Capacity Estimation of IEEE 802.15.4 Chains of Sensor Nodes

Evaggelos Chatzistavros, George Stamatelos

Department of Electrical and Computer Engineering,
Democritus University of Thrace
Xanthi, 67100, Greece
Email: ec3526@ee.duth.gr

***Abstract*—In the context of an integrated water management project, we derive an analysis based on numerical modelling for throughput estimation in an IEEE 802.15.4 wireless sensor network (WSN). It takes into account the number of nodes in a cluster network, as well as transmitted packet size. We focus on the IEEE 802.15.4 compliant slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm. Theoretical estimations are verified using the ns-2 network simulator. The configuration examined is a chain network formed by wireless sensor nodes where the first node is the source of data packets and the last is the traffic sink. Simulation results show that there is a satisfactory approximation between the theoretically estimated and the simulated values.**

Keywords–Performance Evaluation; Wireless Sensor Networks; Analytical Model; Personal Area Network.

I. INTRODUCTION

Wireless sensor networks are widely deployed in a variety of applications, including home monitoring and automation [1]–[3], environmental monitoring [4] [5] and health monitoring [6]–[8]. Depending on system requirements and the type of application, sensor nodes are usually deployed in three different topologies, i.e., peer-to-peer (also called point to point), star and mesh. In the peer-to-peer network, nodes can directly communicate with each other, without the mediation of a Personal Area Network (PAN) Coordinator. All sensor nodes in a star topology are connected to a PAN coordinator. Node communications are routed through the coordinator. A tree topology is considered a hybrid of both the peer to peer and star configurations. It consists of different hierarchical levels, the lowest of which forms one or more star networks.

An environmental monitoring system is proposed in the context of the CYBERSENSORS project [9]. The system architecture under consideration employs two distinct subsystems: a physical /chemical parameters monitoring subsystem and a visual monitoring subsystem, as shown in Fig. 1. Regarding the first, it consists of wireless sensor probes communicating with a PAN coordinator, forming an IEEE 802.15.4-compliant WSN [10]. In the second subsystem, Visual Sensor Nodes communicate with an IEEE 802.11n router (forming a Wireless Local Area Network (WLAN)) [11]. Data collected from both networks are forwarded to a remote server through a 3G/HSPA broadband link [12]. Using a peer-to-peer setup can extend WSN range, especially when efficient self - configurability and large area coverage are important [13].

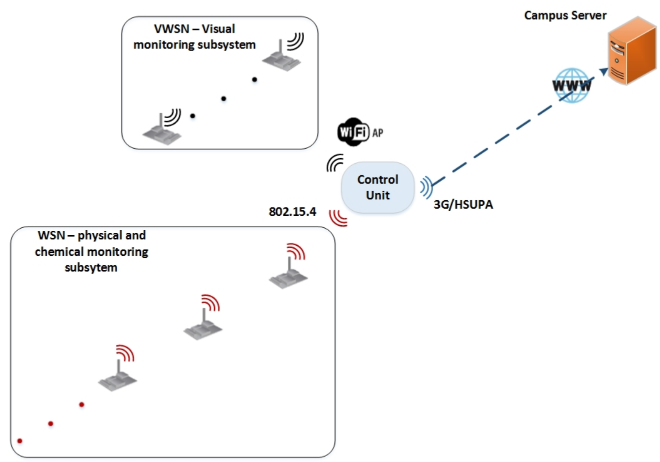

Figure 1. System architecture for integrated water management.

In this paper, we look into performance issues associated with the sensors subsystem responsible for sampling and storing of physical (i.e., suspended particles, temperature) and chemical (i.e., conductivity, dissolved oxygen, nitrate, pH, heavy metals) quality metrics [4]. Sensor nodes operate in an IEEE 802.15.4/Zigbee framework for the wireless data transmission of the collected measurements. Within this high frequency monitoring platform, sensor nodes will be deployed along a river bank.

