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# MODELLING AND ANALYTICAL STUDY OF IEEE802.15.4 WIRELESS SENSOR NETWORK

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Abstract : Wireless sensor networks (WSNs) have a tremendous potential to improve the efficiency of many systems, for instance, in building automation and process control. Unfortunately, the current technology does not offer guaranteed energy efficiency and reliability for closed-loop stability. The main contribution of this paper is to provide a modeling, analysis, and design framework for WSN protocols used in control applications. The protocols are designed to minimize the energy consumption of the network, while meeting reliability and delay requirements from the application layer. The design relies on the analytical modeling of the protocol behavior. First, modeling of the slotted random access scheme of the IEEE 802.15.4 medium access control (MAC) is investigated. For this protocol, which is commonly employed in WSN applications, a Markov chain model is used to derive the analytical expressions of reliability, delay, and energy consumption. By using this model, an adaptive IEEE 802.15.4 MAC protocol is proposed. The protocol design is based on a constrained optimization problem where the objective function is the energy consumption of the network, subject to constraints on reliability and packet delay. The protocol is implemented and experimentally evaluated on a test-bed. Experimental results show that the proposed algorithm satisfies reliability and delay requirements while ensuring a longer lifetime of the network under both stationary and transient network conditions.

Keywords : wireless sensor network (WSN) , IEEE802.15.4, Medium Access Control,GTS, CAP,

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## I.INTRODUCTION

Recently there has been a growing interest in the use of Low Rate Wireless Personal Area Networks (LR-WPAN) [1] driven by the large number of emerging applications such as home automation, health-care monitoring and environmental surveillance. To fulfill the needs for these emerging applications, IEEE has created a new standard called IEEE 802.15.4 for LR-WPAN, which has been widely accepted as the de facto standard for wireless sensor networks. Unlike IEEE 802.11 [2], which was designed for Wireless Local Area Networks (WLAN),it focuses on short range wireless communications. The goal of the IEEE 802.15.4 LR-WPAN is to support low data rate connectivity among wireless sensors with low complexity ,cost and power consumption [3]. It specifies two types of network topologies, which are the beacon-enabled star network and the non beacon-enabled peer-to-peer network. For the beacon-enabled network, it defines the Guaranteed Time Slot (GTS) to provide real-time guaranteed service for delay-sensitive applications. In the non beacon-enabled network the GTS is reserved time slots such that it is requested, al-located and scheduled to wireless sensors that need guaranteed service for delay-sensitive applications. Existing GTS scheduling algorithms include First-Come-First-Served (FCFS) [1],priority-based [4] and Earliest Deadline First (EDF) [5] methods. Such

FCFS and priority-based scheduling methods have critical drawbacks in achieving real-time guarantees. Namely ,they fail to satisfy the delay constraints of delay-sensitive transactions. Further, they lead to GTS scarcity and GTS underutilization. On the other hand, the EDF-based scheduling method provides delay guarantee while it does not support delay-sensitive applications where arrival of the first packet has a critical impact on the performance.

To solve these problems, we design the optimal work-conserving GTS Allocation and Scheduling (GAS) algorithm that provides guarantee service for delay-sensitive applications in beacon-enabled networks. Not only does the GAS satisfy the delay constraints of transactions, but also it reduces GTS scarcity and GTS under utilization. Further, it supports delay-sensitive applications where arrival of the first packet has a critical impact on the performance .Through the extensive simulation results, we show that the proposed algorithm out performs the existing scheduling methods. Our algorithm differs from the existing ones in that it is an on-line scheduling and allocation algorithm and allows transmissions of bursty and periodic transactions with delay constraints even when the network is overloaded.

## II. **Overview of the IEEE 802.15.4**

the IEEE 802.15.4 standard is appealing for many different applications and is the dominant protocol in the real market of WSNs [6].In this section, we give an overview of the key points of IEEE 802.15.4 protocol.

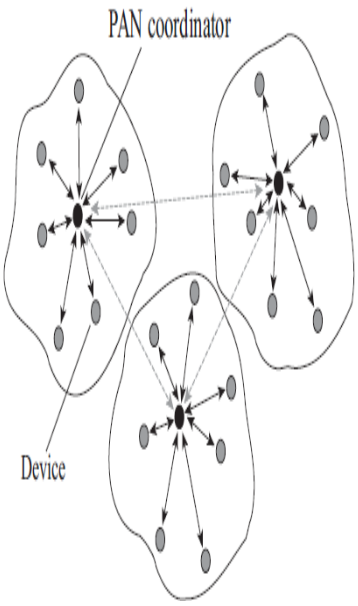


**Fig1.** Typical star network topology of IEEE 802.15.4. The packets generated by the sensor nodes (grey circle) are transmitted toward the PAN coordinator (black circle) depicted in the middle of each cluster.

