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TikTak: A Scalable Simulator of Wireless Sensor Networks Including Hardware/Software Interaction

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Abstract

We present a simulation framework for wireless sensor networks developed to allow the design exploration and the complete microprocessor-instruction-level debug of network formation, data congestion, nodes interaction, all in one simulation environment. A specifically innovative feature is the co-emulation of selected nodes at clock-cycle-accurate hardware processing level, allowing code debug and exact execution latency evaluation (considering both protocol stack and application), together with other nodes at abstract protocol level, meeting a designer's needs of simulation speed, scalability and reliability. The simulator is centered on the Zigbee protocol and can be retargeted for different node micro-architectures.

Keywords: WSN Simulation, Hardware-Software Co-Emulation

1. Introduction

Since the introduction of the concept of wireless sensor networks (WSNs) it appeared that, though the basic elements (nodes) are usually simple because of size and cost constraints, they can be arranged in order to interact with each other and form complex systems [1]. Due to the resulting complexity, the existence of a simulation environment becomes a more and more valuable tool in order to implement and test software/algorithms/protocols in an efficient way, saving time and money.

The particular characteristics of WSNs cause the developers to jointly face problems traditionally found in embedded systems and network programming. Seen as a stand-alone embedded system the node contains parts that require low level programming, because node firmware has to interact directly with hardware peripherals as sensors, serial ports, timers, rx/tx modems. Usually the code correctness and its performance impact can be debugged and tested only on the actual WSN hardware, because of the continuous mutual node interaction, or on an accurate hardware simulator of a single node, which interprets the code of the embedded CPU and emulates hardware reactions.

At the same time it has been clear that software development in WSNs has to consider the interactions between nodes at protocol and data communication level: data communication is rarely in the form of a single, point-to-point link and may require an accurate and extensive testing using the concepts and the tools typical of network programming (*i.e.* analysis of packets, routing, latency, etc.).

We developed our simulator in order to specifically address the problem of embedded software debug and testing, with a particular emphasis on hardware-software interactions and execution time accuracy, while at the same time allowing the simulation of large networks with acceptable speed. To the best of our knowledge, WSN simulators presently in use are vastly oriented to high level protocol emulation, which has the advantage of allowing high simulation speed, but cannot model accurately code execution at node level, since nodes are only abstract entities and actual hardware resources have not a representation within the simulation.

A survey of existing WSN simulation tools can be found in [2]. Common simulation framework are NS-2 [3], OMNeT++ [4], Prowler [5], TOSSIM [6], OPNET [7].

Generally speaking, network simulators are oriented toward an abstract view of resources and network components, which is required for fast network simulation, but the high level view may prevent the accurate simulation of node internal details, which should be tested and debugged in the implementation design flow.

As an example, NS-2 [3] is a very popular simulator based on discrete event simulation. It was written for general network protocols simulation and, in the specific ambit of wireless networks, the simulator support 802.11 and 802.15.4 type wireless MAC. However, NS-2 has no capability to model real-time OS or application code, especially regarding code execution delays. Due to its high level view, neither actual embedded code can be simulated in NS-2, making it non-useful for code test and debug.

OMNeT++ [4] is another public source, component-based network simulator that supports WSNs through extension modules. OMNeT++ can run applications written for WSN OSes, such as TinyOS [8] applications, which are converted automatically to simulator-compatible C++ code. As for NS-2, OMNeT++ cannot model OS and application layer execution time delay, neither simulate actual sensor embedded code.

TOSSIM [6] is a network simulator that is part of TinyOS [8] distribution. TOSSIM is a hardware emulator that can run actual application code, making debug possible. A limitation of TOSSIM is the assumption that all nodes execute the same code and that, in order to speedup simulation, execution time is not modeled accurately. For example, application code is assumed to be executed in zero time.

A particular note can be written on ATEMU [9], since it emulates an AVR processor and a complete hardware platform, which allow firmware test and debug (OS and application) including execution time and latency. However, the accuracy of ATEMU is achieved at the expense of high processing requirements for the simulation and poor scalability.