In [14], authors proposed an analytical performance model for a sensor network with specific delay and packet delivery ratio requirements. Their model is validated using the ns-2 simulator [15] for a star-topology sensor network. A Markov renewal process [16] is embedded for the calculation of saturation throughput. Authors in [17] developed an analytical model using Markov chains, for both a one-hop star topology, as well as a multi-hop sensor network. They examine the unslotted IEEE 802.15.4 CSMA/CA algorithm, validated by Monte Carlo simulations. A worst-case modeling methodology based on Network Calculus [18] [19] is described in [20]. Sensor nodes forming a cluster-tree network compete for channel access following the slotted CSMA/CA algorithm.

In the following sections, we propose a method for calculating network capacity when a number of remote sensor nodes are employed for data acquisition and the rest for packet forwarding to the PAN coordinator. Throughput is derived as a function of the number of relay nodes in the network and

 ISBN: 978-1-61208-347-6

packet size. These results will be used for the deployment of an operational sensor network.

The rest of the paper is organized as follows: the analytical model is described in Section II. Model evaluation is presented in Section III, while conclusions are drawn in the last section.

II. Numerical Analysis

Two distinct data transfer modes are supported by an IEEE 802.15.4 network, i.e., beacon enabled and non - beacon enabled. In the beacon enabled mode, the PAN coordinator transmits periodic beacons, allowing node synchronization. This scheme employs the superframe structure. The $macBeaconOrder$ (BO) attribute describes the interval at which the coordinator shall transmit beacon frames. The Beacon Interval (BI) is related to the macBeaconOrder as follows:

BI = $aBaseSuperframeDuration$* 2^{BO}

for $0 \leq BO \leq 14$,

where,

$aBaseSuperframeDuration$= $aNumSuperframeSlots$*$aBaseSlotDuration$

The length of the active portion of the superframe is described by the $macSuperframeOrder$ (SO) attribute. The Superframe Duration (SD) is related to the SO attribute as follows:

SD = $aBaseSuperframeDuration$* 2^{SO}

for $0 \leq SO \leq BO$

The active portion of each superframe is divided into $aNumSuperframeSlots$ = 16 equally spaced slots and is composed of three parts: a beacon, a Contention Access Period (CAP) and a Contention Free Period (CFP). If SO $<$ BO, the active superframe portion is shorter compared to the BI, allowing nodes to enter sleep mode.

A numerical analysis model for throughput estimation is developed in this paper. As stated in the previous paragraph, we assume there is no CFP period.

A. Two nodes transmission

Our analysis begins with the simplest scenario, where a node transmits its data directly to the PAN coordinator. We also assume equal BO and SO values greater than 4. In this case, a node transmits its packets during a single time slot of a superframe. If BO (and consequently SO) $<$ 4, a node will not complete its transmission during the current time slot and should wait for the next superframe to complete transmission, as indicated by the Medium Access Control (MAC) mechanism. Also in this analysis, there are no Guaranteed Time Slots (GTS) during a superframe.

We assume that there are no other contending nodes to gain channel access within the range of the sensor nodes. The Backoff Exponent (BE) parameter is related to how many backoff periods a device shall wait before attempting to assess a channel. In the case of two transmitting nodes, it is limited to its lowest value BE=3, due to low contention levels. Based on the slotted CSMA/CA algorithm, the total duration of a frame transmission is calculated as:

$$T_{tot} = (d_{BE} + d_{fr} + d_{LIFS} + d_{trn} + d_{CW} + d_{ack}) \times T_s \quad (1)$$

where

- d_{BE} : backoff period duration, in symbols
- d_{fr} : the duration of a frame transmission, in symbols
- d_{LIFS} : Interframe Spacing Time, the number of symbols separating two successive frames,
- d_{trn} : turnaround time, the number of symbols required to switch the RF transceiver from receive to transmit mode in order to transmit an acknowledgement,
- d_{CW} : time required for the necessary clear backoff periods prior to the transmission. There are two Contention Window (CW) slots, each of 20 symbols length,
- d_{ack} : transmission time required for an acknowledgement frame, in symbols.

