionally hindered by coexistence interference scenarios with other technologies sharing such unlicensed bands [4].

Typically, both IEEE 802.15.4 along with other coexistence technologies operating over the ISM band rely on a form of carrier sense multiple accesses with collision avoidance (CSMA/CA). However, occasionally IEEE 802.15.4 enabled networks would be at a disadvantage within such scenarios due to their relatively lower levels of transmission power. Accordingly, within a given IEEE 802.15.4 coexistence scenario with other interfering technologies, sensor nodes would normally sense interfering transmissions and backoff their own impending transmissions. On the other hand, due to relatively low power levels transmitted by sensor nodes, devices from interfering systems might often fail to sense that a given sensor node has captured the wireless medium [5]. As a result, the coexistence technologies impact IEEE 802.15.4 performance by two folds; firstly, the inherent increase in the shared channel load limits the achievable throughput of IEEE 802.15.4 networks. Secondly, un-controllable interference transmissions might severely deteriorate packet error rates for IEEE 802.15.4 transmissions that have successfully captured the wireless channel.

Extensive studies have been dedicated to investigate coexistence issues within IEEE 802.15.4 enabled wireless sensor networks. The research within such domain has spanned from modeling and analyzing the impact of coexistence scenarios on IEEE 802.15.4 performance (such as, [5–9]) to devising various schemes to mitigate the impact of such interference such as channel assignment algorithms (e.g., [10,11]), spectrum sharing methods (e.g., [5,12,13]) along with techniques for adaptive clear channel assessment (e.g., [14]). Forward error correction (FEC) could also be considered as another avenue that may evolve to alleviate coexistence problems. While the original IEEE 802.15.4 standard relies on spreading codes to offer transmission robustness against errors, the prevalence of collision events may impose FEC as a mechanism for

* Tel.: +202 25795525.
E-mail address: tallal.el-shabrawy@guc.edu.eg

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IEEE 802.15.4 packets to survive external interference (for example, considerations for FEC has been included in standardization efforts of IEEE 802.15.4 g task group for PHY Amendment for Smart Utility Network [15]).

The aim of this paper is to analyze the capability of convolutional codes as FEC candidates in relieving IEEE 802.15.4 network throughput from external coexistence interference. Accordingly, an analytical model is first developed to derive the network throughput of IEEE 802.15.4 networks suffering from external interference with deployment of FEC codes. The proposed analytical model builds on the analysis proposed in [16] which has the advantage of formulating the network throughput in terms of a direct expression that is solved numerically rather than relying on relatively more complicated two-dimensional Markov chains that has been adopted more frequently in the literature [9,17]. The analysis to be presented herein extends our initial work in [18] on analyzing throughput performance under external interference in absence of FEC. The devised analytical model in this paper for network throughput under FEC deployment reveals that the key variable that controls the ability of FEC to combat collisions due external interference is the percentage of overlap between IEEE 802.15.4 packets and colliding transmissions. This paper proceeds to derive an analytical model for deriving a collision threshold percentage that sets the limit for the ability of the Viterbi decoder to evade packet loss due to external interference under the assumption of a binary erasure channel (BEC) to model the underlying collision channel environment. The derived thresholds are combined with the derived expression for IEEE 802.15.4 network throughput to evaluate optimal coding rates to utilize under different external interference coexistence scenarios. Analysis of numerical results reveals that the best coding rate to be deployed is the one that introduces just enough redundancy (corresponding to the derived collision percentage threshold) that makes the decoding of IEEE 802.15.4 packets indifferent to the collision events from external interfering transmissions.

To the best knowledge of the authors, while the performance of FEC within the context of IEEE 802.15.4 has been investigated in the literature (e.g., [5,19]), no work in the literature has been dedicated to devise an analytical model of IEEE 802.15.4 network throughput that is coupled with packet error rates under FEC deployment. The rest of this paper is organized as follows; Section 2 summarizes CSMA/CA protocol employed in IEEE 802.15.4 and outlines the corresponding network throughput analysis proposed in [16]. Section 3 extends the model proposed in [16] to evaluate IEEE 802.15.4 network throughput under external interference with FEC deployment. Numerical results and analysis of best FEC to be utilized under a given external interference configuration are presented in Section 5. Finally, Section 6 shall be dedicated for conclusions.