The standard specifies the physical layer and the MAC sublayer for low-rate wireless networks. The star network is a basic network topology presented in Figure 1, where all N nodes contend to send data to the PAN coordinator, which is the data sink. The standard defines two channel access modalities: the beacon-enabled modality, which uses a slotted CSMA/CA and the optional guaranteed time slot (GTS) allocation mechanism, and a simpler unslotted CSMA/CA without beacons. The communication is organized in temporal windows denoted super frames. Figure 2.shows the super frame structure of the beacon-enabled mode. In the following, we focus on the beacon-enabled modality.

The network coordinator periodically sends beacon frames in every beacon interval $T_{BI}$ to identify its PAN and to synchronize nodes that communicate with it. The coordinator and nodes can communicate during the active period, called the super frame duration $T_{SD}$, and enter the low-power mode during the inactive period. The structure of the super frame is defined by two parameters, the beacon order (BO) and the super frame order (SO), which determine the length of the super frame and its active period, respectively, they are

**$T_{BI}$ = a Base Super frame Duration × 2BO , (2.1)**

**$T_{SD}$ = a Base Super frame Duration × 2SO , (2.2)**

where $0 \leq SO \leq BO \leq 14$ and a Base Super frame Duration is the number of symbols forming a super frame when SO is equal to 0. In addition, the super frame is divided into 16 equally sized super frame slots of length a Base Slot Duration. Each active period can be further divided into a contention access period (CAP) and an optional contention free period (CFP), composed of GTSs. A slotted CSMA/CA mechanism is used to access the channel of non time-critical data frames and GTS requests during the CAP. In the CFP, the dedicated bandwidth is used for time-critical data frames. Figure 2.5 illustrates the date transfer mechanism of the beacon-enabled mode for the CAP and CFP. In the following section, we describe the data transmission mechanism for both CAP and CFP.

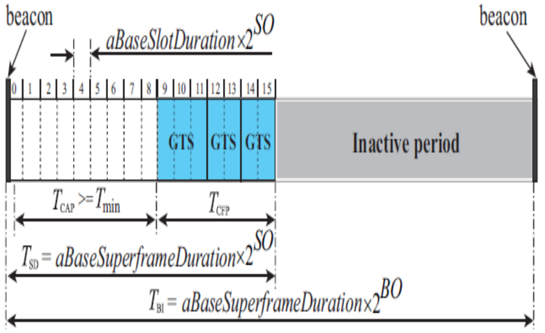


Fig 2. Superframe structure of IEEE 802.15.4.

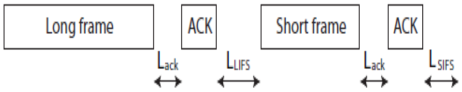
Figure 3 describes the date transmission with inter-frame spacing (IFS) period with and without ACKs. By knowing the duration of an ACK frame, ACK timeout, IFS, data packet length, and header duration, we define the successful packet transmission time Ls and the packet collision time Lc with ACK and the successful packet transmission time Lg without ACK as

$L_s = L_p + L_{w,ack} + L_{ack} + L_{IFS}$ ,

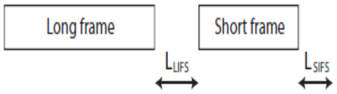
$L_c = L_p + L_{m,ack}$ ,

$L_g = L_p + L_{IFS}$ ,

where Lp is the total packet length including overhead and payload, Lw,ack is ACK waiting time, Lack is the length of the ACK frame, $L_{IFS}$ is the IFS time, and Lm,ack is the timeout of the ACK. To account for the data processing time required at the MAC sublayer, two successive frames transmitted from a node are separated by at least an IFS period; if the first transmission requires an ACK, the separation between the ACK frame and the second transmission is at least an IFS period. Note that the waiting time to receive ACK is in the range aTurn around Time (12 symbols) to aTurn around Time + a Unit Back off Period (12 + 20 symbols). The IFS period depends on the length of the transmitted data frames.



(a) Acknowledged transmission



(b) Unacknowledged transmission

Fig 3. Data frame transmission mechanism with and without ACK.