In this paper, we present a WSN simulation framework developed to test and debug real systems, considering both accuracy and simulation speed. The simulator can accurately emulate a hardware node, executing through interpretation the whole embedded CPU code (user code and communication protocol stack code), at cycle-accurate level. Multiple nodes can be emulated at this level while they interact each other through the presence of a communication framework that emulates the physical layer of the network, including signal attenuation and interferences/collisions between nodes. At the same time, our simulator can emulate a node at higher level of abstraction, relying on the same protocol stack, which is in this case compiled and executed natively on the host machine (we will call them the native nodes) and which runs hundreds of times faster than the interpreted one. In this way, a complex system can be emulated completely relying on the accuracy of the hardware emulator for a restricted number of nodes and on the speed of the native nodes for the remaining ones.

The remaining parts of the paper are organized as follows: Section 2 presents a general overview of our simulator and its main parts, Section 3 describes the node components (emulated hardware and native nodes), Section 4 describes the communication framework that emulates the physical layer. Finally, Section 5 shows some examples along with results and simulation speed.

2. Simulation Environment

The block diagram of the simulation environment is shown in **Figure 1**. The whole environment is written in C/C++ and compiles and runs under Linux.

A node emulator represents each physical node. The node emulators are launched as independent processes on the host machine. There are two kinds of node emulators, which are not distinguished in **Figure 1** because at this level they behave the same. The first is a hardware emulator, which can run embedded code as a real node since it contains a complete executable model of an 8-bit microcontroller and an 802.15.4 compatible hardware transceiver.

The embedded software running on the node is written in C and compiled with a cross-compiler for the embedded CPU. It is composed of an application layer that implements the node functionalities and a protocol stack, which implements the wireless protocol services and drives the emulated transceiver.

The C application code and protocol stack, compiled natively on the host machine, composes the second kind of node. The protocol stack contains some modifications with respect to the embedded one since the emulated transceiver is not present and the lower layer of the protocol stack directly interacts with the simulator communication layer.

The central part of the simulator is a communication framework which acts as an interconnection server (we will call it the PHY-server). Its main function is the sup-

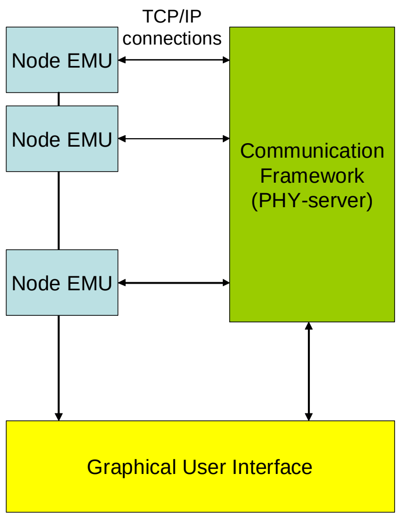


Figure 1. Simulator block diagram.

port of data communications between nodes through TCP/IP connections, emulating the physical layer of the WSN. The PHY-server is a TCP/IP server that listens for packets coming from the nodes. Each node (both hardware emulated and native nodes) creates a TCP/IP link with PHY-server as part of its initialization routines, using the connection to communicate to the central server during the whole simulation. We chose TCP/IP as communication layer considering the possibility of accelerating the simulation of large WSNs by means of distributed processing.

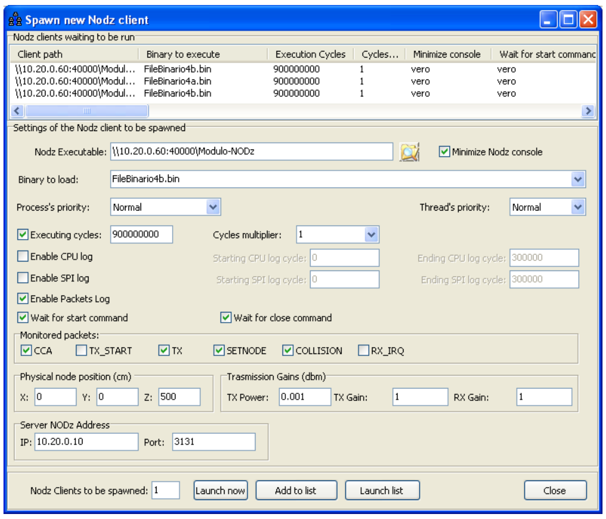
The PHY-server has also the role of simulation management since it is responsible of node creation, initialization and control.