The 250 kbps data rate supported by the IEEE 802.15.4 standard are equivalent to 62.5 $\frac{ksymbols}{sec}$. The duration of a symbol, T_s equals to $\frac{1}{62500\frac{symbols}{sec}} = 0.016\frac{ms}{symbol}$

The maximum frame size is 133 bytes (102 bytes application data + 25 bytes PHY overhead + 6 bytes MAC overhead). d_{fr} expressed in symbols is equal to:

$$d_{fr} = \frac{133\frac{bytes}{frame} \times 8\frac{bits}{byte}}{4\frac{bits}{symbol}} = 266\frac{symbols}{frame} \quad (2)$$

As the number of symbols forming the basic time period used by the CSMA/CA algorithm is 20 symbols, each time period described below must be expressed as an integer multiple of 20 symbols. $d_{LIFS}, d_{trn}, d_{CW}$ and d_{ack} values are defined by the IEEE 802.15.4 standard.

Therefore,

- d_{BE} = (2^{BE}-1)*$aUnitBackoffPeriod$, where $aUnitBackoffPeriod$ is equal to 20 symbols
- d_{ack} = 10 symbols. A total of 20 symbols are reserved
- d_{LIFS} = 40 symbols
- d_{trn} = 12 symbols. As in t_{ack} 20 symbols occupied
- d_{CW} = 2*20=40 symbols

Based on the above estimations and (1), T_{tot} is equal to:

$$\begin{aligned} T_{tot} &= (d_{BE} + d_{fr} + d_{ack} + d_{LIFS} + d_{trn} + d_{CW}) \times T_s \\ &= 526\frac{symbols}{frame} \times 0.016\frac{ms}{symbol} = 0.008416\frac{sec}{frame} \quad (3) \end{aligned}$$

Subsequently, the chain throughput approximation is equal to:

$$S = \frac{1}{0.008416 \frac{sec}{frame}} = 118 \frac{frame}{sec} \times 133 \frac{bytes}{frame} \times 8 \frac{bits}{byte} \quad (4)$$

Taking into account only the application payload, application throughput is equal to:

$$S_{ap} = 118 \times 102 \times 8 \simeq 96.29 kbps \quad (5)$$

B. N-nodes chain analysis

When increasing chain size to three nodes, the second node forwards packets received from the last (third), to the coordinator. The absence of collisions maintains node contention low, so the BE parameter is still limited to its lowest value BE = 3 for the first two nodes of the chain. The PAN coordinator is not involved in contention, as it only receives packets. The number of symbols now required for a packet transmission is twice the number of those involved in the two-node analysis, i.e., 1052 symbols.

The successive packets of a single connection interfere with each other as they move down the chain, forcing contention in the MAC protocol. As node contention increases with network size, the BE index increases as well. Contention reaches maximum level when the chain consists of more than 3 sensor nodes. According to the slotted CSMA/CA algorithm (shown in Fig. 2 [10]), the BE index reaches its maximum value macMaxBE = 5.

