An IEEE 802.15.4 Wireless Sensor Network for Energy Efficient Buildings

Chiara Buratti, Alberto Ferri and Roberto Verdone

1 Abstract

The realisation of energy efficient buildings is a very innovative and challenging field of application for wireless sensor networks. To achieve the goal of minimising the buildings energy consumption and optimising the energy use, the deployment of sensor nodes is crucial. These sensors, in fact, could be used to measure the power consumed by the different appliances. The eDIANA project, funded by FP7 of the European Commission through the ARTEMISIA framework, is focused on this target. In this paper we consider a building composed of apartments, where a number of IEEE 802.15.4 standard-compliant sensors are distributed. Performance, in terms of packet error rate, average delays and energy consumption, is evaluated and the impact of the interferences is shown. Moreover, different network topologies are studied and compared. The aim of this study is to show the applicability of the IEEE 802.15.4 standard to the eDIANA application scenario and provide some guidelines for designing the network.

2 Introduction

In the recent years the problem of energy saving has attracted the attention of many researches in a plethora of fields. In Europe 40% of the energy is

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Chiara Buratti
WiLAB, DEIS, University of Bologna, Italy e-mail: c.buratti@unibo.it

Alberto Ferri
WiLAB, DEIS, University of Bologna, Italy e-mail: albertfe83@gmail.com

Roberto Verdone
WiLAB, DEIS, University of Bologna, Italy e-mail: roberto.verdone@unibo.it

consumed in buildings, more than by industry or transport. The tendency shows that the total energy consumption has been rising since 1990 and will continue if strong actions will not be taken.

The eDIANA (Embedded Systems for Energy Efficient Buildings) project [1], funded by the European Commission within FP7 through the ARTEMISIA framework, addresses the need of achieving energy efficiency in buildings through innovative solutions based on networked embedded systems.

The main goal of eDIANA is to achieve greater efficiency in the use of resources, prioritizing energy as scarce resource, more flexibility in the provision of resources and better situation awareness for the citizen and for service and infrastructure owners. This will be achieved through the deployment of embedded systems throughout the eDIANA environment of buildings. eDIANA is a strong application-oriented initiative which is focused on the design, development and validation of the eDIANA platform, which will integrate intelligent embedded devices, installed in residential and non residential buildings to improve energy efficiency and optimize overall energy consumption, production and storage.

The main elements of the eDIANA scenario are the cells, that could be single houses, apartments or working units, and the macro-cells, which are in general groups of cells. Each macro-cell identifies the contract with the energy service provider. Therefore, in case of apartments the cell will coincides with the macro-cell; whereas in management buildings the macro-cell will be composed of different cells, the working units using the same contract.

To handle and optimize energy use in cells and macro-cells, the knowledge, in real time, of the power consumed or produced (in case, for example, of the presence of photovoltaic panels) by every electrical appliance is fundamental. To such aim, wireless sensors could be distributed in the environment to forward the monitored data to a control unit, denoted as concentrator, in charged of optimally managing energy consumptions. The control is performed at the cell (cell-level concentrator, CLC) and at the macro-cell level (MCLC). In Figure 1 an example of management building scenario is shown.

Sensors could be also used to detect an event [2], [8]. As an example, in case a person approaches a washing machine, the concentrator could start providing energy to the machine; in this case the sensor is used to detect the arrival of a person in a room.

Such wireless sensor network (WSN) must be able to work in a fully unplanned context; all the cells need to work under a self-paradigm, and the issue of interference between separate uncoordinated cells is one of the most relevant. The WSN could be also complemented by a network using power line communication modems.

The eDIANA project started on February 2009. At the time when this paper is written, the scenario and system requirements are not fully described, and the technical solutions (e.g. air interfaces) are still to be selected. However, at the University of Bologna (one of the 22 partners, and leader of the task related to the communication network), simulation activities to determine candidate radio technologies already started. This paper reports on the current state of simulations, based on a scenario which is compliant to eDIANA structure, and the assumption that IEEE 802.15.4 will be the first candidate as air interface technology for the WSN component. The integration with the power line communication network will be considered at a later stage.