Finally, the simulation environment interacts with the user through a graphical user interface. The GUI application, which connects directly to the PHY-server, is used to configure the WSN structure and the properties of each node (**Figure 2**). The GUI also shows, in a structured way, data produced by the simulator, as node status, the packets sent and received by each node, code execution and debug messages logging (**Figure 4**).

3. Node Simulators

3.1. Hardware Emulated Node

The hardware node is a cycle-accurate emulator of an embedded system composed of an 8-bit microcontroller and a wireless transceiver. In the present version, we implemented the emulation of a Freescale HCS08 microcontroller [10] and an MC13192 802.15.4 - compatible transceiver [11] as shown in the block diagram in **Figure 3**. The diagram closely resembles Freescale development board 13192-SARD (Sensor Application Ref-



Nodz clients waiting to be run

Client path	Binary to execute	Execution Cycles	Cycles...	Minimize console	Wait for start commanc
\\10.20.0.60:40000\Modul...	FileBinario4b.bin	900000000	1	vero	vero
\\10.20.0.60:40000\Modul...	FileBinario4a.bin	900000000	1	vero	vero
\\10.20.0.60:40000\Modul...	FileBinario4b.bin	900000000	1	vero	vero

Settings of the Nodz client to be spawned

Nodz Executable: \\10.20.0.60:40000\Modulo-NODz ✓ Minimize Nodz console

Binary to load: FileBinario4b.bin

Process's priority: Normal Thread's priority: Normal

✓ Executing cycles: 900000000 Cycles multiplier: 1

☐ Enable CPU log Starting CPU log cycle: 0 Ending CPU log cycle: 300000

☐ Enable SPI log Starting SPI log cycle: 0 Ending SPI log cycle: 300000

✓ Enable Packets Log

✓ Wait for start command ✓ Wait for close command

Monitored packets: ✓ CCA ☐ TX_START ✓ TX ✓ SETNODE ✓ COLLISION ☐ RX_IRQ

Physical node position (cm) X: 0 Y: 0 Z: 500

Trasmission Gains (dbm) TX Power: 0.001 TX Gain: 1 RX Gain: 1

Server NODz Address IP: 10.20.0.10 Port: 3131

Nodz Clients to be spawned: 1

Figure 2. GUI window, node configuration.

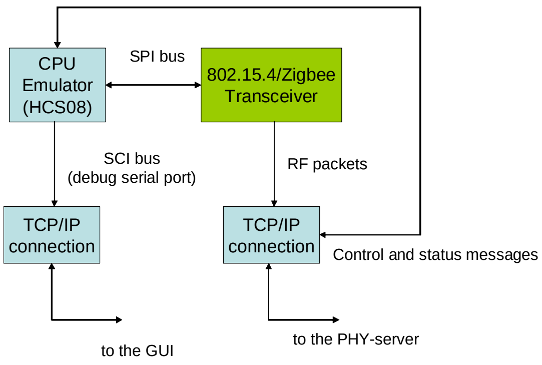
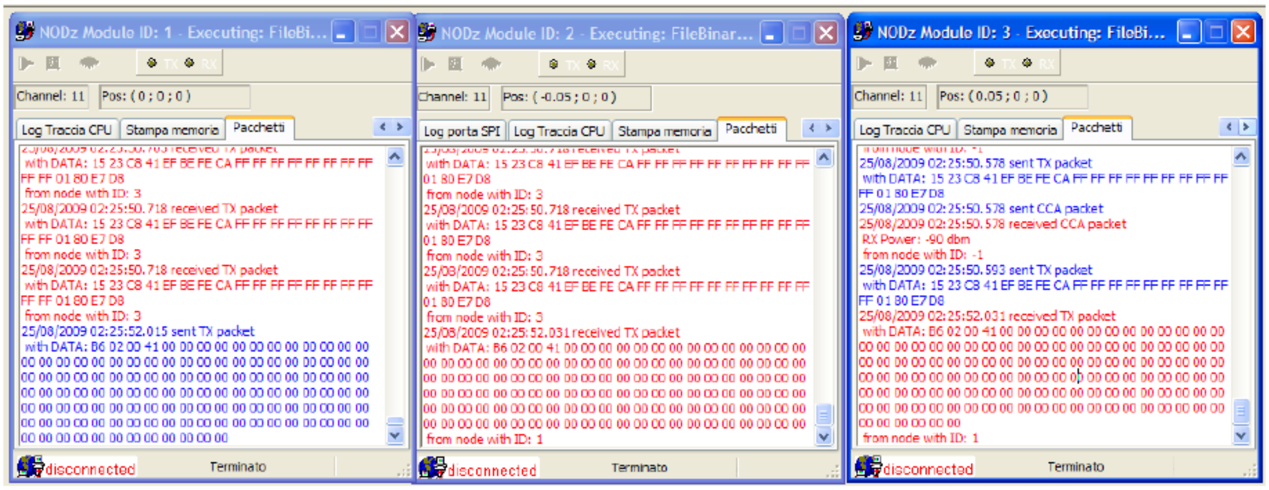


