Performance analysis of 802.15.4 wireless standard

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ABSTRACT

In recent years, low distance wireless connectivity is having an exponential growth. Fast design and verification of the performances of the wireless network is becoming a necessity for electronic industry to hit the more and more restrictive market requests. A system level model of the network is indispensable to ensure fast and flexible design and verification. In this work a SystemC model of the IEEE 802.15.4 standard is presented. The model has been used to verify the performances of the 802.15.4 standard in terms of efficiency and channel throughput as a function of the number of nodes in the network, of the dimension of the payload and of the frequency with which the nodes try to transmit.

Keywords: wireless communication, IEEE 802.15.4, SystemC

1. INTRODUCTION

The protocols for low distance wireless communications are becoming more and more important. Widely used protocols for wireless sensor networks are Bluetooth and ZigBee. The ZigBee (the lower layers of the protocol is the IEEE 802.15.4) standard was developed specifically for remote monitoring and control. 802.15.4 networks [1-3] are designed to conserve the power of the slave nodes. This standard is particularly addressed to applications characterized by low-rate and low energy consumption such as: infrastructure security, environment and habitat monitoring, health monitoring and industrial sensing [4-6]. Considering the potential applications of the standard, the evaluation of the performances of IEEE 802.15.4 based networks through simulations is essential in order to allow faster and more efficient system development.

Great is the research interest on low power personal area networks (WPAN), in particular for the 802.15.4 standard. The 802.15.4 MAC layer uses the CSMA-CA algorithm to access the channel and reduce the collision probability: each device tries to use the channel after a random delay. This mechanism makes non deterministic the performances of this wireless standard. Many research works have been recently developed to investigate the performances of the 802.15.4 standard. Experimental measurements have been carried out on wireless networks with 4 devices to estimate the effective data rate [7]. In [8] experimental measurements have been carried out on wireless networks with 2 devices with different size of the data frame. Simulations and measurements have been carried out in [9] to investigate how the BER versus SNR are affected changing the communication parameters of physical layer. In [10-14] analytic probabilistic models have been developed to estimate the collision probabilities of the devices of the same network. Simulators of 802.15.4 networks implementing the MAC and Physical layers have been developed and used for a performance study.

SystemC [17-18] is an emerging standard based on C++ that supports design abstraction at the RTL, TLM and behavioral level. These characteristics result to be really powerful on a distributed system-modeling problem, since they allow the description of communication and computation aspects at different abstraction levels. The SystemC environment have been used to create a model of the baseband layer of the wireless Bluetooth protocol in order to estimate the performances of Bluetooth networks [19-20].

In this work a SystemC model of the IEEE 802.15.4 standard is proposed. The MAC layer, PHY layer and a model of the wireless channel have been implemented. The model has been used to verify the performances of the 802.15.4 standard in terms of efficiency (percentage of packets transmitted successfully), channel throughput, power dissipation (amount of time the transmitter or receiver must be on) as a function of the number of nodes in the network, of the dimension of the payload and of the frequency with which the nodes try to transmit. In particular the analysis has been carried out to evaluate network performances with an high number of nodes. Networks with up to 30 nodes have been simulated and an extrapolation with 1500 nodes has been derived.

Section 2 reports some details of the 802.15.4 protocol. In Section 3 the SystemC model of the 802.15.4 protocol is summarized. Finally, Section 4 reports the results of the simulations.

2. IEEE 802.15.4 WIRELESS NETWORKS

The IEEE 802.15.4 standard [1] has been developed specifically for remote monitoring and control. 802.15.4 networks are designed to save the power of the slave nodes. For most of the time, a slave device is in deep-sleep mode and wakes up only for a fraction of time to confirm its presence in the network. The targets of 802.15.4 are low cost applications, where the battery cannot be changed (battery life time of 1-2 years) with limited requirements of bandwidth. The supported over-the-air nominal data rates are 250 kbps for the 2.4 GHz band, frequency band that we consider in this paper.

Since the 802.15.4 nodes are not synchronized, a collision in the channel may occur when the nodes try to transmit at the same time. The 802.15.4 MAC layer uses the collision avoidance medium access (CSMA-CA) algorithm to access the channel and to reduce the collision probability. This algorithm yields high throughput and low latency for low duty cycle devices, like sensors and controls. Unfortunately the CSMA-CA algorithm reduces the effective maximum information rate to about 125 kbps in case of a single node that uses the channel.