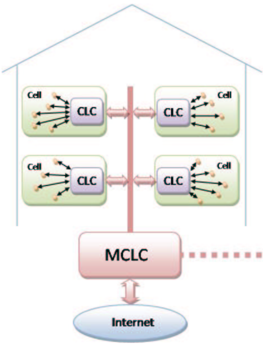

Fig. 1 The eDIANA scenario.

In this paper, we consider an apartment (a cell) and a building, composed of a number of cells (a macro-cell), where a number of sensors (hereafter denoted as nodes) are distributed in given positions. IEEE 802.15.4 standard-compliant nodes [6] are distributed and we assume that one personal area network (PAN) is formed in each cell and that the PAN coordinator is located at the CLC.

The application requires the CLC receives data measured by sensors with a given periodicity. To this aim the CLC, that is the coordinator of the PAN, periodically sends queries and waits for replies. The data measured by sensors could be a sample of power consumed by an electrical appliance, or a sample of temperature, etc. We assume that nodes use the beacon-enabled mode defined by the standard (i.e., the query coincides with the beacon packet). Nodes transmit their data via a direct link (star topology), or through a two-hop communication network (tree rooted at the coordinator). Finally, according to the standard, we assume that the different PANs work at different frequencies selected among the 16 carriers made available by the standard.

Owing to the complexity of the application, different performance should be studied. As an example, if a person approaches a washing machine for using it, the data transmitted by the sensor to allow the providing of energy to the machine should be received by the CLC with a certain reliability and with a limited delay. Also energy consumption issues are fundamental, to avoid a frequent re-charge of sensors batteries. Therefore, to evaluate the applicability of 802.15.4 to the eDIANA scenario, we evaluate performance in terms of packet error rate, average delays and energy consumption. The impact of interference on network performance is evaluated and also suitable comparison between different network topologies (star and tree) is accounted for.

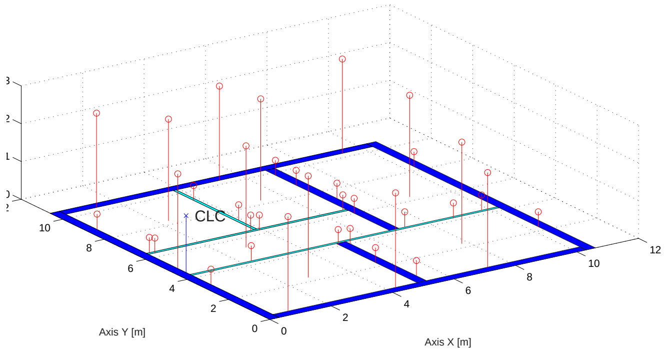

Fig. 2 The eDIANA apartment scenario considered.

3 The Reference Scenario and Channel Model

We consider an apartment and a building, composed of different apartments per floor, and possibly having different floors. In Fig. 2 the map of the single apartment is shown. One coordinator (denoted as CLC in the Figure) and 36 nodes are deployed in the different rooms. Sensors placed on the walls of the rooms are set at 0.4 m from the floor, since we assume they are located in the plugs for monitoring energy consumption. The sensors in the centre of the rooms are on the ceiling, at 2.70 m. They can be used to control the intensity of the light that could change depending on the presence or not of people in the room. Finally, nodes placed nearby the windows are at 2.50 m. The PAN coordinator is placed at 1.5 m into the electric panel of the house. Its task is to control the WSN and exchange data, via power line communication with the power meter and the cell-level concentrator of the macro-cell.

Two different kind of walls are considered: thin (0.1 m) and thick (0.3 m). Also the presence of the ceiling is accounted for.

The multi-wall channel model described in [9] is used. According to this model the loss in dB between two nodes at a distance d, is given by:

$$L = k_0 + k_1 ln(d) + N_{wt} \cdot L_{wt} + N_{wl} \cdot L_{wl} + N_c \cdot L_c \quad (1)$$

where k_0 and k_1 are two constants; L_{wt}, L_{wl} and L_c are the losses introduced by the thin and thick walls and the ceiling, respectively. N_{wt}, N_{wl} and N_c are the number of thin and thick walls and the number of ceilings between the two communicating nodes, respectively. We set $L_{wt} = 5.9$ dB and $L_{wl} = 8$ dB (see results in [9] related to 2.4 GHz frequency) and $L_c = 14$ dB [10].