Figure 3. Emulated hardware node block diagram.

erence Design) [12].

Applications can be compiled using the IAR [13] HCS08 C compiler and can leverage on the services pro-



Channel: 11 Pos: (0 ; 0 ; 0)

```
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF
FF FF 01 80 E7 D8
 from node with ID: 3
25/08/2009 02:25:50.718 received TX packet
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF
FF FF 01 80 E7 D8
 from node with ID: 3
25/08/2009 02:25:50.718 received TX packet
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF
FF FF 01 80 E7 D8
 from node with ID: 3
25/08/2009 02:25:52.015 sent TX packet
 with DATA: B6 02 00 41 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00
```

disconnected Terminato

Channel: 11 Pos: (-0.05 ; 0 ; 0)

```
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF FF FF
01 80 E7 D8
 from node with ID: 3
25/08/2009 02:25:50.718 received TX packet
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF FF FF
01 80 E7 D8
 from node with ID: 3
25/08/2009 02:25:50.718 received TX packet
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF FF FF
01 80 E7 D8
 from node with ID: 3
25/08/2009 02:25:52.031 received TX packet
 with DATA: B6 02 00 41 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
 from node with ID: 1
```

disconnected Terminato

Channel: 11 Pos: (0.05 ; 0 ; 0)

```
25/08/2009 02:25:50.578 sent TX packet
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF FF
FF 01 80 E7 D8
25/08/2009 02:25:50.578 sent CCA packet
25/08/2009 02:25:50.578 received CCA packet
 RX Power: -90 dbm
 from node with ID: -1
25/08/2009 02:25:50.593 sent TX packet
 with DATA: 15 23 C8 41 EF BE FE CA FF FF FF FF FF FF FF FF FF
FF 01 80 E7 D8
25/08/2009 02:25:52.031 received TX packet
 with DATA: B6 02 00 41 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00 00
00 00 00 00 00 00
 from node with ID: 1
```

disconnected Terminato

Figure 4. GUI, nodes activity windows.

vided by Freescale Zigbee proprietary library [14]. The node emulator executes the same binary application code which can be loaded in the physical hardware board, since it includes the MCU peripherals (timers, UARTs, I/O, etc.) of the MC9S08GT60 MCU (the same HCS08 model of the SARD board) and the MC13192 transceiver emulator.

The simulation proceeds with cycle accuracy for the MCU and transceiver components. The transceiver operates emitting final physical layer packets to the PHY-server using a TCP/IP connection.

From the simulation environment point of view the emulated hardware node is an independent process in the host machine that interacts with the simulator through TCP/IP connections. The connections are used to transport WSN packets but also to control and configure each node.

3.2. Host Native Node

The native node was created for performance purposes and it is an abstract object composed of an open source embedded Zigbee protocol stack [15] compiled directly for the host machine (Linux). Minor modifications have been applied in order to remove compilation problems, removing the transceiver driving code and inserting code that sends the RF physical packets toward the PHY-server, by means of a TCP/IP connection.

The protocol stack acts as a library and the application code plus the protocol stack are compiled and linked before the simulation using the host C compiler (the Linux gcc compiler). The result is an executable which can run directly on the host machine and whose block diagram is represented in **Figure 5**. During the simulation each native node is launched as an independent process in the host machine, as for the emulated hardware node.

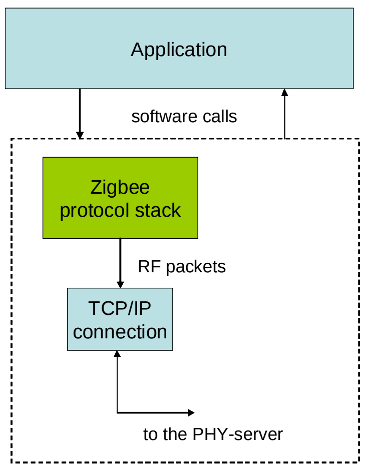


Figure 5. Native node block diagram.