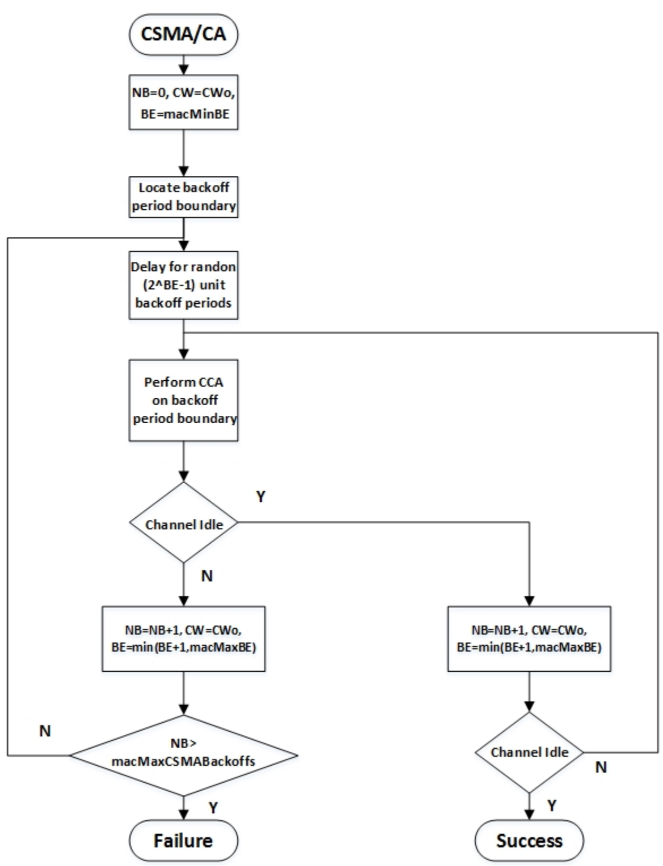

Figure 2. Slotted IEEE 802.15.4 CSMA/CA algorithm (from [10]).

An 802.15.4 node's ability to send is affected by the amount of competition it experiences. For example, node 3 in a 7-node chain experiences interference from 4 other nodes, while node 1 is interfered with by two other nodes. This means that node 1 could actually inject more packets into the chain than the subsequent nodes can forward. In the n-nodes chain illustrated in Fig. 3, the last is the source and the first is the data sink. Packets travel along a chain of n-1 intermediate hops until they reach their destination. For the first transmission between nodes n-1 and n-2 contention is low, thereby the BE value is kept at its lowest value, i.e., 3. For the subsequent n-2 hops contention levels are higher since three or more nodes potentially attempt to gain access to the channel at the same time. Due to the increased contention levels, the BE index maintains the macMaxBE value.

Subsequently, we proceed to the calculation of the throughput equation. We assume a Constant Bit Rate (CBR) application (to model the periodical sensor sampling) which transmits packets of size k bytes (data payload). The frame size (send by the PHY layer) is k + 33 (PHY + MAC overhead) bytes, which is equal to:

$$(k+33)\frac{bytes}{frame} \times \frac{8\frac{bits}{byte}}{4\frac{bits}{symbol}} = 2 \times (k+33)\frac{symbols}{frame} \quad (6)$$

The maximum backoff duration, d_{BE}, depends on the number of nodes forming the network. The remaining terms in (1), i.e., d_{ack}, d_{LIFS}, d_{trn} are constant. Based on the above estimation and (4), data throughput can be approximated by the following equation:

$$S = \frac{1}{\frac{T_{tot}\frac{symbols}{frame}}{62500\frac{symbols}{sec}}} \times k\frac{bytes}{frame} \times 8\frac{bits}{byte} = 500 \times \frac{k}{T_{tot}} kbps \quad (7)$$

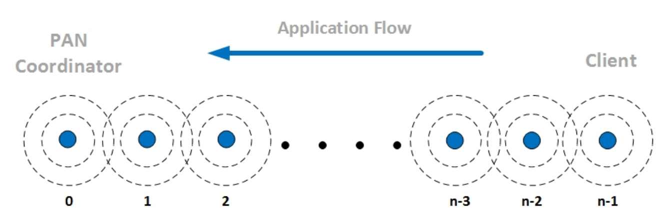

Figure 3. Chain consisting of n sensor nodes.

In order to verify the accuracy of (7), we conduct a number of simulations. Details on the simulated topologies and corresponding results are presented in the following section.

III. MODEL EVALUATION

Here, the ns-2 simulator is used to verify the accuracy and scaling of the model already discussed. Nodes are configured according to the IEEE 802.15.4 standard, operating at 2.4 GHz with a maximum transmission rate of 250 kbps. The simulation parameters are listed in Table I.