For what concerns the packet capture model, we use a threshold model. We assume that a packet is correctly received when both the following conditions are satisfied: (i) $P_r > P_{r_{min}}$, where $P_{r_{min}} = -85$ dBm is the receiver sensitivity and P_r is the received power given by: $P_r[dBm] = P_t[dBm] - L[dB]$, where P_t is transmit power and L is given by eq. (1); (ii) $\frac{C}{I} \geq \alpha$, where C is the power received from the useful signal and I is the sum of the interference powers. We distinguish between co-channel (I_{co}), adjacent (I_{ad}) and alternate channel (I_{al}) interferences. I is given by: $I = I_{co} + w_{ad}\, I_{ad} + w_{al}\, I_{al}$, where the two weights are set according to the standard [6], therefore $w_{ad} = 0.44$ and $w_{al} = 0.44\, 10^{-3}$; finally, we set $\alpha = 3.5$ dB.

4 The IEEE 802.15.4

The beacon-enabled mode of the 802.15.4 is used [6]. According to the standard time is organised in a superframe structure, managed by the coordinator, composed of three parts: an inactive part, the Contention Access Period (CAP), where the access to the channel is managed through a slotted Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) algorithm and the Contention Free Period (CFP), where a maximum number of seven Guaranteed Time Slots (GTSs) can be allocated by the coordinator to specific nodes. Each superframe starts with a packet denoted as beacon, transmitted by the coordinator, which coincides with the query.

The duration of the active part and of the whole superframe, depend on the value of two integer parameters ranging from 0 to 14: the Superframe Order, denoted as SO, and the Beacon Order, denoted as BO. In particular, the duration of the whole superframe (i.e, the interval of time between two successive beacons), denoted as T_q, is given by: $T_q = 16 \cdot 60 \cdot 2^{BO} \cdot T_s$, where T_s is the symbol time, equal to 16 μsec. Whereas the duration of the active part of the superframe (composed of CAP and CFP), denoted as T_a, is given by: $T_a = 16 \cdot 60 \cdot 2^{SO} \cdot T_s$.

For the sake of conciseness we do not report the details of the CSMA/CA algorithm, but we refer to the standard [6].

An acknowledge mechanism is performed: each node, after the transmission of a packet, waits for the acknowledge packet for an interval of time equal to 54 T_s. In case the acknowledge is not received the packet is retransmitted till the maximum number of retries is reached, or the superframe ends. We assume in fact, that each node has one packet to be transmitted per superframe and in case it doesn't succeed in transmitting it correctly by the end of the current superframe the packet will be lost.

As stated above, two topologies are accounted for: stars and trees. In case of star topologies, nodes transmit their packets via a direct link to the coordinator, by using the active part (CAP or CFP) of the superframe defined by the coordinator. In case of tree, instead, the Zigbee-compliant tree-based topology is realised [3]. A tree rooted at the coordinator is formed and the inactive part of the superframe is used to allow children nodes in the tree to transmit toward the respective parents [7]. The tree-based topology and the access to the channel used in this case is described in the following.

4.1 The tree-based topology

When the number of nodes in the PAN gets larger, star topologies are not suitable and peer-to-peer or tree-based topologies should be used [3]. A three-level tree, rooted at the PAN coordinator (namely, at level zero) is considered. Level 1 nodes receive data from level 2 nodes and forward them to the PAN coordinator. The tree-based topology defined by the Zigbee Alliance [3] is accounted for.

The tree is formed according to the following procedure. The PAN coordinator sends the beacon and nodes that receive this packet could become level 1 nodes, that on their turn transmit beacon packets to allow other nodes (level 2 nodes) to join the network. To balance the number of level 1 and level 2 nodes we impose a maximum number of level 1 nodes. The maximum is set to a given percentage, denoted as p_1, of nodes in the network. This means that, being N the number of nodes in the network if the number of nodes triggered by the PAN coordinator is larger than $N \cdot p_1$, $N \cdot p_1$ nodes will be randomly selected as level 1 nodes, whereas the remaining nodes will become level 2 nodes.