4. PHY-Server

The central coordinator of the simulation is a process we call the PHY-server. A block diagram of the PHY-server is represented in **Figure 6**. We can see that it communicates with each node and the GUI through TCP/IP connections and is responsible of the following functionalities:

- It listens for commands coming from the GUI regarding node and simulation configuration, nodes position, simulation control (start, stop);
- It sets up the network creating the nodes as child processes, individually configuring and controlling them;
- It allows the nodes to exchange packets emulating the physical communications layer, including signal attenuation, noise and conflicts;
- It maintains the global simulation time progress, allowing the synchronization between nodes.

The following paragraphs will go into more details about each of the functionalities.

4.1. Node/Simulation Configuration

The PHY-server is basically a background process that waits for commands from the user by means of a graphical interface. The communication takes place through a dedicated TCP/IP connection, allowing the GUI to run remotely.

Before the beginning of any simulation, a complete network must be specified, including, at least, two nodes, a Zigbee coordinator and a Zigbee RFD. The kind of node must be selected (hardware emulated node or native node). In the first case, a binary image of the compiled embedded firmware must be supplied, which can be different for each node. In the second case, the node itself is an executable, produced as described previously in Section 3.2.

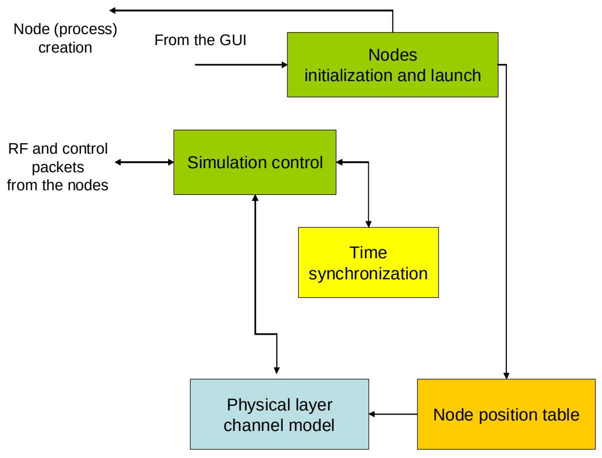

Node (process) creation
From the GUI
Nodes initialization and launch
RF and control packets from the nodes
Simulation control
Time synchronization
Physical layer channel model
Node position table

Figure 6. PHY-server block diagram.

Further information that must be supplied regards the data needed in the emulation of the physical communication layer as node position, transmission power, receiver signal threshold, background noise.

Finally, optional parameters to be specified are the set of tracing data that should be sent to the GUI. The parameters must be specified essentially for simulation time speedup, since the network simulation can include many details from the higher abstraction level (e.g. per node packet activity) to lower abstraction level (per node physical layer activity, including channel monitoring) and the details of the hardware emulated nodes (e.g. instructions trace, CPU registers state, etc.).

When the PHY-server receives a complete set of data for a node it proceeds with its creation and its inclusion in the network.

4.2. Network Setup

The network setup functionalities regard the creation of each node, its configuration/initialization and control. The PHY-server launches each new node as a process in the same host machine or on a different host machine, sending also the configuration (*i.e.* the firmware for the hardware-emulated node) to the node. As part of its initialization, each node establishes a TCP/IP connection to the PHY-server, which will be used for the emulation of the physical communication layer. Each node also establishes a direct connection with the GUI, which is used to send node activity information. In case of the hardware -emulated node, the information can include hardware details as instructions log and processor/peripheral state as usually required by an embedded system software test/ debug session.

4.3. Emulation of the Physical Communication Layer

The main functionality of the PHY-server is the emulation of the physical radio communication during the network simulation. The PHY-server maintains a list of the instantiated nodes, including their positions. During the simulation, it computes the state of the received signal for each node including the presence of a radio signal coming from a transmitting node, background noise, and interference of other transmitting nodes that are colliding with the first.

