Chapter 1

PERFORMANCE ANALYSIS OF ZIGBEE WIRELESS SENSOR NETWORKS WITH RELAYING

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Abstract In wireless sensor networks, the need for transmitting information from sensors to a far Access Point (AP) out of direct transmission range might make the use of *relaying* crucial. The goal of this paper is to study the impact of relaying in Zigbee wireless sensor networks. In particular, we focus on Zigbee wireless sensor networks and analyze scenarios where the sensors transmit to an AP (or *coordinator*) (i) directly, (ii) through a relay node (or *router*), or (iii) through two relays. We study how the network performance (in terms of delay, transmission rate, and throughput) is influenced by the number of sensors, the traffic load, and the use of ACKnowledgment (ACK) messages. This performance analysis is carried out with simulations, analytical considerations, and experimental measurements. Our results show that the use of one or two relays, combined with the use of ACK messages (not efficiently managed by the upper layers of the network protocol stack), may cause a significant performance degradation. On the opposite, if ACK messages are not used, then the performance improves significantly. In addition, we also consider the impact of the network lifetime on the network transmission rate.

1. INTRODUCTION

Wireless sensor networks are an interesting research topic, both in military [1–3] and civilian scenarios [4,5]. In particular, remote/environmental monitoring, surveillance of reserved areas, etc., are important fields of application of wireless sensor networking techniques. Typically, very low power consumption and low-cost hardware are required [6].

One of the latest standards for wireless networking with low transmission rate and high energy efficiency has been proposed by the Zigbee

Alliance [7,8]. Experimental analyses of Zigbee wireless sensor networks, taking into account the impact of the most important system parameters (e.g., the Received Signal Strength Indication (RSSI), throughput, network transmission rate, and delay) are presented in [8–10].

In this paper, we evaluate the impact of the presence of one or two *relay nodes* (also referred to as *routers*) on the network performance. Both experimental and simulation results, obtained using a wireless sensor network constituted by PICDEM Z nodes (produced by Microchip) [11] and the Opnet simulator [12], respectively, are presented. As performance indicators, we use *network transmission rate*, *delay*, and *throughput*. We evaluate the impact of the number of nodes and the packet length on the system performance. In addition, we investigate the impact of the variation of the ACKnowledgment (ACK) window duration (i.e., the time interval during which a node waits for an ACK message after transmitting its data). A simple-minded analytical framework is also proposed to validate the simulation results. Finally, we characterize the behavior of the network transmission rate as a function of the network lifetime, given by the percentage of sensors' deaths which make the network dead, in the presence of *clustering*. A small number of required sensors' deaths (i.e., a short network lifetime) can be interpreted as a stringent Quality of Service (QoS) condition.

2. ZIGBEE STANDARD OVERVIEW

The Zigbee standard is suited for the family of Low-Rate Wireless Personal Area Networks (LR-WPANs), allowing network creation, management, and data transmission over a wireless channel with the highest possible energy savings. Three different types of nodes are foreseen by the Zigbee standard: (i) *coordinator*, (ii) *router*, and (iii) *end device*. In the absence of a direct communication link from an end device to the coordinator, the router is employed to relay the packets towards the correct destination. The coordinator, in addition to being able to relay the packets itself, can also create the network, exchange the parameters used by the other nodes to communicate (e.g., a network IDentifier (ID), a synchronization frame, etc.), and send network management commands. The router and coordinator are referred to as *Full Function Devices* (FFDs), i.e., they can implement all the functions required by the Zigbee standard in order to set up and maintain communications. The end devices, which are also referred to as *Reduced Function Devices* (RFDs), can only collect data from sensors, insert these values into proper packets, and send them to destination nodes.

The Zigbee standard is based, at the first two layers of the ISO/OSI stack, on the IEEE 802.15.4 standard [13], which employs a *non-*

persistent Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) Medium Access Control (MAC) protocol and operates in the 2.4 GHz band (similarly to the IEEE 802.11 standard [14]). In addition, the IEEE 802.15.4 standard provides an optional ACK message to confirm the correct delivery of a packet. In a scenario with transmission of ACK messages, the access mechanism of the non-persistent CSMA/CA MAC protocol is slightly modified. More precisely, after successful transmission of a data frame, a time interval, denoted as Short InterFrame Spacing (SIFS), is reserved. The duration of this interval is longer than the duration of an ACK message and shorter than the ACK window duration. Therefore, the receiving node can send an ACK message back immediately, avoiding any collision. If the SIFS is too short, this mechanism may incur some problems in the presence of a router. In this case, in fact, the sum of the transmission times of the two ACK messages may be longer than the SIFS: therefore, the second ACK message may collide with other on-going transmitted packets (from other nodes). This problematic behavior is exacerbated in the case with two routers.

We remark that the medium access mechanism in Zigbee wireless networks makes use of a *back-off algorithm* to reduce the number of packet collisions. A node, before transmitting a new packet, waits for a period randomly chosen in an interval defined during the network start-up phase. After this period has elapsed, the node tries to send its packet: if it detects a collision, it doubles the previously chosen interval and waits; if, instead, the channel is free, it transmits its packet. This procedure is repeated five times, after which the waiting interval is maintained fixed to its maximum value. This back-off algorithm makes it likely, in the considered scenarios with low traffic loads, that a node will eventually succeed in transmitting its packet.

3. EXPERIMENTAL AND SIMULATION SETUP

Our experimental wireless sensor network is constituted by PICDEM Z nodes produced by Microchip [11]. All the experiments have been performed in an indoor scenario, and the PICDEM Z nodes have been configured in order to remain active all the time. Two network configurations have been considered for the experimental tests, with RFDs connected to the coordinator (i) directly, as shown in Figure 1.1 (a), or (ii) through a router, as shown in Figure 1.1 (b), respectively. In both these *experimental* scenarios, the number of packets transmitted by the RFDs is equal to 1000.

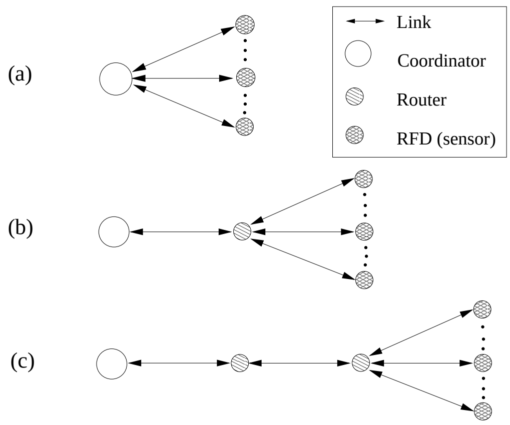


Figure 1.1. Possible sensor network topologies: three RFDs are connected to the coordinator (a) directly, (b) through one router, or (c) through two routers.