2. Network throughput of IEEE 802.15.4 enabled networks in beacon-enabled mode

In this paper, CSMA/CA operating in the beacon-enabled mode of IEEE 802.15.4 shall be considered with the network configured in a star topology and under the assumption of saturated traffic. The operation of the underlying CSMA/CA is summarized as follows:

Each arriving MAC layer packet goes initially through a backoff period which depicts a random number of backoff slots chosen between 0, $2^{BE}-1$ where *BE* is the backoff exponent that is initially set to *macMinBE*. After each backoff period expires, a given sensor node goes through a clear channel assessment phase (CCA) that determines whether the channel is declared free (CCA success) resulting in packet transmission or busy (CCA failure) forcing the sensor node to enter a new backoff period. Successful CCA depicts sensing a free channel for an interval T_{CCA} within each of two

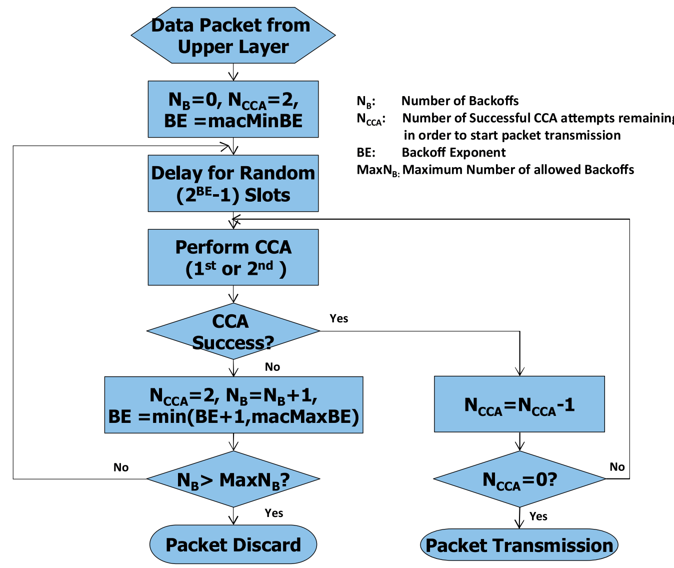

Fig. 1. Flow chart for considered IEEE 802.15.4 CSMA/CA operation.

consecutive backoff slots of duration T_{slot}. Each CCA failure on the other hand increases the backoff exponent *BE* by one with a maximum *BE* of *macMaxBE*. Successful packet transmission is followed by an inter-frame spacing (IFS) interval before which a sensor node would restart the transmission process for a new packet under the saturated traffic assumption. The CSMA/CA considered is summarized in Fig. 1.

In [16], a theoretical model for network throughput of the CSMA/CA scheme described in Fig. 1 was introduced. The model in [16] derives the network throughput of an IEEE 802.15.4 enabled wireless sensor network as,

$$S = nLp_{cca}p_{sens}(1-p_{sens})^{n-1} \tag{1}$$

where S depicts the total network throughput, n is the number of sensor nodes in the network, L is the packet size in terms of number of backoff slots, p_{sens} is the probability that a given node senses the wireless channel within a certain backoff slot and p_{cca} is the probably of successful CCA for a given sensor node. In essence Eq. (1) represents the network throughput in terms of the probability that a given sensor node is the only node sensing the channel at a given backoff slot ($p_{sen}\,(1-p_{sen})^{n-1}$) and the probability that such sensor successfully passes the CCA phase (p_{cca}) multiplied by the packet length depicting the number of backoff slots occupancy for successful transmissions (L) and the number of sensor nodes within the network (n).

Furthermore, in [16] p_{sens} and p_{cca} are derived as two interrelated functions as follows:

$$p_{sens} = \frac{1}{T_{bk}+1+\frac{1}{L+1}+\left(L+L_{IFS}+\frac{L}{L+1}\right)p_{cca}} \tag{2}$$

where T_{bk} is the expected backoff period and L_{IFS} is the inter-frame spacing interval. As postulated in [16], assuming *macMinBE* = *macMaxBE*, all backoff periods would be selected randomly from $\left\{0, 1, \ldots, 2^{macMinBE}-1\right\}$ for an expected duration T_{bk} given as,

$$T_{bk} = 0.5 \times \left(2^{macMinBE}-1\right) \tag{3}$$

For the probability of successful CCA, it has been derived in [16] as follows:

$$p_{cca} = \frac{1}{1+(L+1)\left[1-p_{sens}-(1-p_{sens})^{n}\right]} \tag{4}$$