The nodes interact with the PHY-server sending both control and data packets. Control packets at the physical communication layer emulation are used to send request from the receiver (e.g. when a node turns on the receiver to inspect if the channel is occupied before transmitting) while data packets are used to send the actual physical packets to the PHY-server. When the PHY-server receives a control packet it always replies with the requested information (e.g. channel signal strength used by the node receiver to determine if the channel is free or busy).

The radio communication emulation is centralized in the PHY-server, which means that the nodes will never exchange packets directly, but only through the PHY -server. This centralized policy allows the PHY-server to log data packets for network traffic monitoring and, in case, to modify data packets (e.g. inserting controlled errors at bit level) to emulate noise and interference presence.

Effectively, when the PHY-server receives a data packet (*i.e.* a physical packet sent by a transmitter) it broadcasts the packet to all nodes. In order to test network/firmware response/robustness to packet errors, the real radio channel characteristics are emulated applying formulas for signal attenuation, background noise, interference by other nodes and computing the bit error rate for each receiver. The packets are then modified inserting random errors accordingly.

In the present version of the simulator, signal attenuation and interference are computed applying a simple free-space law, but, due to the modularity of the function, the computation could be modified or obtained from an external EM field simulator.

4.4. Simulation Time Synchronization

A critical aspect of the simulation is time accuracy and synchronization between simulated nodes. The PHY -server provides for the generation of a global simulation clock. Since a clock accurate simulation would induce excessive overhead, each node is granted a variable-length time slot, in the order of a fraction of milliseconds of simulated time. During the time slot the node can run freely, advancing its internal state. The generation of external events, such as packet transmission and RF channel monitoring causes the time slot to break prematurely and leave the control to the PHY-server. Ideally, shorter time slots should be preferred since they generate more accurate simulations, but accuracy has a trade off with simulation speed because of the overhead of the start-stop procedure, which gets more and more frequent.

5. Examples and Results

5.1. Comparison with a Physical Zigbee Network

In this Section, we show a comparison between the results obtained by our simulator and the results obtained using an actual physical Zigbee network. The nodes for the physical network are built around a Texas Instruments CC2431 Zigbee transceiver [16] using the open source Zigbee stack [15] (the same used in the simulator).

The configurations used are showed in **Figure 7**; in both cases the RFD sends a 10 K bytes data block to the Zigbee coordinator, using a direct single-hop connection (configuration I) or through a router (configuration II).

To further increment the exploration space, the packet payload size is set to three values (93, 43 and 20 bytes). The experiment is supposed to be performed in absence of interference (no packet losses in the simulator and very low losses in the real case).

Table 1 and **Table 2** show the results. The throughputs obtained by the simulator are in substantial accordance with the real case, showing a slightly higher throughput due to the complete absence packet losses in the simulator. As expected, throughput decreases when packet payload size is reduced due to the overheads of packet headers and transmission interval guards between packets.

5.2. Simulation Time and Numbers of Nodes

In this section we present the results on simulation time considering a variable number of nodes, both in terms of execution time (real time) and simulated time. The network is composed by a coordinator, a RFD node and a variable number of routers between them. The RFD sends small packets to the coordinator (ping) and wait for a reply (pong). The simulated time is maintained constant to approximately 20 s.

The results of the simulation are shown in **Table 3**, where 0 #routers means a direct connection between the RFD and the coordinator nodes. The traffic reported is the total traffic generated by the PHY-simulator on the host platform, and is composed by control, synchronization and data messages. As exposed in Section 4.4, execution time can be reduced by increasing the granularity of the synchronization events between the node simulators the central PHY-server. As an example, the time slots are increased from the 32us used in the simulation in **Table 3** to 128us, and the results are shown in **Table 4**. We can notice about a 3.6x speedup from the previous results and an analogous reduction in the traffic generated.

The two other tests we report are based on an increasing number of RFD nodes that want to communicate directly with the coordinator. The first one is a traffic-intense application, in which each node needs to transfer a block of 13 K bytes of data to the coordinator using the maximum (87 bytes) packet payload size. The network and the simulator are particularly stressed because of the high network activity.