In order to validate and extend our experimental results, we make use of the Opnet Modeler 11.5 simulator [12] and a built-in Opnet model for a standard (without router) Zigbee sensor network created at the National Institute of Standards and Technology (NIST) [15]. Both in the case of simulation and in the case of experimental results, we consider a scenario where the sensors transmit to the coordinator, which only collects the performance statistics and, if required, sends back the ACK message. The adopted simulation model does not consider power attenuation due to transmission in a non-ideal channel and, in addition, does not take into account multipath phenomena which, instead, influence experimental results. In some cases, in fact, experiments had to be repeated because of the presence of people crossing the wireless communication links between nodes. Besides the topologies in Figure 1.1 (a) and Figure 1.1 (b) (analyzed also experimentally), the developed simulator allows to evaluate a wider set of topologies, such as that shown in Figure 1.1 (c), corresponding to a scenario where the RFDs communicate to the coordinator through two routers. In Section 4.4, an even more complex network simulation setup will be used, as a generalization of the model shown in Figure 1.1 (b). More precisely, we will consider a *clustered* scenario, where RFDs are grouped into clusters. Each cluster is associated with a relay, which forwards the data received from its RFDs to the coordinator.

Since the Opnet model for a Zigbee network developed at NIST [15] does not make use of a router, we have implemented a router model which receives the packets (from the RFDs or another router) and properly changes some parameters (such as destination and source addresses) in order to allow the coordinator to send back ACK messages to the

RFDs. More precisely, we assume an ideal "binding" between the source nodes (RFDs) and the destination node (coordinator). In other words, whenever the RFDs are not directly connected with the coordinator, they send data packets to the router which, in turns, substitutes the destination address embedded in the packet header with the new destination address (i.e., the coordinator address) and forwards the packet. In the NIST Opnet simulator the *channel* is modeled as an infinite buffer: when a node generates a packet, it inserts it in the channel buffer and schedules its transmission after a period of time associated with processing and transmission delays. After this interval, the simulator checks if there is any collision:[1] if so, the node reschedules its transmission; if not, the packet is sent and the destination node (the coordinator in the case of direct transmission or, in the case of transmission through routers, at first the routers and then the coordinator) starts processing the packet. Once the router has relayed the packet to the coordinator, it waits for the ACK message from the latter (for a time interval corresponding to the ACK window duration) and does not accept any other incoming packet: this is due to our implementation, where no transmission queue has been inserted in the router. A time description of this behavior is summarized in Figure 1.2. As it will be shown later, this specific implementation of the router leads to a significant performance loss. We are currently working on the extension of the relay model, to make it more efficient and compliant with its experimental implementation in the PICDEM Z nodes.

We remark that both simulation and experimental tests have been performed in the *beaconless* mode. All *simulation* durations, except for those related to lifetime analysis, have been set equal to 1 hour.

4. PERFORMANCE ANALYSIS

We now characterize the network performance, evaluating the impacts of (1) the number of sensors, (2) the traffic load, (3) the ACK window duration, and (4) the network lifetime.

4.1 IMPACT OF THE NUMBER OF SENSORS

We distinguish between scenarios *with* and *without* the use of ACK messages respectively.

[1]The simulator just checks if there is any other transmission scheduled for the interval during which a node wants to transmit. If there is a transmission, it declares a collision. Otherwise, if no transmission is scheduled, the simulator declares the channel idle and notifies the destination node (either the coordinator or the router, depending on the scenario) that there is a transmission in progress.

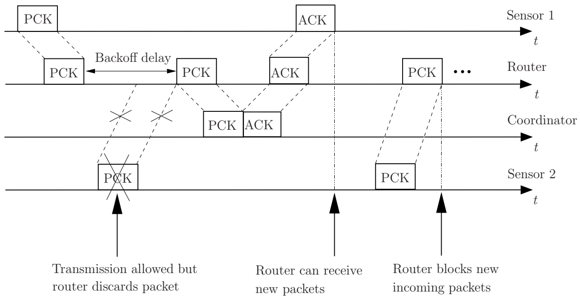


Figure 1.2. Temporal description of the behavior of a router in the presence of a new incoming packet.

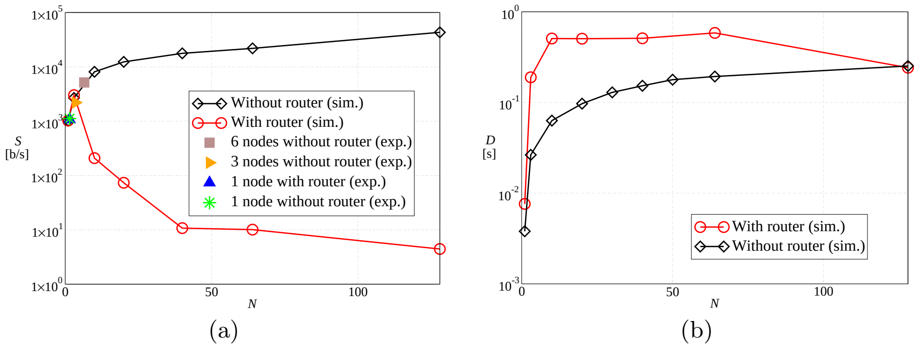


Figure 1.3. Network performance, as a function of the number of transmitting nodes, in terms of (a) network transmission rate (at the coordinator) and (b) delay, in the case with packet length $L = 64$ byte/pck and packet generation rate at the RFDs equal to $g_{\text{pck}} = 2$ pck/s. Two scenarios are considered: (i) direct transmission between remote nodes and coordinator (lines with diamonds) and (ii) relayed transmission through a router (lines with circles). The symbols (in figure (a)) are associated with experimental results, while the curves correspond to simulation results

With the Use of ACK Messages. The packet length is set to $L = 64$ byte/pck and a fixed packet generation rate, equal to $g_{\text{pck}} = 2$ pck/s, is considered. While the value of L has been chosen as intermediate between the minimum and the maximum packet lengths admitted by the Zigbee standard, the value of g_{pck} has selected to make the experiments feasible. The PICDEM Z nodes, in fact, use a single memory register for both transmitted and received packets. Therefore, if the transmission rate is too high, the router cannot relay the packets and may experience a buffer overflow.