ISBN: 978-1-61208-347-6

TABLE I. SIMULATION PARAMETERS

IEEE Standard	IEEE 802.15.4
MAC Protocol	Beacon Enabled CSMA - IEEE 802.15.4
Transmission range	20 m
Beacon Order - BO	7
Superframe Order - SO	7
Number of nodes	2 to 100
Application Type	Constant Bit Rate
Offered Traffic Load	10 to 250 kbps
Packet Size	25, 50, 75, 100 bytes
Simulation time	200 sec
Application duration	50 sec
Bit Error Rate (BER)	perfect channel conditions (0)

The WSN topology consists of a sensor nodes chain of increasing length from 2 to 10 nodes, forming a cluster network of static nodes. Each node has an effective transmission range of 20 meters (an interference range of 35 meters) and is located 15 meters away from its immediate neighbors. All nodes operate as Full Function Devices (FFDs), with the first one being the PAN coordinator and the last one serving as the application client. The rest are relay nodes, forwarding received packets from the client to the coordinator.

A CBR flow is applied, running for 50 seconds, four times for each topology, each time sending packets of different size, i.e., 25, 50, 75 and 100 bytes. In the CYBERSENSORS project, data wil be collected and forwarded periodically, which makes the choise of CBR data model appropriate. For each configuration, the transmission data rate increases from 10 to 250 kbps with steps of 10 kbps each. Prior to the initiation of the CBR flow and data collection, network simulation runs for a time period of 150 seconds, necessary to reach a stable state in terms of node synchronization and association. Average throughput values are simulated for four different packet sizes in Fig. 4.

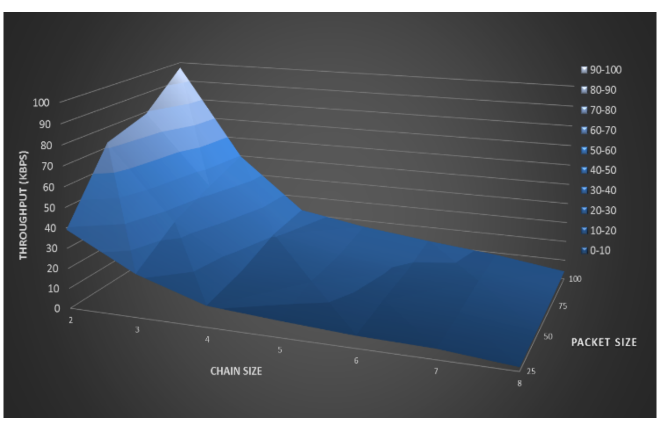

Figure 4. Average throughput (simulated) for a maximum chain length of 8 nodes.

Average throughput for the case of a three-nodes-chain with payload 100 bytes per packet is 49.6 kbps. For the same network size, when packet size is reduced to 25 bytes, the corresponding value degrades to 21.46 kbps. Packet loss levels not explicitly shown here follow the reverse gradient of the curves in Fig. 4, since high throughput values correspond to low packet losses.

Figures 5 and 6 present a comparison between throughput calculated by the numerical analysis model in the previous section and that obtained through simulations for different network sizes and offered traffic load. In both figures, the deviation between corresponding lines varies from 0.023 to 3.179 kbps (minimum and maximum values, respectively), with an average deviation value of 1.008 kbps.

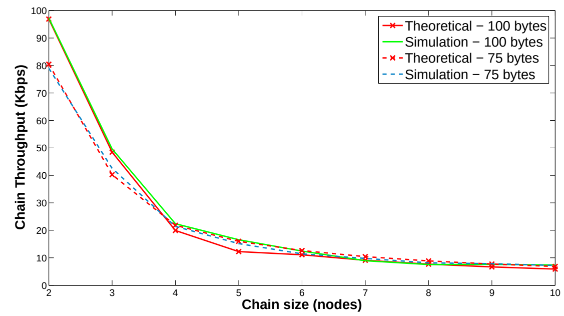

Figure 5. Theoretical vs simulated throughput achieved along a chain of nodes, as a function of the chain length and packet sizes (100 and 75 bytes/packet) and a maximum chain size of 10 nodes.