Table 5 shows the results. Since increasing the number of nodes increases the total size of data to be transferred, simulated time gets longer and data throughput decreases due to network congestion and contention as shown by the packet error rate (PER) column. **Figure 8** shows graphically the dependence of execution time from the number of nodes. Remarking that this is a high demanding test, we can see a change in the curve slope, which generally indicates resource saturation on the

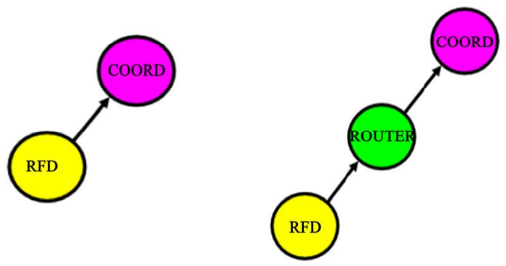


Figure 7. Configuration I (left) and configuration II (right).

Table 1. Measured vs. simulated throughput in configuration I.

Payload Bytes	Data Kbytes	Measured throughput (Kbits/s)	Simulated throughput (Kbits/s)
93	10	83	90
43	10	50	56
20	10	26	28

Table 2. Measured vs. simulated throughput in configuration II.

Payload Bytes	Data Kbytes	Measured throughput (Kbits/s)	Simulated throughput (Kbits/s)
93	10	43	49
43	10	26	30
20	10	14	15

Table 3. Execution time with 32us time slots.

# routers	Execution time (s)	Simulated time (s)	Traffic (MB)
0	80.24	20	194.99
1	125.93	20	195.04
2	167.61	20	195.43
3	207.83	20	195.32

Table 4. Execution time with 128us time slots.

# routers	Execution time (s)	Simulated time (s)	Traffic (MB)
0	22.15	20	49.35
1	33.68	20	49.37
2	45.42	20	49.40
3	58.73	20	49.55

Table 5. Simulation results – traffic-intense application.

# RFD nodes	execution time (s)	simulated time (s)	Throughput Kbits/s	PER %
1	15	1.5	70	0
2	40	2	52	2.5
3	100	2.5	42	4
4	150	3	35	6
5	200	3.5	30	7.5
6	350	4.5	23	10.5
7	550	5	21	11.5
8	1300	6.5	16	16
9	2100	7.5	14	19
10	2900	8.5	12	22
11	3700	9.5	11	23
12	4500	11	9.5	24
13	5300	12	8.5	25.5
14	6100	13	8	27

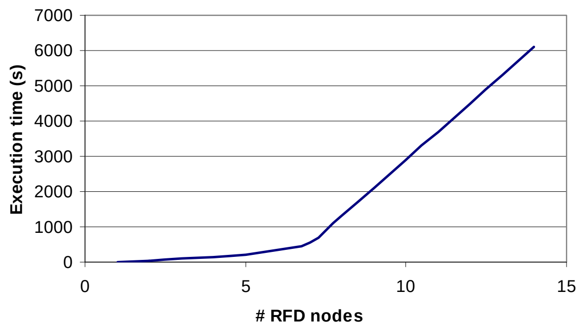


Figure 8. Execution time vs. # of RFD nodes.

simulating host machine (a standard desktop, 2 G Byte RAM, PC).

Figure 9 and **Figure 10** show the throughput and the Packet Error Rate in relation to the number of nodes. We report the test using three different packet payload sizes (87 bytes, 44 bytes and 22 bytes).

The second test is an application based on a set of nodes that send low traffic volumes (a case where the Zigbee protocol is more suited). **Figure 11** shows the transmission latency (the time difference between when a source node sends a packet and when it receives a reply from the destination) considering a variable number of nodes for the worst and average case. Since the network is not saturated, increasing the number of nodes does not increase significantly the average latency.

Secondly, the same test is repeated in presence of interfering nodes (Zigbee nodes that send data using the same channel). **Figure 12** and **Figure 13** report the results. On the x-axis is the number of interfering nodes, **Figure 12** regards the presence of a single RFD transmitting node while **Figure 13** regards the presence of 10 RFD transmitting nodes (in addition to the interfering nodes). We can notice a linear dependence of the average latency with the number of interfering nodes.

Finally, **Table 6** reports a resume of the comparison between the characteristics of our simulator and other

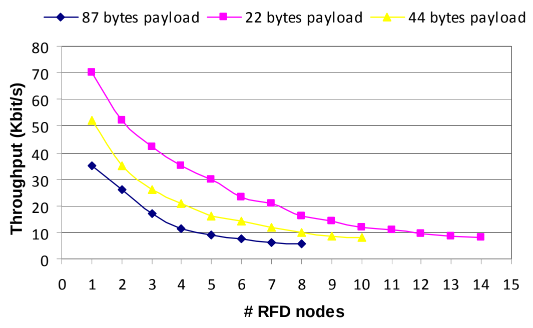


Figure 9. Throughput vs. # RFD nodes.