The network transmission rate, defined as the average number of bits received per second, and the delay, defined as the time interval between packet generation and packet correct reception, are shown, as functions of the number of the nodes N, in Figure 1.3 (a) and Figure 1.3 (b), respectively. Two network configurations are considered: (i) direct transmission from the RFDs to the coordinator (see Figure 1.1 (a)) and (ii) transmission through a router (see Figure 1.1 (b)). We first comment on the network transmission rate, then on the delay.

As one can see from the simulation results in Figure 1.3 (a), in the presence of direct transmission from the sensors to the coordinator, the network transmission rate is an increasing function of the number of sensors and saturates at approximately $N = 128$ sensors. In the presence of a router, instead, there is a drastic reduction of the transmission rate for small values of N. The network transmission rate reaches its maximum in correspondence to $N = 3$ sensors and then starts decreasing with N. In Figure 1.3 (a), experimental results for the network transmission rate are also shown. In the case without the router, the experimental results are in excellent agreement with the simulations. In the case with the router, instead, the experimental results on the network transmission rate do not agree with the simulations. The reason for this mismatch will be explained in the following paragraph. In the case with a router, the slope change at $N = 3$, however, can be justified as follows. When the number of nodes is small, the transmission rate is high, since the relaying capabilities of the router can still compensate for the increasing number of collisions between the packets transmitted by the RFDs. For a number of nodes larger than 10, the decrease is due to the fact that the relaying capabilities of the router are reduced because the number of collisions is larger and it is more likely that the channel is occupied by another transmitting node.

In order to justify the simulation/experimental results, we propose a simple and intuitive approach to evaluate the saturation value of the network transmission rate in *ideal* conditions. In the case without the router, the transmission rate tends to saturate to an ideal maximum value *if*, after transmission of an ACK message from the coordinator, a new packet is immediately available from an RFD. Considering the experimental values for the data packet length ($L = L_{\text{payload}} =$ 64 byte/pck), the packet header length ($L_{\text{header}} = 80$ b/pck), the data-rate ($R_{\text{b}} = 250$ kbps), the ACK message length ($L_{\text{ack}} = 88$ b/pck), and neglecting processing and propagation delays, the saturation value of the network transmission rate is

$$S^{\text{sat}} = \frac{L \cdot R_{\text{b}}}{L + L_{\text{ack}} + L_{\text{header}}} = 188.2 \text{ kb/s}. \tag{1.1}$$

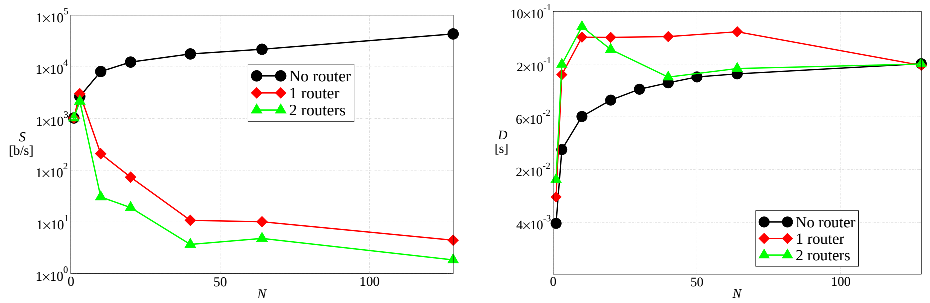
In the presence of a router, instead, one has to consider not only the transmission from the sensors to the router, but also the transmission from the router to the coordinator: this doubles the number of bits to be transmitted. Therefore, the effective network transmission rate saturates at

$$S^{\text{sat}} = \frac{L \cdot R_{\text{b}}}{2 \cdot (L + L_{\text{ack}} + L_{\text{header}})} = 94.1 \text{ kb/s}. \tag{1.2}$$

Comparing the analytical values in (1.1) and (1.2) with the simulation results in Figure 1.3 (a), the following comments can be made. In the absence of the router, the network transmission rate obtained with simulations (line with diamonds) approaches the saturation value in (1.1); at the opposite, in the presence of a router, the saturation value in (1.2) is not approached (in the considered range of values of N) by the simulation results (line with circles). Note that the theoretical limits do not take into account the impact of control messages, and the particular router implementation in the simulator. This justifies why the maximum transmission rate predicted by the simulations is lower than the theoretical value in (1.2). In order to obtain more accurate analytical results, in the Appendix we adapt the analytical framework in [16], relative to IEEE 802.11 networks, to IEEE 802.15.4 networks.

Considering the delay performance shown in Figure 1.3 (b), in the *absence* of a router the delay between two subsequent received packets is an increasing function of N. As for the network transmission rate, the saturation value of the delay is approximately reached around $N = 128$ sensors. In the *presence* of a router, instead, the delay behavior can be characterized as follows. For small values of N, this delay is higher than the delay in the absence of the router, in agreement with the network transmission rate behavior in correspondence to small values of N. For large values of N, instead, the delay reduces and becomes basically equal to that in the absence of a router. This is due to the fact that the router (in the simulator) relays the received packets almost immediately (due to the limited number of packets which effectively are able to access the channel and reach destination), so that the channel is likely to be free from other transmissions from the RFDs.

In Figure 1.4 (a) and Figure 1.4 (b), the network transmission rate and the delay are analyzed, as functions of the number N of sensors, in all topologies shown in Figure 1.1. Looking at Figure 1.4 (a), the curves related to the scenarios without a router and with a single router are the same as in Figure 1.3 (a). In the case with two routers, the network transmission rate has a very similar trend with respect to the case with a single router. As explained in Section 3, if the router is waiting for an ACK message from the coordinator, it refuses any new incoming data packet until it can forward the ACK message received from the coordinator. In the case with 2 routers, when the traffic load is low, the network transmission rate is close to that related to the case with 1



(a) (b)

Figure 1.4. Network performance, as a function of the number of transmitting nodes, in terms of (a) network transmission rate (at the coordinator) and (b) delay, in the case with $L = 64$ byte/pck and packet generation rate $g_{\text{pck}} = 2$ pck/s. Three scenarios are considered: (i) direct transmission without a router (curves with circles), (ii) transmission through a router (curves with diamonds), and (iii) transmission through two routers (curves with triangles). An ACK message is sent back from the coordinator to the RFDs to confirm the correct data reception.

router. When the offered traffic increases, the relaying capabilities of the routers drastically reduce, because of the larger number of nodes which try to access the channel. In particular, since each packet travels through a three-hop path, it is likely that each router, which can no longer receive new incoming packets. When the number of nodes is small, the number of collisions is small, so that each router is likely to deliver its packet almost immediately. On the opposite, if a router cannot relay a packet, data transmissions from other nodes fail.