Depending on the application, an IEEE 802.15.4 network may operate in two topologies: star topology or peer-to-peer topology. The architecture investigated in this work is a star topology, shown in Figure 1. The sensor nodes continuously send data to the Personal Area Network (PAN) coordinator.

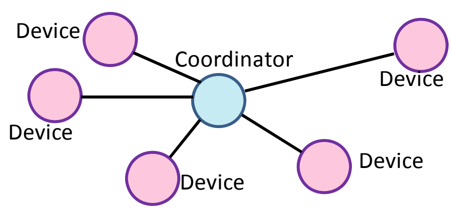


Figure 1. 802.15.4 standard star topology

Two types of devices can participate to a IEEE 802.15.4 network: Full Function Device (FFD), implementing the complete MAC, and Reduced Function Devices (RFD), implementing part of the MAC. Only FFD can be the coordinator of the PAN.

In the 802.15.4 standard the nodes of the network use the collision avoidance medium access (CSMA-CA) mechanism for transmission. Before a transmission, a node must wait for a random backoff time to reduce the probability of collision between nodes of the same network.

The IEEE 802.15.4 uses two types of channel access mechanism, depending on the network configuration.

- Unslotted CSMA-CA: used by nonbeacon-enabled networks. Each time a device wishes to transmit, it waits for a random period. If the channel is idle, the device transmits its data. If the channel is busy, the device waits for another random period before trying to access the channel again. Acknowledgment frames are sent without using a CSMA-CA mechanism.
- Slotted CSMA-CA: used by beacon-enabled networks, where the backoff slots are aligned with the start of the beacon transmission. Each time a device wishes to transmit data frames, it shall locate the boundary of the next backoff slot and then wait for a random number of backoff slots. If the channel is busy, following this random backoff, the device waits for another random number of backoff slots before trying to access the channel again. If the channel is idle, the device can begin transmitting on the next available backoff slot boundary.

When a device wishes to transfer data in a nonbeacon-enabled PAN, it transmits the data frame, using unslotted CSMA-CA, to the coordinator. The coordinator acknowledges the successful reception of the data by transmitting an optional acknowledgment frame. When a device wishes to receive data from the coordinator in a nonbeacon-enabled PAN, it transmits a MAC command requesting the data, using unslotted CSMA-CA. The coordinator acknowledges the successful reception of the data request by transmitting an acknowledgment frame, then the coordinator transmits the data frame, using unslotted CSMA-CA, to the device. If requested, the device acknowledges the successful reception of the data frame by transmitting an acknowledgment frame. This sequence is summarized in Figure 2.

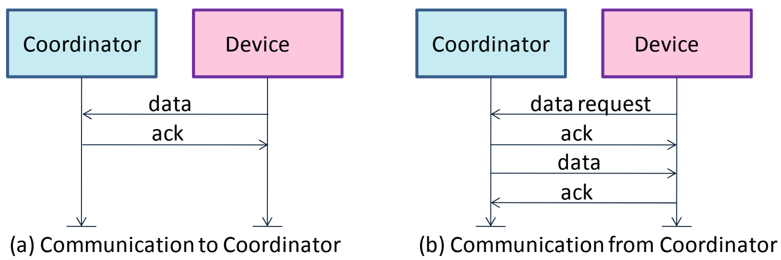


Figure 2. Communication to Coordinator (a) and from Coordinator (b) in a nonbeacon-enabled PAN

The structure of the frames are defined in the standard. The data frame, including SHR and PHR, consists of 15-133 bytes:

- synchronization header (SHR, 5 bytes),
- physical layer header (PHR, 1 byte),
- MAC header (MHR, 7-23 bytes),
- payload data (MSDU, 0-102 bytes)
- MAC footer (MFR, 2 bytes).

The ack frame consists of 11 bytes:

- synchronization header (SHR,5 bytes),
- physical layer header (PHY, 1 byte),
- MAC header (MHR, 3 bytes),
- MAC footer (MFR, 2 bytes).

The data request frame is a command frame, consisting of 17-33 bytes:

- synchronization header (SHR,5 bytes),
- physical layer header (PHY, 1 byte),
- MAC header (MHR, 7-23 bytes),
- MAC payload (MSDU, 2 bytes)
- MAC footer (MFR, 2 bytes).