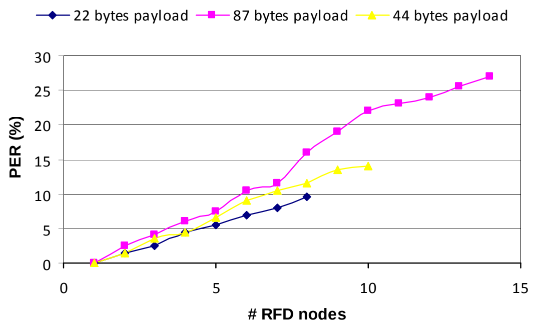


Figure 10. Packet error rate vs. # RFD nodes.

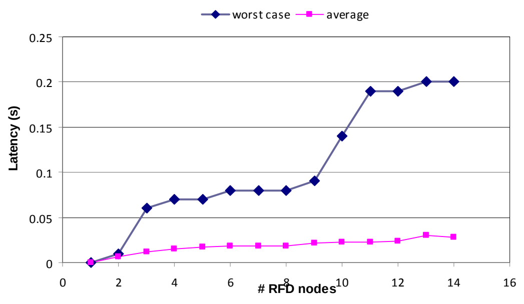


Figure 11. Transmission latency vs. # RFD nodes.

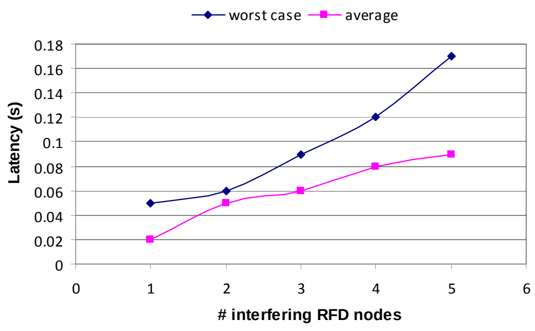


Figure 12. Transmission latency vs. # RFD interfering nodes (1 RFD transmitter).

WSN simulators presented in Section 1

6. Conclusions

We reported the structure and the results obtained by the

Table 6. Comparison between simulators.

Simulator	Supported network	Radio model	OS and SW execution time modeling	HW/SW interaction modeling	Scalability
NS-2	802.11, 802.15.4, DSDV, DSR, TORA, AODV	shadowing, 2-ray ground, free space	no	no	Yes
OMNET++	802.11	free space, 2-ray ground	no	no	Yes
TOSSIM	CSMA	probabilistic bit error	no	no	Yes
ATEMU	CSMA	free space	yes	yes	No
TikTak	Zigbee	free space, probabilistic bit error	yes	yes	Yes

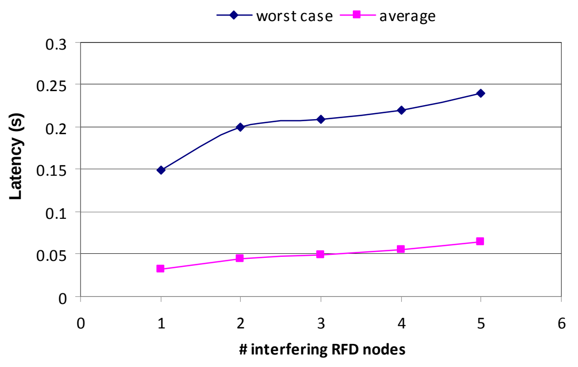


Figure 13. Transmission latency vs. # RFD interfering nodes (10 RFD transmitters).

TikTak WSN simulator we have developed. The simulator is composed in a modular way, and nodes can be emulated at two levels of abstraction. The major characteristic is the ability to simulate the program and stack latency because of low-level hardware emulation of the nodes and to allow the test and debug of embedded codes as in final application. At the same time, emulation at protocol level allows to increase the simulation speed when timing accuracy is less stringent.

The physical channel model is, at the moment, a free -space attenuation model, but the modularity allows the insertion of more elaborate models.

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