In Figure 1.4 (b), the delay performance is evaluated in scenarios with no router, one router, and two routers, respectively. Note that while in the *absence of a router* the delay is an increasing function of N, in the presence of *one router* and in the presence of *two routers* the delay first increases significantly (it reaches its maximum for $N \simeq 10$) and decreases to the same asymptotic value observed in the absence of a router. In all cases, the delay saturates for increasing values of N. In particular, in the presence of one router, the delay is higher than in the case with two routers for large values of N. This fact can be explained considering that in the presence of two routers, the number of exchanged packets is small (and, consequently, the number of collisions is large). Therefore, a node, which can access the channel, transmits almost immediately.

***Without* the Use of ACK Messages.** In this section, the network performance is analyzed in a scenario with *no* transmission of ACK messages. As in the case with the use of ACK messages, the network topologies shown in Figure 1.1 are considered. Unlike in Figure 1.2, in this case the ACK message transmission disappears: as soon as the

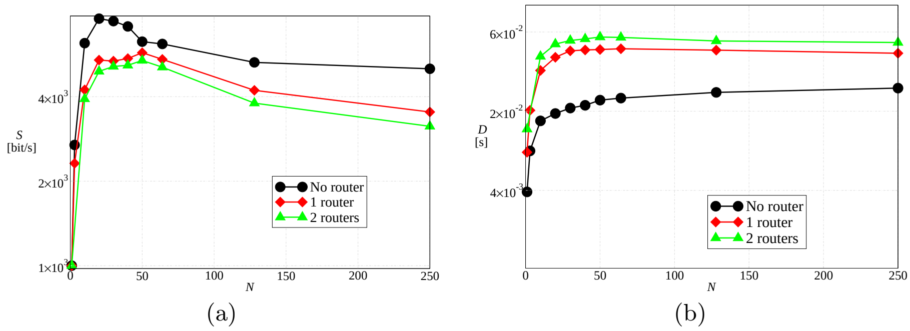


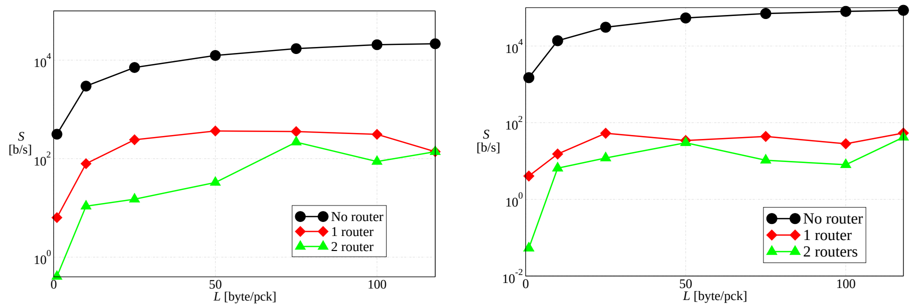
Figure 1.5. Network performance, as a function of the number of transmitting nodes, in terms of (a) network transmission rate (at the coordinator) and (b) delay, in the case with $L = 64$ byte/pck and $g_{\text{pck}} = 2$ pck/s. Three scenarios are considered: (i) direct transmission without a router (curve with circles), (ii) transmission through a router (curve with diamonds), and (iii) transmission through two routers (curve with triangles). ACK messages are not used.

router sends a data packet to the coordinator, the former is ready to receive a new incoming data packet from an RFD. Therefore, the probability of finding the router ready to process new packets increases. The simulation setup is, but for the absence of ACK messages, the same as in the case with ACK messages.

In Figure 1.5 (a), the network transmission rate is shown as a function of the number of RFDs. Various network configurations are considered: (i) absence of the router (as in Figure 1.1 (a)), (ii) presence of one router (as in Figure 1.1 (b)), and (iii) presence of two routers (as in Figure 1.1 (c)). As one can see from the results in Figure 1.5 (a), the behavior of the network transmission rate is similar in all these network configurations. For small values of N, the network transmission rate rapidly increases until it reaches its maximum between $N = 10$ and $N = 50$ (depending on the network configuration). Beyond this maximum value, the network transmission rate decreases, with a trend typical of networks using the CSMA/CA MAC protocol [17]. Expression (1.1) for the saturation value of the network transmission rate in a scenario with no router can be rewritten as follows:

$$S^{\text{sat}} = \frac{L \cdot R_{\text{b}}}{L + L_{\text{header}}} = 216.2 \text{ kb/s}. \quad (1.3)$$

Comparing (1.1) with (1.3), one can observe that, at the denominator, the term related to L_{ack} has been eliminated. Therefore, in the absence



(a) (b)

Figure 1.6. Network transmission rate, as a function of the packet length, in networks with (a) $N = 20$ RFDs and (b) $N = 100$ RFDs, respectively. The packet generation rate at the RFDs is $g_{\rm pck} = 2$ pck/s. Three scenarios are considered: (i) direct transmission between RFDs and coordinator (lines with circles), (ii) transmission through a router (lines with diamonds), and (iii) transmission through two routers (line with triangles). ACK messages are sent back from the coordinator to confirm correct data reception.

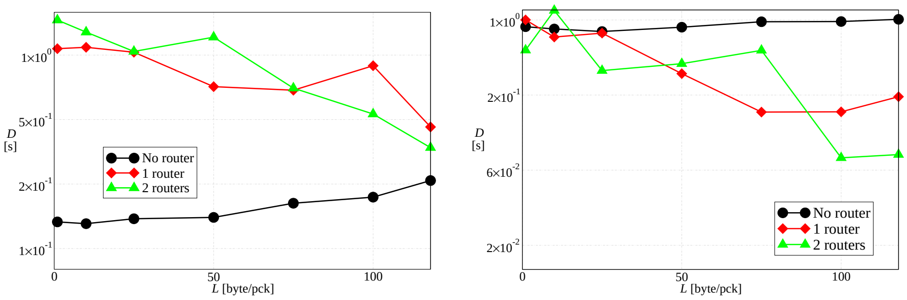
of ACK messages, the saturation value of the network transmission rate is expected to be higher than in the case with ACK messages.[2]

The delay is shown, as a function of the number of RFDs, in Figure 1.5 (b). For all considered network configurations, the delay increases rapidly for small values of N and then saturates at values of N between 10 and 20. Since no ACK message is sent, the delay is marginally influenced by the presence of a router, as already highlighted in Figure 1.4 (b). In this case, in fact, because the number of exchanged control messages per data packet is smaller (no ACK message is sent, for instance), it is more likely that the channel is found free and, therefore, the router can process new data packets.