In a nonbeacon enabled PAN, the number of bytes to be transmitted in the channel is 31+n (data frame) + 11 (ack frame) to transmit to the coordinator n payload bytes (from 1 to the maximum of 102 bytes), and 33(data request frame) +11(ack) +31+n(data frame) +11(ack) to transmit to the device n payload bytes. Furthermore, the ack frame must be sent after a time of 12 symbols (equivalent to 6 bytes).

Therefore, while the nominal throughput is 250kbps, the effective maximum nominal information throughput is

$\frac{n}{31+n+6+11}250\ kbps$ for transmission to the coordinator, with a maximum of $\frac{102}{150}250=170\,kbps$

$\frac{n}{33+6+11+31+n+6+11}250\ kbps$ for transmission to the device, with a maximum of $\frac{102}{200}250=127,5\,kbps$

The CSMA-CA mechanism causes a further reduction to the effective nominal information throughput of the network. Being the CSMA-CA a random algorithm, a deterministic relationship of the real throughput cannot be found. The effective throughput depends on the number of devices of the PAN, the frequency with which they want to use the channel and the number of data bytes sent. In this work a simulative investigation of the effective performances of the 802.15.4 standard, in particular with a great number of devices.

3. IEEE 802.15.4 SYSTEMC MODEL

SystemC is an emerging standard modeling platform based on C++ that supports design abstraction at the RTL, behavioral and system level [17-18]. Design methods for integrated circuits based on hardware description languages (such as VHDL or Verilog), when applied to these systems, lead to long simulation time and force the designer to introduce useless details about the design; these methods are not suitable for SoC design that requires a high abstraction level and efficient IP management and reuse. The use of C/C++ models is profitable to describe complex IP integration and IP behaviors, for which not all internal details are necessary, in order to early confirm the design specifications and to be early delivered to third parties for evaluation.

The proposed SystemC model of the IEEE 802.15.4 standard supports both FFD and RFD devices. It follows exactly the stratification defined by the standard and consists of two modules, as reported in Figure 2: one that implements the physical layer features and the other that implements the MAC layer features. All interface functions defined by the standard have been implemented for both MAC and Physical layer modules. Moreover, a testbench module has been build up emulating the service-specific convergence sublayer (SSCS) and the upper layer of the protocol. A wireless channel model has been defined as a digital module with a single output and multiple inputs, one for each one of the devices. The channel emulates :

- the effect of noise in the channel with an inversion of the bit in the channel controlled by a random number generator;
- the collision between packets;
- fading caused by path-loss under the hypothesis of free-space propagation conditions.

The effect of the noise in the channel has not been considered in results reported in this work.

The SystemC modules have been designed at behavioral level with the aim of:

- create a fast simulation environment of the lower layers of the 802.15.4 standard;
- verify the performance in presence of noise;
- verify the performance with different number of devices and different parameters of the network;
- use this behavioural model as a golden model for future design of these layer at RTL level;
- analyze the power dissipation of the digital and RF part.

The MAC module is organized in asynchronous sc_threads. Each sc_thread is activated only when necessary, in order to reduce the CPU simulation time. The treads are organized in groups depending on their functionalities:

- MAC management threads implement the functionalities of changing of internal variables, switching on and off of the receiver and transmitter, tracking of the beacon frame, guaranteed time slot (GTS) management, transaction management, local clock generation, activation of the timer.
- MAC frame processing threads implement the functionalities of frame processing, that is: incoming and outgoing frame security, parsing, authentication and decoding of incoming frames, parsing, signature and coding of

outgoing frames, reception and transmission of frames and all the mechanism related to the CSMA-CA medium access algorithm and SIFS/LIFS handling.

- MAC primitives threads implement the primitives coming from the SSCS layer: management of the queue of the frame, reading and writing of the PIB attributes, activation of MAC functionalities such as scan, beacon tracking, reset of local variables.

The MAC module passes data and control information to the physical module using a Physical Service Data Unit (PSDU). A PSDU can either be a Data Frame, a Beacon Frame, an ACK Frame or one of the Command Frames.