## III. Networked Control Systems

Networked control systems (NCSs) are spatially distributed systems in which the sensors, actuators, and controllers connect through a communication network instead by traditional point to-point connections, as shown in Figure 4. The significant advantages over traditional control architectures include reduced wiring and cost, increased modularity, easier maintenance, and high flexibility and reconfigurability. Networked control has become an enabling technology for many military, commercial and industrial applications such as mobile sensor networks remote surgery , industrial automation . Wireless communication is playing an increasingly important role in NCSs. Transmitting sensor measurements and control commands over wireless links allows rapid deployment, flexible installation, fully mobile operation and prevents cable problems in the control applications .Figure 4 depicts the general structure of NCSs where a plant is remotely commissioned over a network. Outputs of the plant are sampled at periodic or aperiodic intervals by the sensor and forwarded to the controller through a network. When the controller receives the measurements, a new control command is computed. The control is forwarded to the actuator attached to the plant. Research on NCSs sometimes considers structures simpler than the general one depicted in Figure 2.7. For example, many practical NCSs have several sensing channels and the controllers are collocated with the actuators, as in heat, ventilation and air-conditioning control systems. It is also common to consider single feedback loops closed over a network .

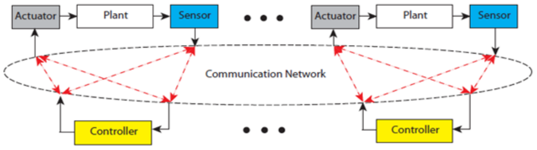


Fig 4. General networked control systems structure.

## IV. System Model

We consider a star network with a coordinator and N nodes (see Table A.1 for main symbols used in this section). Every node contends to send data packet1 to the coordinator. The coordinator acts as a data sink and we assume it does not experience the hidden node problem. Throughout this section we consider applications where nodes asynchronously generate packets for transmission. We consider the underlying minimum time unit corresponding to aUnitBackoffPeriod, as defined in the IEEE 802.15.4 standard and we denote it Tb. In the standard, Tb corresponds to 20 symbols in the physical layer (i.e., 320 $\mu$ s for 2.45GHz). When a node just has sent a packet successfully or just discarded a packet, we assume that a new packet is generated with probability $\eta_t$. If a new packet is not generated, then the node tries to generate a new packet after hTb s, where h is a positive integer. This packet is generated with probability $\eta_p$. We consider two different types of data packets: non time-critical data packets to be transmitted during the CAP, and time-critical data packets to be transmitted during the CFP using the GTS allocation mechanism. When a node decides to generate a data packet, it generates a non time-critical data packet with probability $\eta_d$ and time-critical data packet with probability $1 - \eta_d$ in our model. A node uses a beacon-enabled slotted CSMA/CA algorithm to send a non time-critical data packet and a GTS request to the coordinator during the CAP. Note that the packet transmission is successful if an ACK packet is received. For a time-critical data packet, the node informs the need of GTS resources by sending the request during the CAP. The coordinator allocates a number of GTSs by considering the received GTS requests. Each node may need to send a multiple number of time-critical packets wherein each packet has a fixed length due to the maximum length of a packet defined in the standard. The requests are stored in a queue of the coordinator, and wait to be served in the next superframes, where the related GTS may be allocated. If too many requests arrive with respect to the coordinator queue size, then we have a queue overflow. We assume an ideal channel condition of physical layer and perfect channel channel sensing capability of nodes. Furthermore, we make the natural assumption that each node forwards a non time critical packet or a GTS request within 2TBI i.e., the maximum packet delay of the CAP is 2TBI.

Based on the introduced model and assumptions, we propose an analytical model of the slotted CSMA/CA algorithm of the CAP and the GTS allocation of the CFP based on two Markov chain models in Sections 4.4 and 4.5. Then, in Section 4.6, we connect these to have a model that allows us to investigate the performance of the hybrid MAC of IEEE 802.15.4 in terms of the reliability of the CAP, the average delay of the CAP, the queueing delay of the CFP, and the throughput of the network.

### 4.1Modeling of CAP

Here, we develop a generalized Markov chain model of the slotted CSMA/CA algorithm of the beacon-enabled IEEE 802.15.4 MAC. The core contribution of the analysis is the derivation of the stationary probability distribution of the chain, which is summarized by Proposition 2. Compared to previous results, the novelty of this chain consists in the modeling of the retry limits for each packet transmission, the ACK, the inclusion of unsaturated traffic regimes, packet

size, and superframe structure. We will also discuss the strength of the proposed Markov chain model with respect to previous studies, which do not take into account the superframe structure accurately Let b(t), c(t), e(t) and f(t) be the stochastic processes representing the back off stage,the state of the backoff counter, the state of retransmission counter, and the state of deferred transmission at time t experienced by a node. The binary variable f(t)indicates if a transmission has been deferred (f(t) = 1) or not (f(t) = 0), which is due to the limited size of superframe duration to transmit a packet. By making the natural assumption that nodes start sensing independently, the stationary probability $\tau$ that a node attempts a first carrier sensing in a randomly chosen time slot is constant and independent of other nodes. The quadruple (b(t), c(t), e(t), f(t)) is the state evolution of the Markov chain. We use (i, j, k, l) to denote a particular state.