4.2 IMPACT OF TRAFFIC LOAD

In Figure 1.6 and Figure 1.7, the network transmission rate and the delay are shown, as functions of the packet length L, in two scenarios with (a) $N = 20$ RFDs and (b) $N = 100$ RFDs, respectively. The packet generation rate is fixed to the value $g_{\rm pck} = 2$ pck/s and ACK messages are used. Looking at Figure 1.6, both in the presence and in the absence of a router, the transmission rate increases rapidly and then tends to saturate (except for some fluctuations introduced by the limited number of delivered packets). As one can observe, the network transmission rate with direct transmission to the coordinator (no router) is basically

[2]We remark that the simple analytical approach used to derive (1.3) is approximated. Therefore, the value in (1.3) is optimistic with respect to the maximum network transmission rate in Figure 1.5 (a).



(a) (b)

Figure 1.7. Delay, as a function of the packet length, in networks with (a) $N = 20$ RFDs and (b) $N = 100$ RFDs, respectively. The packet generation rate at the RFDs is $g_{\text{pck}} = 2$ pck/s. Three scenarios are considered: (i) direct transmission between RFDs and coordinator (lines with circles), (ii) transmission through a router (lines with diamonds), and (iii) transmission through two routers (line with triangles). ACK messages are sent back from the coordinator to confirm correct data reception.

equal to the total network traffic load, whereas it is approximately two orders of magnitude lower in the presence of a router. The network transmission rate in the presence of one or two routers is heavily affected by the limited relaying capabilities of the router in the presence of a high traffic load. The delay, on the other hand, is approximately constant, with respect to L, in the absence of the router and slightly varying in the case of transmission through one or two routers. Intuitively, the delay in the presence of the router is given by the sum of the delays (i) between the RFDs and the router and (ii) between the router and the coordinator. The former delay is shorter than the latter since, according to our Opnet model, the router relays a packet right after receiving it, so that it is likely to find the channel free. Processing and propagation delays are negligible—they are three orders of magnitude lower than the transmission delay.

In Figure 1.6 (a) and Figure 1.7 (a), the performance results (in terms of network transmission rate and delay) in a scenario with $N = 20$ RFDs are shown. The performance behaviors are basically the same of those shown in Figure 1.6 (b) and Figure 1.7 (b), relative to scenarios with $N = 100$ RFDs. This fact can be justified as follows. According to the chosen packet generation rate, the network traffic load is small and, therefore, the number of collisions is limited. In the presence of a router, instead, the network performance is heavily influenced by the packet loss due to the absence of a transmission queue at the relay node, which discards any new incoming data packet—while relaying another data packet—without taking any trace of it. Therefore, when the offered traffic load increases, the network performance improves.

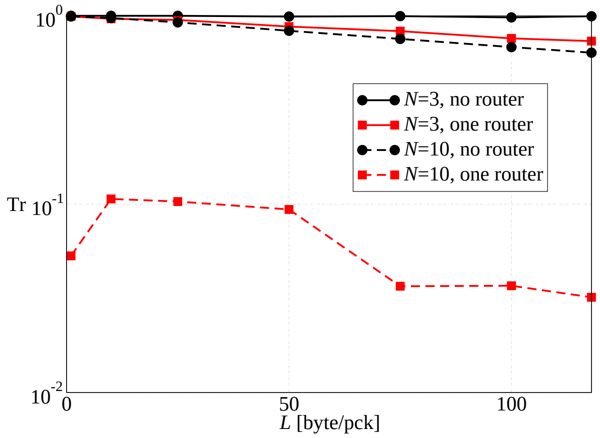
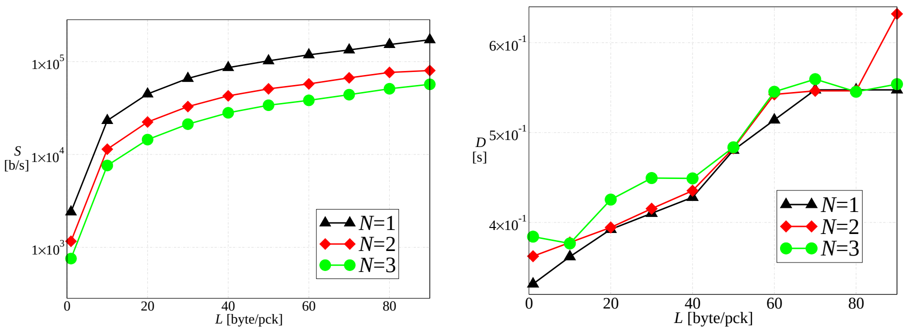


Figure 1.8. Throughput, as a function of the packet length L, in four scenarios: (i) 3 RFDs sending messages directly to a coordinator (solid line with circles) or (ii) through a router (solid line with squares), (iii) 10 RFDs sending messages directly to a coordinator (dashed line with circles) or (iv) through a router (dashed line with squares).

In Figure 1.8, the *throughput*, defined as the ratio between the number of data packets correctly delivered at the coordinator and the number of data packets sent by the RFDs, is shown as a function of the packet length. Two possible values for N are considered, namely 3 and 10. As one can see, the throughput in the case of *direct transmission* is basically equal to 1, regardless of the value of N, and decreases slightly for increasing values of L. This behavior is due to the fact that the total network traffic load for the considered values of L is too low to create congestion with the used CSMA/CA MAC protocol. Both in the case with direct transmission and in the case of transmission through one router, the throughput reduces for increasing values of N. This is due to the used MAC protocol and the specific router implementation. In fact, since the router immediately relays a received packet, for increasing number of sensors the probability of a collision in an idle interval increases significantly. In the scenario with $N = 3$ RFDs and one router, the throughput is close to that in the case of direct transmission, due to the limited offered traffic and collisions. In the case with $N = 10$ RFDs and one router, instead, the throughput is heavily affected by the traffic load. In this case, in fact, due to the larger number of collisions, the network transmission rate first increases for small values of L and then decreases for larger values of L. In this case, it is possible to identify an "optimal" traffic load (very low) which maximizes the throughput. This maximum is around $L = 10$ byte/pck.