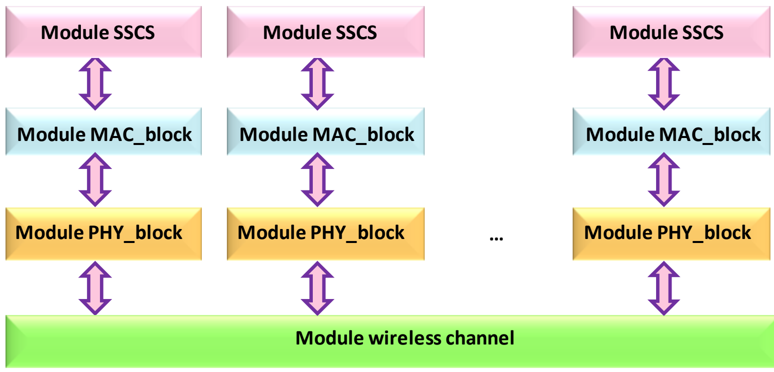


Figure 3. SystemC architecture of the 802.15.4 network

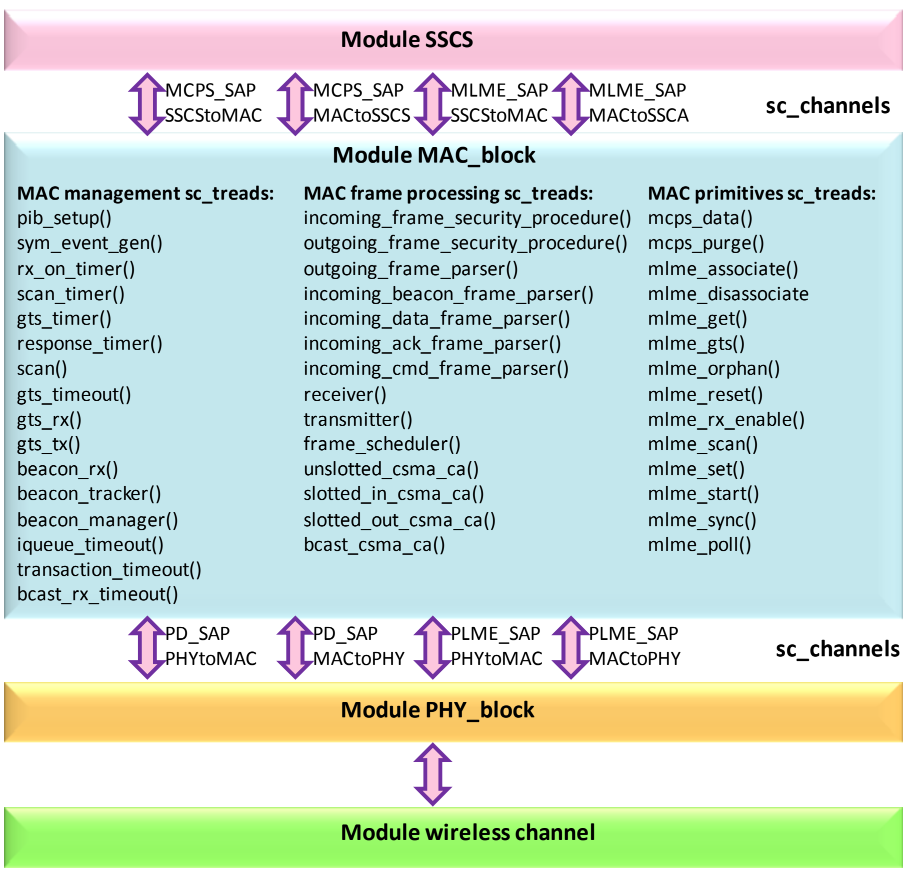


Figure 4. SystemC architecture of the 802.15.4 MAC

4. SIMULATION RESULTS

The proposed model has been used to simulate an IEEE 802.15.4 a nonbeacon-enabled network with star topology, therefore the unslotted CSMA-CA mechanism is used. The sensor nodes send data to the pan coordinator. In the simulations each device sends 720 bytes to the coordinator, the simulation stops when all the devices send successfully all the data to the coordinator. If the device does not receive the acknowledge from the coordinator, the data is retransmitted. The network performances are analyzed in different conditions:

- different number of devices, from 1 to 30, that communicates with a central PAN Coordinator;
- different size of the payload, from 8 to the maximum of 102 bytes;
- after transmission the device waits for a constant time period T, from 0 to 1sec, then the device tries to transmit data again.