According to the Zigbee specifications, nodes work in beacon-enabled mode: each child node tracks the beacon of its parent and transmits its own beacon at a predefined offset with respect to the beginning of its parent beacon. The offset must always be larger than the parent superframe duration and smaller than beacon interval. This implies that the beacon and the active part of child superframe reside in the inactive period of the parent superframe: no overlap between the active portions of the superframes of child and parent is present. This concept can be expanded to cover more than two nodes: the selected offset must not result in beacon collisions with neighbouring nodes. Obviously a child will transmit a beacon packet only in case it is a router. Each child will transmit its packet to the parent in the active part (CAP or CFP) of the parent superframe.

We assume that all the active parts of the superframes generated by the routers and by the coordinator have the same duration (i.e., we set a unique value of SO). In these conditions, assuming to allocate the first part of the superframe to the PAN coordinator (for receiving data from level 1 nodes) once we set BO, the number of level 1 routers that will have a portion of superframe available for receiving data from their children, will be equal to $2^{BO-SO}-1$ [7]. If a larger number of level 1 routers is present, some of them will not have a portion of superframe available, their children cannot access the channel and their packets will be lost.

5 Numerical Results

In this Section some examples of results that could be achieved through the simulation platform, are shown. The simulator used is written in C and results are achieved by simulating 10.000 superframes (meaning 10.000 transmissions from sensors to the PAN coordinators).

Results are obtained by setting, if not otherwise specified, $k_0 = 40$ dB, $k_1 = 13.03$, $SO = BO = 2$ and $P_t = 0$ dBm. No GTSs are used here. The scenario simulated is that of Fig. 2 when 36 nodes are present. The cases of lower number of nodes in the apartment are obtained by eliminating one or more nodes per room. For example, in case of 30 nodes, we have 5 nodes per room and we average results obtained by randomly changing the node eliminated from the different rooms.

The performance metrics considered are: (i) the average delay affecting a transmission from a node to the coordinator; (ii) the packet error rate (PER), that is the probability that a packet transmitted by whatever a node in the cell (or in the macro-cell) is correctly received by the coordinator; (iii) the average energy spent by a node per received packet.

The PER takes into consideration losses due to MAC and connectivity: a node is isolated if it does not receive any beacon coming from the PAN coordinator or level 1 nodes (in the tree topology case).

For what concerns the evaluation of the energy consumed by nodes, we assume that nodes spend energy when receive, sense the channel, transmit and do back-off. We set the energy spent to transmit a bit equal to 0.324 $\mu J/bit$; the energy spent to receive or sense a bit equal to 0.39 $\mu J/bit$ and the energy spent in back-off equal to 0.195 $\mu J/bit$. These data are taken from Freescale devices data sheets [11].

The first four Figures are related to the star topology case.

In Fig. 3 the PER as a function of the number of nodes per cell for different values of the packet size, is shown. Here we assume that nodes can perform 3 retransmissions of the same packet within the same superframe. We consider two different scenarios: one cell and two identical cells (the same of Fig. 2) put side by side. As we can see, an increment of the number of nodes competing for the channel and also of the packet size results in an increasing of the PER. Two channel selection strategies are considered: (i) each coordinator randomly selects one of the 16 available channels and results are obtained by averaging over a large number of different realisations of the frequencies choice; (ii) the two cells work on the same channel (co-channel case). As we can see, in the first case the curves for one and two cells are approximatively overlapped. Whereas, in the second case, the PER notably increases in the two-cells case. In the Figure we also show results achieved by considering a random location of the PAN coordinators in the cells (see the curve: 20 bytes, 2 cells (random coord)). By averaging results over different positions of the coordinators the PER increases, since in the previous case the coordinators were at large distance, so that less interferences were produced.

In Fig. 4 the average delay with which a packet coming from whatever a node in the PAN is received by the coordinator as a function of the number of nodes in the cell (single cell case), is shown. By increasing the packet size and the number of retries the delay increases, as expected.