We assume the following notation for the MAC parameters: m $m_o \triangleq$ macMinBEm $\triangleq$ .

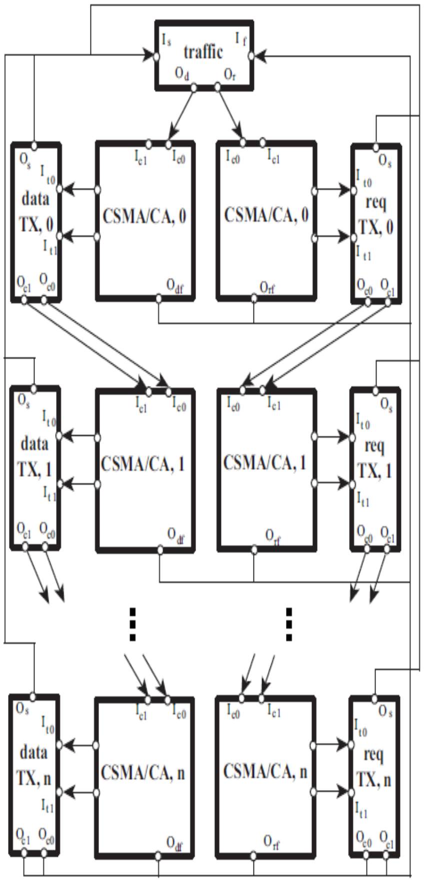


**Fig 5**. Markov chain building blocks modeling the CSMA/CA algorithm of the IEEE 802.15.4 MAC for a single node.

## V. Reliability

The main contributions of this section is the derivation of the probability of successful packet reception, or reliability. With this goal in mind, we derive first the probability that a node attempts CCA1 in a randomly chosen time slot:

$$\tau = \sum_{i=0}^{m} \sum_{k=0}^{n} \sum_{l=0}^{1} S_{i,0,k,l}$$
$$= \left( \frac{1 - g^{n+1}}{1 - g} \sum_{i=0}^{m} \xi_i + \sum_{i=0}^{m} \sum_{k=0}^{n} v_{i,k} \right) S_{0,}$$

This probability depends on the probability that a transmitted packet encounters a collision Pc, the probability that CCA1 is busy $\alpha$, and the probability that CCA2 is also busy $\beta$. These probabilities are developed in the following.

Recall that the term Pc is the probability that at least one of the N −1 remaining nodes transmits in the same time slot. If all nodes transmit with probability $\tau$, then

$$P_c = 1 - (1 - \tau)^{N-1} ,$$

where recall that N is the number of total nodes present in the network. Similarly to , we derive the busy channel probabilities $\alpha$ and $\beta$ as follows. The busy channel probability of CCA1 is

$$\alpha = \alpha_1 + \alpha_2 ,$$

where $\alpha$ 1 is the probability of finding channel busy during CCA1 due to data transmission, namely

$$\alpha_1 = \overline{L}_p \left(1 - (1 - \tau)^{N-1}\right)(1 - \alpha)(1 - \beta) ,$$

where the average length of packet is Lp = $\eta$ dLp,d + (1 − $\eta$ d)Lp,r, and $\alpha$ 2 is the probability of finding the channel busy during CCA1 due to ACK transmission, which is

$$\alpha_2 = L_{\mathrm{ack}} \frac{N\tau(1 - \tau)^{N-1}}{1 - (1 - \tau)^N} \left(1 - (1 - \tau)^{N-1}\right)(1 - \alpha)(1 - \beta) ,$$

where Lack is the length of the ACK. The busy channel probability of CCA2 is

$$\beta = \frac{1 - (1 - \tau)^{N-1} + N\tau(1 - \tau)^{N-1}}{2 - (1 - \tau)^N + N\tau(1 - \tau)^{N-1}} ,$$

The expressions of the carrier sensing probability $\tau$ and the busy channel probabilities $\alpha$ and $\beta$ form a system of non-linear equations that can be solved via numerical methods.

## VI. CONCLUSION

The main contribution of this thesis is to provide a modeling, analysis, and design framework of WSN protocols for control applications. We used an analytical model-based protocol design to minimize the energy consumption of the network, while meeting the reliability and packet delay requirements of control applications. The main idea is to apply the tradeoff between the application requirements and energy consumption of the network, instead of just improving the reliability, delay or energy efficiency. In the design process, the original contribution is the derivation of analytical expressions of the energy consumption of the network, as well as reliability and delay for the packet delivery. This seems suitable for many control applications as they provide stability and performance guarantees. In particular, the contributions of this thesis are presented in four chapters. First, an adaptive IEEE 802.15.4 protocol to support energy efficient, reliable and timely communications by tuning the MAC parameters of the CSMA/CA algorithm is presented.

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