The wireless channel model is able to consider the effect of the noise in the channel, but in the results reported in this work the channel failure is due only to the collision between the transmission of two devices.

The performances monitored in the simulations are:

- the number Channel Access Failure due to collisions;
- the number time the ACK is not received by the device due to collisions;
- the channel efficiency in transmission, expressed as the ratio between the packet correctly received by the pan coordinator and for which the device received an acknowledge, with respect to the number of packets sent by the devices;

$$Tx\,Efficiency = \frac{n_{packets} - n_{no\,ACK} - n_{Channel\,Access\,Failure}}{n_{packets}} = 1 - PER_{tx} = 1 - \frac{n_{no\,ACK} + n_{Channel\,Access\,Failure}}{n_{packets}}$$

- the channel efficiency in reception, expresses as the ratio between the packet correctly received by the pan coordination, with respect to the number of packets sent by the devices;

$$Rx\,Efficiency = \frac{n_{packets} - n_{Channel\,Access\,Failure}}{n_{packets}} = 1 - PER_{rx} = 1 - \frac{n_{Channel\,Access\,Failure}}{n_{packets}}$$

- the effective channel throughput, that is the number payload data bits transmitted, divided by the time required for the transmission;
- Rx power consumption of the device, expressed as the percentage of time the receiver of the device is ON;
- Tx power consumption of the device, expressed as the percentage of time the transmitter of the device is ON.

The first set of simulations has been performed with a number of devices from 1 to 7. After a random initial waiting time, each device transmits continuously data, that is after each transmission the device tries to transmit data again immediately. Figure 5 reports Tx Efficiency, Rx Efficiency, the percentage of acknowledge not received with respect to the total packets sent, the percentage of channel access failure as a function of the number of devices in the network. The payload data in each frame is 102 bytes (a), 72 bytes (b) and 8 bytes (c). The results are averaged over the number of devices and over different simulations performed with different initial conditions.

The efficiency reduces increasing the number of devices, due to the increment of the channel congestion. The Tx efficiency is lower that the Rx efficiency, since the effect of a collision in the acknowledge packets is added to the collision in the data packets. When the data packet size increases, the probability of channel access failure of the data packets increases, therefore the Rx efficiency reduces. Conversely, the number of ack frames lost increases, therefore the Tx efficiency increases increasing the data packet size.

Figure 6 reports the effective channel throughput as a function of the number of devices in the network with different payload data in each frame: 102, 72 and 8 bytes. The increment in the number of devices increases the collisions in the channel and therefore reduces the effective throughput. The increment of the payload data size increases collision probability, as shown in Figure 5. Nevertheless, the maximum effective channel throughput is obtained with the maximum payload data size, 102 byte per frame. The maximum effective channel throughput is about 126 kbps, far from the nominal value of 250 kbps.

The second set of simulation has been performed with a number of devices from 1 to 30. The size of the data is 72 bytes. After a random initial waiting time, each device tries to transmits data after a constant time interval: (a) continuously, (b) after 20ms data, (c) after 50ms data, (d) after 1s. Figure 7 reports Tx Efficiency, Rx Efficiency, the percentage of acknowledge not received with respect to the total packets sent, the percentage of channel access failure as a function of the number of devices in the network.

The efficiency reduces increasing the number of devices, due to the increment of the channel congestion. The increment of the time between each transmission reduces the congestion of the channel and therefore increment the efficiency.