In Fig. 5 we show the average energy consumed by a node in the cell per correctly received packet. This means that we average the energy spent by nodes in the cell over the number of packets correctly received. As we can see, by increasing the number of retries and the packet size the energy consumed increases. Moreover the energy consumed increased by increasing the number of sensors in the cell, since the losses increase and on average the network spend more energy per received packet.

In Fig. 6 a building formed by 8 cells, 4 cells per floor (equal to that shown in Fig. 2), is considered. Two cases of channel selection are accounted for: (i) randomly selection of channels for all the 8 cells; (ii) randomly selection of channels for the cells at the first floor and co-channel interference between cells at the two floor (i.e., a cell at the second floor uses the same channel used by the below cell). The Fig. shows the increasing of the PER due to the presence of the interference coming from the second floor.

Finally, the three-level tree-based topology is compared with the star topology. Different setting of the parameters SO and BO and p_1 are considered. In all the cases shown the tree topology improves performance in terms of PER. This is due to an improvement of the connectivity and also to the decreasing of the number of nodes competing for the channel. However, this improvement is achieved at the cost of larger delays. As far as the tree results, we can note that by increasing p_1 the PER gets larger, since increases the number of level 1 nodes competing for the channel. Moreover, performance improves by increasing BO since more level 1 routers have a part of the superframe allocated to receive data from their children.

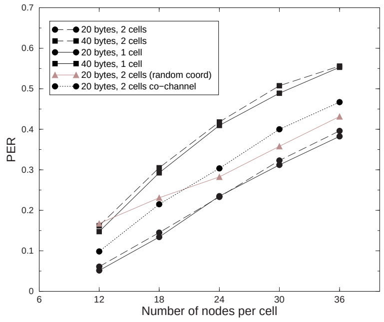

Fig. 3 The PER as a function of the number of nodes per cell, when one or two cells are present.

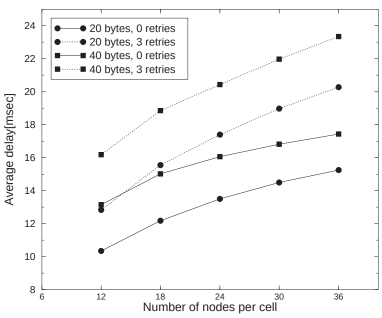

Fig. 4 The average delays as a function of the number of nodes in the single cell case.

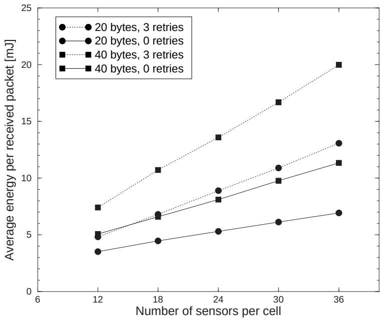

Fig. 5 The average energy spent per received packet as a function of the number of nodes in the single cell case.

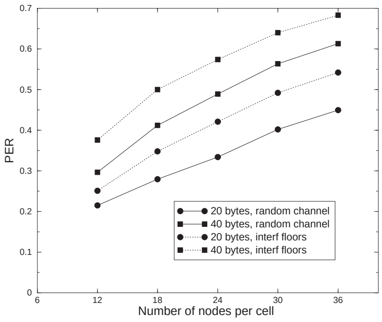

Fig. 6 The PER as a function of the number of nodes in the building case.

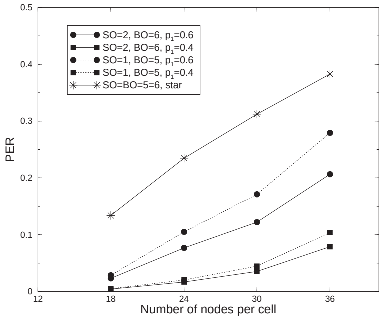

Fig. 7 The PER as a function of the number of nodes in the cell for the tree and star topology cases.

6 Conclusions

In this paper we investigate a new and challenging application scenario for WSNs: energy efficient buildings realisation. The reference scenario of the eDIANA project is reproduced and studied through simulation analysis. Results, in terms of packet error rate, average delay and energy consumption are achieved through the developed tool. These results are the first tests on the applicability of the 802.15.4 technology to the eDIANA scenario, and they represent a first step toward the implementation of the wireless communication part of the eDIANA platform.

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