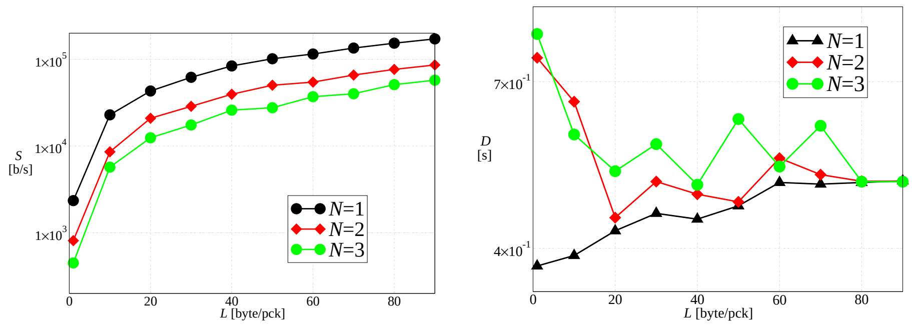
(a) (b)

Figure 1.9. *Experimental* network performance, as a function of the packet length, in terms of (a) network transmission rate and (b) delay. Three scenarios with direct transmission to the coordinator are considered: (i) one RFD (lines with triangles), (ii) two RFDs (lines with diamonds) or (iii) three RFDs (lines with circles). The considered packet generation rate at the RFDs is $g_{\mathrm{pck}} = 2$ pck/s.

In Figure 1.9 and Figure 1.10, *experimental results* relative to the impact of the traffic load on the network performance are presented. The considered network configurations are those shown in Figure 1.1 (a) and Figure 1.1 (b): the RFDs are connected, either directly or through a router, to the coordinator. As discussed in Section 3, the used experimental nodes belong to the PICDEM Z family. In order to make a meaningful comparison, in the experiments we have considered the same packet generation rate ($g_{\mathrm{pck}} = 2$ pck/s) used in the simulator.

In Figure 1.9 (a), the network transmission rate is shown, as a function of the packet length L, in scenarios with (i) one, (ii) two, and (iii) three RFDs, in the case with direct transmission to the coordinator. As intuitively expected, the scenario with the highest network transmission rate is the one with only one RFD transmitting to the coordinator. This is due to the fact that in the presence of more than one RFD, the RFDs trying to access the channel may incur into collisions. Therefore, retransmissions may be needed (according to the used back-off algorithm) and the network transmission rate reduces. In all cases, for short packet lengths, the throughput is low for all network configurations; for increasing values of L, it rapidly increases and tends to saturate for large values of L (i.e., high traffic loads).

In Figure 1.9 (b), the delay is shown as a function of the packet length. It can be noticed that the delay behavior is similar in the three considered scenarios, i.e., with (i) one RFD, (ii) two RFDs, and (iii) three RFDs. This is due to the fact that for the considered values of the network parameters, the traffic load is low and, therefore, an RFD is likely to



(a) (b)

Figure 1.10. Experimental network performance, as a function of the packet length, in terms of (a) network transmission rate and (b) delay. Three scenarios with transmission to the coordinator in the presence of a router are considered: (i) one RFD (lines with triangles), (ii) two RFDs (lines with diamonds) or (iii) three RFDs (lines with circles). The considered packet generation rate at the RFDs is $g_{\text{pck}} = 2$ pck/s.

send a data packet either at its first or second attempt. Therefore, the delay is not influenced by the network traffic.

In Figure 1.10 (a), the network transmission rate is shown, as a function of the packet length, in the presence of a router. In this case, unlike for the simulation results shown in Figure 1.4, the network transmission rate is not affected by the use of ACK messages in a scenario with a router. In Figure 1.10 (a), the network transmission rate rapidly increases, even at small values of L, and then saturates for large values of L. Comparing the results in Figure 1.9 (a) with those in Figure 1.10 (a), it can be noted that the behavior of the network transmission rate is almost identical. This fact can be explained considering that the software implementation of the networking and communication protocols in the PICDEM Z nodes provides all the functionalities required by the Zigbee standard. The nodes employed in the simulations, at the opposite, have only the functionalities of the first two layers of the ISO/OSI stack [18]: therefore, they lack the upper-layer network capabilities that contribute to correct ACK message management. In addition, in the PICDEM Z nodes the router is equipped with a queue where received messages can be stored—we recall that our Opnet router model, instead, does not accept any new incoming packet until it has delivered the current one.

In Figure 1.10 (b), the delay is shown, as a function of the packet length, in a scenario with a router. In the case with $N = 1$, the delay is slightly increasing, since the RFD always finds the channel free. In the scenarios with $N = 2$ and $N = 3$, instead, the delay is high for low values of L, and then decreases for large values of L. This behavior is quite surprising at first sight, since one intuitively expects a higher delay for large values of L. However, the observed behavior can be explained considering that, after a collision, a packet can be delayed for a certain amount of time because of the back-off algorithm. In the experiments with $N = 2$ RFDs, we have observed that while an RFD could not transmit for a certain time interval, the other RFD was sending its messages regularly. In other words, out of the two RFDs one starves and the other gets all the resources. In general, since the RFDs are in the same carrier sensing range, while an RFD is transmitting a packet, the other RFDs must wait (according to the back-off algorithm) before transmitting their packets. In unfortunate situations, it may happen that a node detects the channel as busy for a long time and, therefore, cannot transmit any message. This behavior might also be related to the *capture effect*, which affects IEEE 802.15.4 wireless networks [19].

4.3 IMPACT OF THE ACK WINDOW DURATION

Under the use of ACK messages, it is of interest to investigate the impact of the ACK window duration. While a data packet is transmitted according to the CSMA/CA protocol, an ACK message is transmitted using another protocol. In fact, after successful transmission of a data packet, all RFDs must wait a SIFS interval before transmitting, as this interval is used by the receiving node to send back the ACK message. Therefore, an RFD can estimate the amount of time, denoted as *ACK window duration*, it will have to wait for the ACK message. If an RFD does not receive the ACK message within this estimated time, it stops generating new packets. The standard provides a maximum ACK window duration, after which the packet is declared lost. After a maximum number of attempts (which is pre-determined during the network setup), the data packet is discarded and a new data packet may be generated.