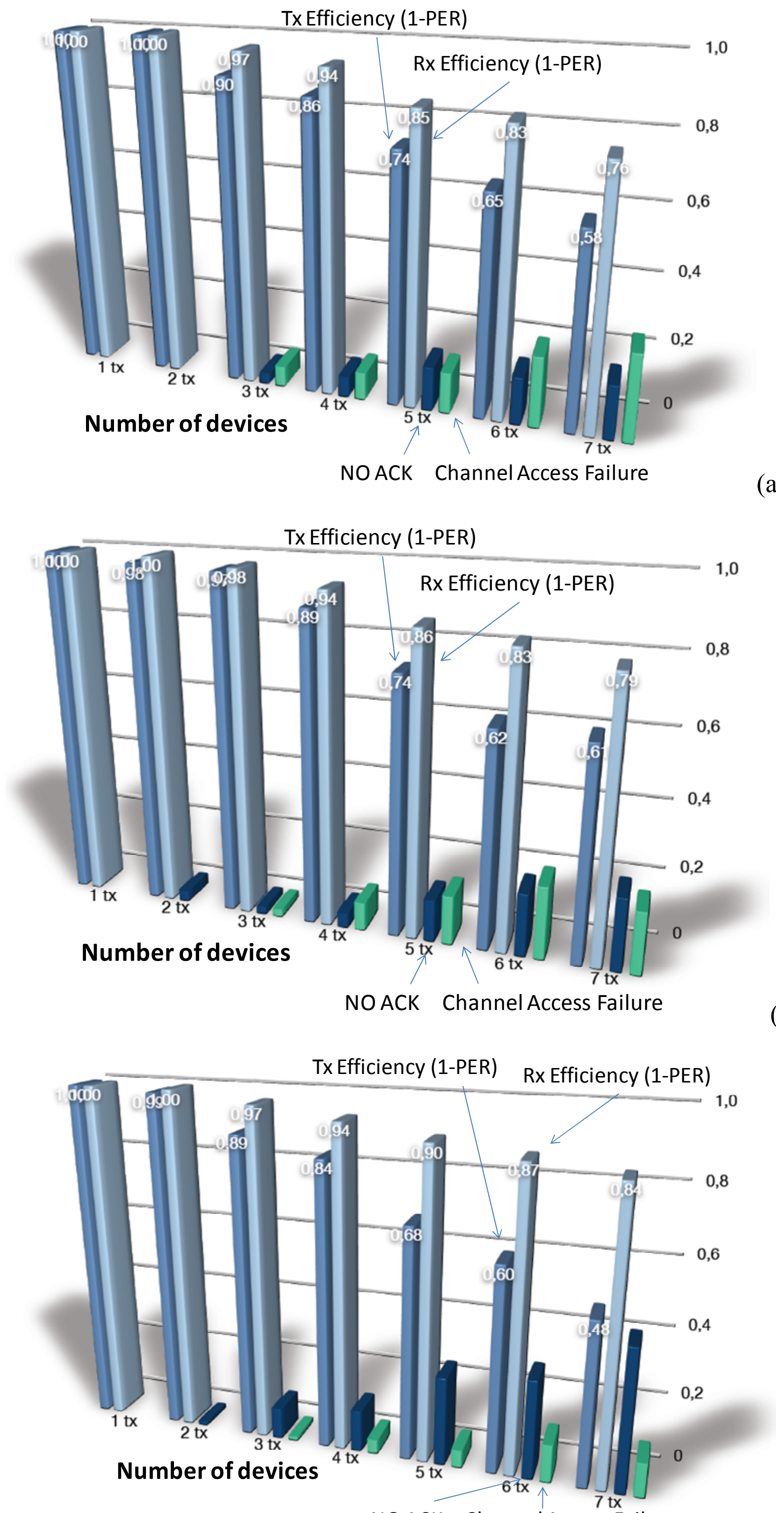
Figure 8 summarizes the results of Figure 7 reporting Tx Efficiency as a function of the number of devices in the network with different time interval between transmissions of each device.

The third set of simulation has been performed with 10, 15 and 30 number of devices on the same network, with different frequency of access in the channel to transmit data. The size of the data is 72 bytes. The CPU time required for a simulation of a network with thousands of devices should be to high. With a high number of devices (greater that 10) the probability of channel access failure is not directly dependent on the number of devices, but on the channel occupation.

Therefore the Tx efficiency obtained by the simulations has been reported, in Figure 9, as a function the product of the number of devices and the frequency (1/T) with which each device tries to transmit data. The interpolating line can be used to estimate the efficiency of a network with a great number of nodes, for example with 1500 nodes transmitting data each second.

5. CONCLUSIONS

The proposed SystemC model enables the fast evaluation of the performances of a wireless network based on IEEE802.15.4 standard. In this work the performances of a nonbeacon-enabled network have been evaluated as a function of the number of devices, of the dimension of the payload and of the frequency with which the nodes try to transmit. The performance of a network with an high number of devices have been estimated. The results are useful in the design of a IEEE802.15.4 wireless network with a high number of nodes.