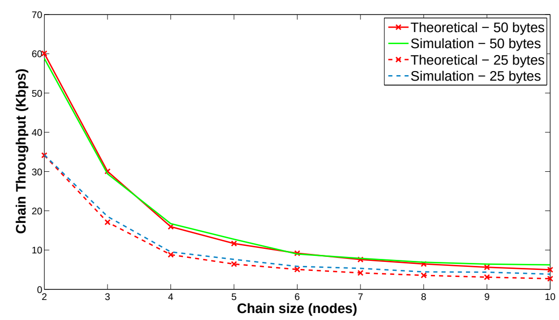

Figure 6. Theoretical vs simulated throughput for 50, 25 bytes/packet.

To evaluate the validity of (7) we also conduct simulations on larger chains of nodes, consisting of up to 100 nodes. Results are shown in Fig. 7 and 8.

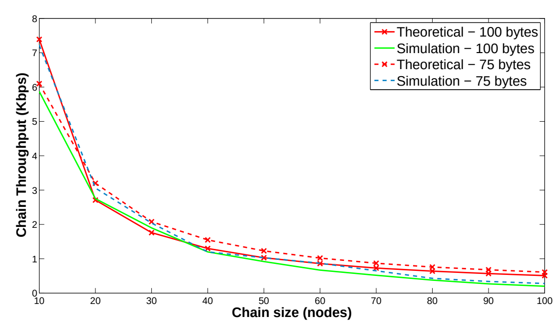

Figure 7. Theoretical vs simulated throughput for 100, 75 bytes/packet for chains of up to 100 nodes.

As the number of nodes increases, the achieved throughput tends to reach very low values. Packet size has a minimum effect to the chain throughput. The proposed model provides a close approximate to the simulated throughput.

To further examine the impact of configuration parameters, we conducted simulations for different BO=SO values, i.e., 5, 6, 8 and 9. Results not presented here, show that there

 ISBN: 978-1-61208-347-6

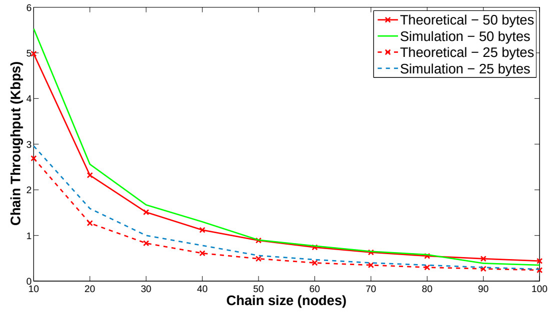

Figure 8. Theoretical vs simulated throughput for 50, 25 bytes/packet.

are no significant differences compared to those presented in this paper. These conclusions further support the validity of our model, since our analysis does not take into account the duration of the active period of a superframe, declared by the SO attribute. Simulation results match with theoretical values even when SO $<$ BO.

IV. Conclusion

A key component of the integrated water management system is the chemical sensors subsystem and its monitoring capabilities. In this framework, we present a numerical model for throughput estimation on a chain of IEEE 802.15.4-compliant sensor nodes forming a cluster network. It provides a useful tool within the scope of an integrated water management project. The proposed numerical analysis and corresponding results will be used for the design, deployment and management of the chemical sensors module.

We evaluate our model through a series of simulations in order to check its accuracy and scalability under different packet and network sizes. The comparison between the numerically estimated and simulation values shows that there is a close match in the majority of the examined cases. This approach scales well with respect to network and packet size.

Acknowledgment

This work is elaborated through an on-going THALES project (CYBERSENSORS - High Frequency Monitoring System for Integrated Water Resources Management of Rivers). The Project has been co-financed by the European Union (European Social Fund - ESF) and Greek national funds through the Operational Program ”Education and Lifelong Learning” of the National Strategic Reference Framework (NSRF) - Research Funding Program: Thales. Investing in knowledge society through the European Social Fund.

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 ISBN: 978-1-61208-347-6