In order to investigate the impact of the ACK window duration, we resort to our Opnet simulator. More precisely, we consider a scenario where $N = 3$ RFDs are sending data messages to a coordinator (i) directly or (ii) through a router (topologies (a) and (b) in Figure 1.1, respectively). The major network parameters are fixed as in the previous simulations (in particular, $g_{\text{pck}} = 2$ pck/s and $L = 64$ byte/pck). In Figure 1.11, the delay is shown as a function of the ACK window duration, in the cases with no router (solid line) and with a router (dashed line). Both in the case of *direct transmission* and with *transmission through a router*, with low traffic, the delay between two subsequent packets is short and increases slowly for increasing offered traffic load. However, the delay curve, in the case with transmission through a router, presents some fluctuations, introduced by the presence of the router, which, in

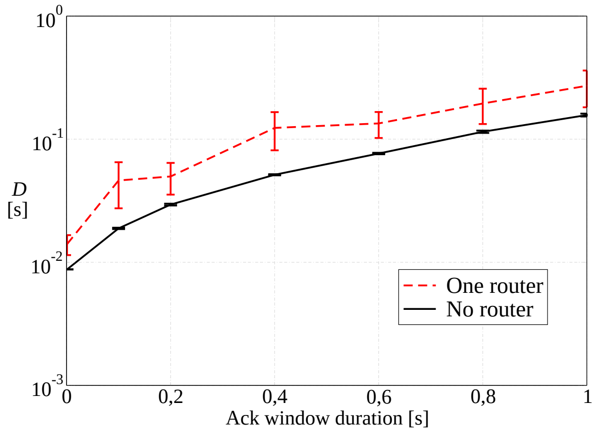


Figure 1.11. Transmission delay, as a function of the ACK window duration, in a network with $N = 3$ RFDs, packet generation interval at the remote nodes given by $g_{\text{pck}} = 2$ pck/s, and fixed packet length $L = 64$ byte/pck. Two scenarios are considered: (i) direct transmission (solid line) and (ii) transmission with router (dashed line).

addition, introduces a further delay due to the retransmission of the packet from the router to the coordinator.

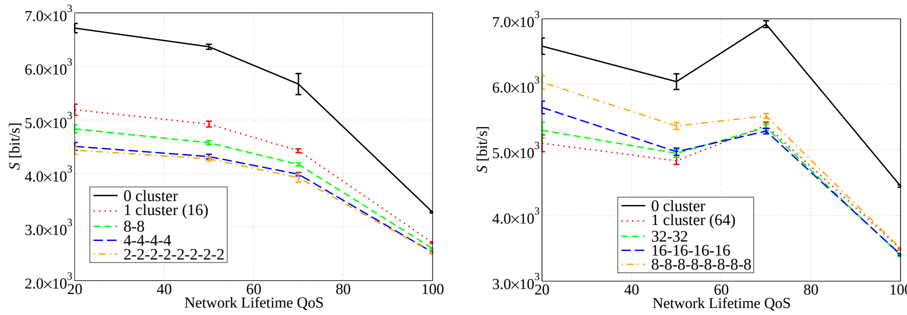
In Figure 1.11, we also show the confidence intervals $(\eta - \sigma, \eta + \sigma)$ associated with each simulation point, with

$$\eta \triangleq \frac{\sum_{i=1}^{n_{\text{Trials}}} D_i}{n_{\text{Trials}}} \qquad \sigma \triangleq \sqrt{\frac{\sum_{i=1}^{n_{\text{Trials}}} (D_i - \eta)^2}{n_{\text{Trials}}}}$$

where n_{Trials} is the number of simulation runs and D_i is the delay value collected in each simulation run. As one can observe, the simulation results in the absence of a router are very reliable (i.e., the confidence interval is very small), whereas, in the presence of a router, the confidence interval is larger, according to the fluctuations introduced in the performance results. Similar considerations (especially in terms of accuracy) hold also for the other simulation results presented in this paper. We did not explicitly indicate the confidence intervals in all figures for the sake of illustrative clarity.

4.4 IMPACT OF NETWORK LIFETIME

A critical issue in wireless sensor networking is the network lifetime, since nodes are typically equipped with a limited-energy battery and may be subject to failures. In order to save as much energy as possible, the sensors may be grouped into *clusters*, i.e., they transmit their data to intermediate nodes (denoted as *cluster-heads*), which may properly



(a) (b)

Figure 1.12. Network transmission rate as a function of the Network Lifetime QoS provided by the network (i.e., the number of RFDs' deaths required to declare the network dead), in various clustering configuration. Two scenarios are considered: (a) 16 RFDs transmitting to the coordinator and (b) 64 RFDs transmitting to the coordinator. The packet length is $L = 64$ bytes/pck and the packet generation rate at each RFD is $g_{\text{pck}} = 2$ pck/s.

modify these data and relay them to the coordinator. In the remainder of this section, we try to analyze the impact of the network lifetime on the performance (evaluated in terms of network transmission rate), considering various clustering configurations.

First, one has to define until when the network has to be considered "alive." Several definitions have been proposed in the literature [20]. In general, the network can be considered alive until a proper QoS condition is satisfied. Obviously, the more stringent is the QoS condition, the shorter is the sensor network lifetime. We consider, as QoS condition, the percentage of RFDs' deaths at which the overall network is assumed to be dead. In other words, if the QoS condition is stringent, the network is considered dead just after a small percentage of the RFD population dies. The lifetime of a single RFD is modeled as an exponential[3] random variable with mean value equal to 300 s. We remark that our results have been obtained in the absence of ACK messages to confirm the correct reception of the packet.

In Figure 1.12 (a), the network transmission rate is shown, as a function of the required QoS, in a scenario with $N = 16$ RFDs. Various configurations are considered, including the case with no cluster (i.e., the RFDs communicate directly to the coordinator) and a few clustered cases (the RFDs in each cluster communicate to an intermediate relay

[3]We point out that an exponential distribution is often considered to characterize the lifetime of technological devices [21]. We did not investigate, from an experimental viewpoint, a more accurate lifetime distribution. Our approach, however, can be applied with any sensor lifetime distribution.

which, in turns, communicate to the coordinator). For a stringent QoS condition, i.e., when the network is considered dead after a small number of sensors' deaths, the network transmission rate is slightly decreasing. When the QoS becomes less stringent, i.e., when the number of RFDs' deaths necessary to make the network dead increases, the network transmission rate quickly decreases. This can be explained considering that when the average number of transmitting nodes is large (this happens for stringent QoS conditions), under the condition of low traffic load, the number of delivered packets is large. When the average number of transmitting nodes decreases (this is allowed for less stringent QoS conditions), the number of delivered packets decreases as well. Moreover, the overall maximum network transmission rate is reached in a scenario with no clustering. Increasing the number of clusters has a negative impact on the network performance, according to the intuition that the relays (i.e., the cluster-heads) act as bottle-necks for data transmission.