(a) 102 bytes

(b) 72 bytes

(b) 8 bytes

Figure 5. Tx Efficiency, Rx Efficiency, percentage of not acknowledge, percentage of channel access failure as a function of the number of devices in the network. The payload data in each frame is 102 byte (a), 72 byte (b), 8 byte (c)

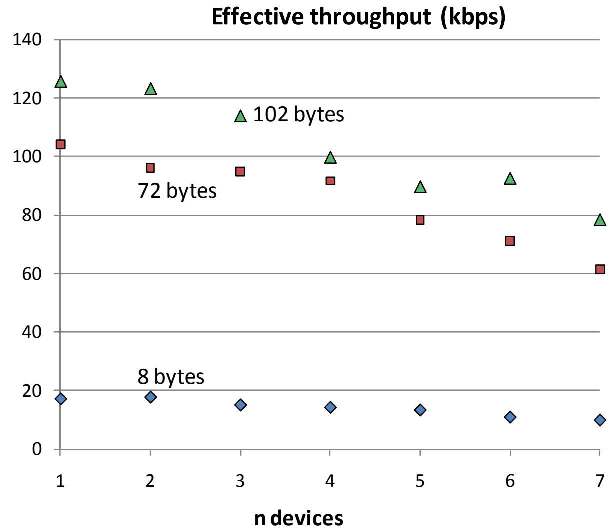


Figure 6. Effective channel throughput as a function of the number of devices in the network with different payload data in each frame: 8 byte, 72 byte, 102 byte

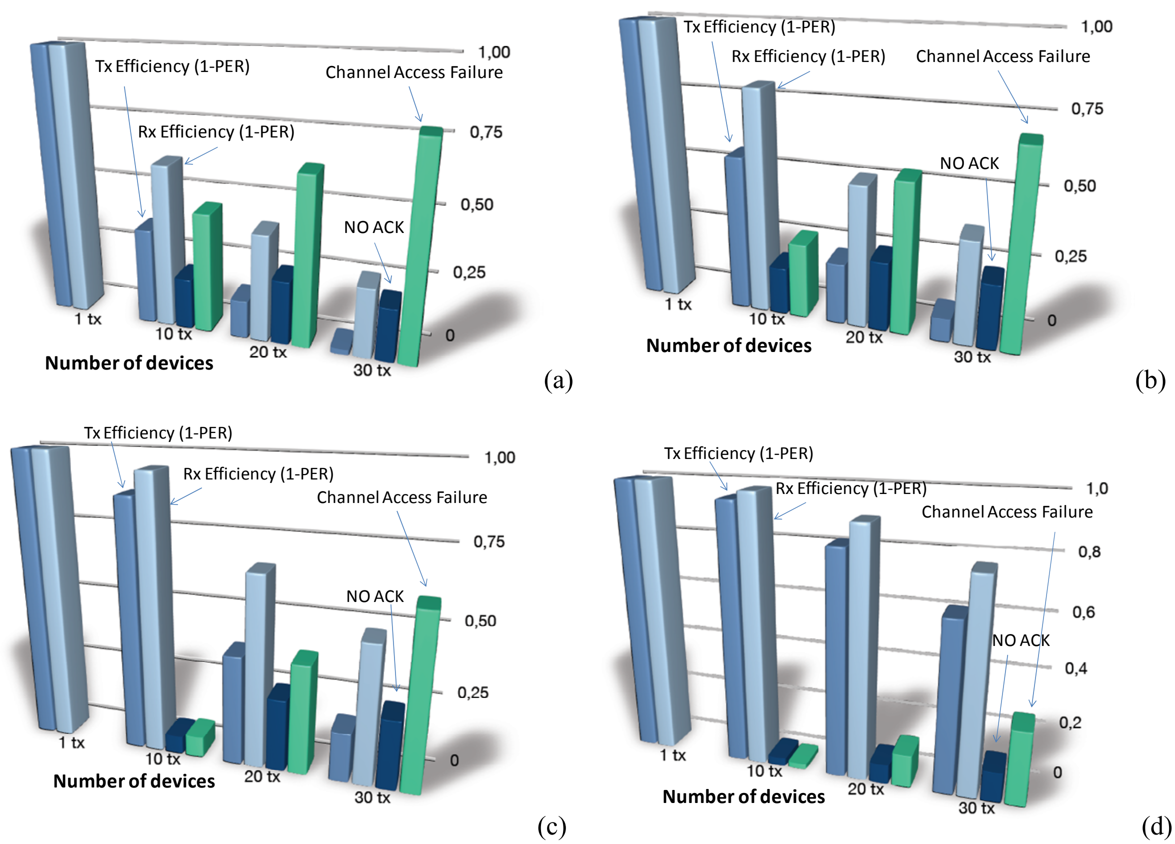


Figure 7. Tx Efficiency, Rx Efficiency, percentage of not acknowledge, percentage of channel access failure as a function of the number of devices in the network. (a) continuous transmissions, (b) transmissions each 20ms, (c) transmissions each 50ms, (d) transmissions each 1s

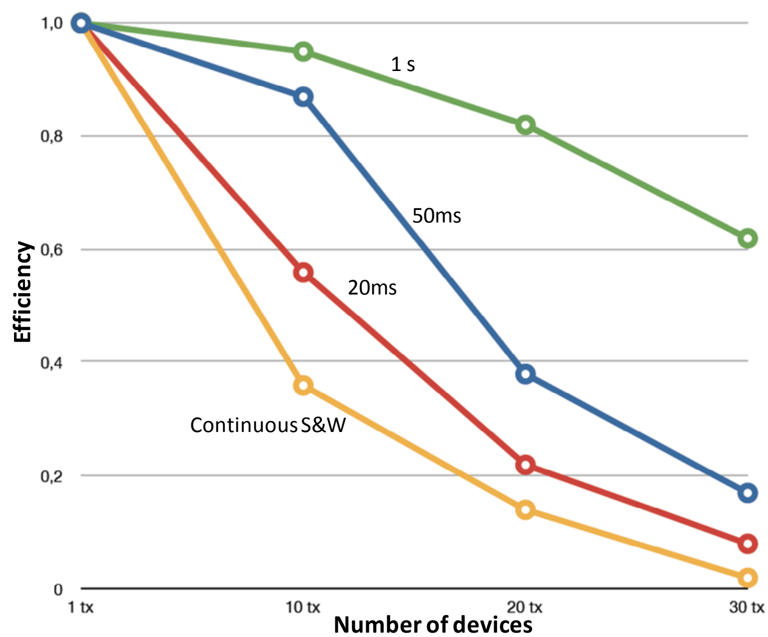


Figure 8. Tx Efficiency as a function of the number of devices in the network with different time interval between transmissions of each device.

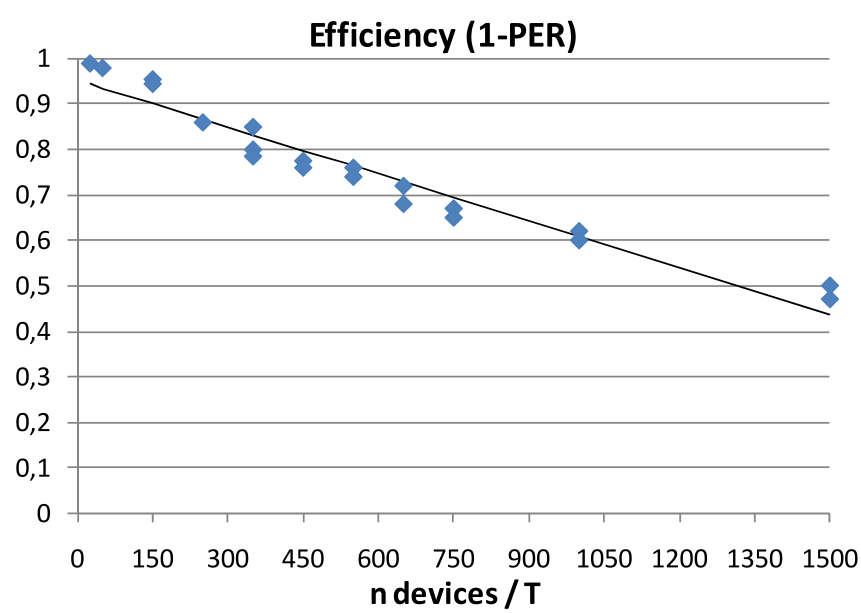


Figure 9. Extrapolation of Tx Efficiency as a function of the number of devices in the network.

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