In Figure 1.12 (b), the network transmission rate is shown, as a function of the percentage of RFDs' deaths, in a scenario with $N = 64$ RFDs. One can observe that, as in the case with $N = 16$ RFDs, the maximum network transmission rate is obtained in the scenario without clusters. However, in the presence of a large number of RFDs ($N = 64$), the impact of the clustering configuration is different from the case with a small number of RFDs ($N = 16$). If direct transmission is impossible, the preferred clustering configuration is either the one with 4 clusters (with a stringent QoS condition) or that with 1 cluster (with a less stringent QoS condition). Therefore, the best configuration is not always the one with the smallest number of clusters, but depends on the number of RFDs and the number of RFDs' deaths which can be tolerated by the network (i.e., the QoS condition).

5. CONCLUDING REMARKS

In this paper, we have analyzed the impact of *relaying* on the performance of wireless sensor networks. In particular, we have presented simulation and experimental results, together with simple analytical considerations. Our simulator is based on Opnet, and our experiments have been carried out using PICDEM Z nodes. Various topologies have been considered, including direct transmission from the RFDs to the coordinator (absence of relaying), the presence of one relay, and the presence of two relays. In all scenarios, the system performance has been evaluated considering the impact of (1) the number of sensors, (2) the traffic load, (3) the ACK window duration, and (4) the network lifetime (associated with various clustering configurations). In scenarios with at least one router, our results show that the performance is highly degraded if ACK messages are used, and can be improved either by limiting the number of simultaneous transmitting nodes (possibly through efficient synchronization between the RFDs) or by eliminating completely the use of ACK messages—this improvement is, of course, possible because of the low traffic load typical of sensor networks. In a scenario with clustering, we have discovered that the best system configuration (in terms of number of clusters) depends on (i) the number of RFDs and, consequently, (ii) the required network lifetime. In other words, there is *not* a single configuration which provides the best performance for all network/communication conditions.

APPENDIX: ANALYTICAL APPROXIMATION OF THE SIMULATION RESULTS

In IEEE 802.11 networks, the MAC protocol is given by the Distributed Coordination Function (DCF), which corresponds to a *slotted 1-persistent* CSMA/CA MAC protocol. The MAC protocol of the IEEE 802.15.4 standard differs from the DCF in the sense that (i) the access is *unslotted* and (ii) the used CSMA/CA protocol is *non-persistent*. In order to apply the framework in [16] (valid for a slotted scenario) to a Zigbee network (which uses an unslotted communication scheme), we consider a "mini-slotted" time subdivision. The mini-slot dimension, denoted as σ, corresponds to the duration of a symbol in the Opnet simulations—this is also expedient for comparison purposes between analytical and simulation results. In fact, all time parameters available in the Opnet simulator are expressed as multiples of this value. In [16], the analysis is presented only for a scenario with many RFDs connected directly to the coordinator, as shown in Figure 1.1 (a). Therefore, a comparison between analysis and simulations is possible only in this case. A simple analytical framework applicable to a scenario with a router, in fact, does not lead to reasonable, yet accurate, results. Our conclusion is that a novel Markov chain-based approach, inspired by [16], should be developed in a 2-router scenario, and we are currently pursuing this research direction.

In [16], the following expression for the network transmission rate is derived:

$$S = \frac{L}{T_{\mathrm{s}} - T_{\mathrm{c}} + \frac{\sigma(1-P_{\mathrm{tr}})/P_{\mathrm{tr}} + T_{\mathrm{c}}}{P_{\mathrm{s}}}} \tag{1.4}$$

where L is the data packet length, σ is the duration of a mini-slot, T_{s} is the average time interval during which the channel is sensed busy, T_{c} is the average time interval during which the channel is sensed busy by each station during a collision, P_{tr} is the probability that there is at least one transmission in the slot, and P_{s} is the probability of successful

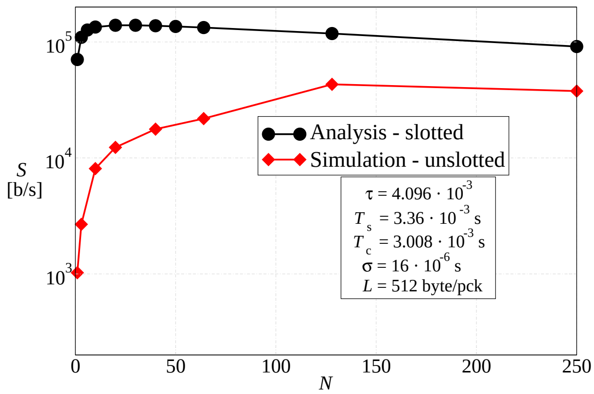


Figure 1.13. Network transmission rate, as a function of the number of RFDs, in a scenario with direct transmission to the coordinator. The results are obtained through simulation (line with squares) and analysis (line with circles). The parameters used in the simulation are shown in the figure.

transmission through the channel. In particular, $P_{\rm tr}$ can be expressed as $P_{\rm tr} = 1-(1-\tau)^N$, where τ is the probability that an RFD transmits and N is the number of nodes. The probability $P_{\rm s}$, instead, can be expressed as

$$P_{\rm s} = \frac{N\tau(1-\tau)^{N-1}}{1-(1-\tau)^N}\,.$$

Therefore, expression (1.4) for S can be rewritten as follows:

$$S = \frac{L}{T_{\rm s} - T_{\rm c} + \frac{\sigma(1-\tau)^N + T_{\rm c}[1-(1-\tau)^N]}{N\tau(1-\tau)^{N-1}}}\,. \qquad (1.5)$$

In Figure 1.13, the network transmission rate is shown, as a function of the number of nodes N, in a scenario with direct transmission from the RFDs to the coordinator. The parameters employed in the analysis are summarized in the figure. The difference between the curve obtained with the analysis (line with circles) and the curve given by the simulations (line with diamonds) can be explained by observing that the analysis is based on a slotted network, whereas the simulation corresponds an unslotted networking scenario—note that the simulation curve in Figure 1.13 is the same of that in Figure 1.4 (a) relative to the case with no router. A direct comparison of the two curves shown in Figure 1.13 shows that asymptotically (for increasing values of N) the analytical results are in agreement with the simulation results. In fact, when the offered load is high, the main difference between slotted and unslotted networks is the presence of synchronization, which, in the former case, leads to a (slight) performance improvement. In order to provide a more detailed comparison between the analytical framework and the simulation setup, we are extending the Markov chain-based approach to the CSMA/CA-based medium access technique to the case with one or more routers.

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