

Using Radio Irregularity for Increasing Residential Energy Awareness

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Abstract — Radio irregularity phenomenon is often considered as a shortcoming of wireless networks. In this paper, the method of using radio irregularity as an efficient human presence detection sensor in smart homes is presented. The method is mainly based on monitoring variations of the received signal strength indicator (RSSI) within the messages used for the communication between wireless smart power outlets. The radio signals used for the inter-outlets communication can be absorbed, diffracted or reflected by objects in their propagation paths. When a human enters the existing radio communication field, the variation of the signal strength at the receiver is even more expressed. Based on the detected changes and compared to the initial thresholds set during the initialization phase, the system detects human presence. The proposed solution increases user awareness and automates the power control in households, with the primary goal to contribute in residential energy savings. Compared to conventional sensor networks, this approach preserves the sensorial intelligence, simplicity and low installation costs, without the need for additional sensors integration.

Keywords — Energy awareness, presence detection, radio irregularity, RSSI, smart outlets, Smart Home, Zigbee.

I. INTRODUCTION

THE evidences for climate changes due to human activities are becoming even more expressed each year. Excessive residential energy consumption obligates power plants to generate more electric energy by increasing the level of fossil fuels combustion. More energy consumed in households and industry implicates more fossil fuels to be burnt, which strongly affects the environment through carbon dioxide emission. In order to save the environment and also to save the money spent for electricity bills it is necessary to increase the energy awareness among people. An idea on how to present energy wasting to consumers is by enabling the overview of energy consumption on demand. The solution for such an approach is in the use of smart meters (smart outlets or LCD panels) which show the energy consumption of each plugged device for a specific period of time. Smart outlets

are aimed to help people live a greener lifestyle by enabling them to monitor and control the power consumption of each single device. By using smart meters, consumers are able to identify the largest energy consumers at home and change their behavior in a way that decreases their energy consumption.

In the authors' previous research, an energy saving concept implemented as the Ecosystem for Smart Home (ESH) [1] has been proposed. ESH integrates a controller device, wireless smart outlets, wireless light switches and a number of residential sensors together to a smart energy residential network. ESH is enabled for automatic energy management by interpreting various user-defined scripts given in a form of power saving schemes. By integrating sensors for human detection, the interaction with the environment is automated. The system is enabled to react by itself without the need for a user to intervene.

In this paper, the method for passive indoor human detection applied to a smart energy residential wireless network is proposed. The method utilizes only wireless nodes which are the part of existing home electrical installations (smart power outlets and smart light switches) and communication signals between them. Since human body interferes with the radio signal, irregularities in radio signature can be used as an indication of human presence within a room. Therefore, the nodes perform two tasks: (a) the power switch control of plugged devices and the electricity consumption overview; (b) human presence detection enabled by the analysis of the radio irregularities between radio transceivers embedded in wireless nodes. Presented processing algorithm for human detection is of negligible complexity compared to the conventional sensors. The proposed method increases user awareness by enabling a certain level of sensorial intelligence for automated operations with a primary goal to achieve energy savings in a household. The advantage of the proposed approach compared to the initial ESH solution is in the reduction of the number of physical devices and the elimination of additional sensors. Received signal strength indicator (RSSI) variations monitoring algorithm is, for the first time, applied solely to smart wireless power outlets by extending them to detect human presence.

The remainder of the paper is organized as follows. In Section II, related work is presented. In Section III the authors explain the method of using RSSI variations caused by radio irregularity for indoor human detection. The method is applied to the existing smart energy infrastructure, explained in Section IV, by introducing the

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level of sensorial intelligence for automated operations. The experimental results given in Section V confirm the usability of the proposed solution for human detection. At the end of the paper in Section VI, a conclusion with the proposal for future improvements is given.

II. RELATED WORK

The European Union and the European Regulators' Group for Electricity and Gas have proposed an initiative to encourage installation of smart meters in all homes across Europe during the next decade [2]. Smart meters would enable the energy to become "visible" to all consumers which can then react upon it, resulting in a higher efficiency. The global market faces large expansion of commercially available solutions for power metering. The most popular commercially available solutions in Europe such as *digitalSTROM* [3], *Plogg* [4] and *Plugwise* [5] enable control of electrical appliances by using smart power outlets. Smart outlets allow control of the plugged device's power supply, measure its power consumption and enable communication with various user interfaces. Several academia studies have also noted smart outlets as efficient devices for increasing the energy awareness and money savings [5-7]. Utility companies also benefit because smart meters will completely remove the need for manual meter reading and ensure accurate bills.

The aforementioned energy feedback solutions provide a very technical consumption overview and a reduced set of controlling commands which are dependent on user's interaction. Although users have the insight into consumption data, in many cases they take no corrective actions that would decrease the consumption. Consumers' habits on energy saving are changing very slowly. The main issue indicated in existing systems is that the energy management is based on a user's instruction, without the possibility for the system to adapt automatically. For instance, an energy saving system should be able to automatically switch off the light if no humans are present in a room for a period of time. To enable the system to react automatically, it is necessary to establish the interaction with the environment. This interaction involves a number of sensors, used mainly for human detection, that help creation of a smart home ecosystem. Conventional sensors for human and motion detection (passive infrared, 3D camera...) require additional installation procedures, costs, complex data processing and mostly, burdensome wiring interfaces [9], [10]. Therefore, in order to preserve the transparency of ubiquitous devices for interaction with the environment, another approach needs to be considered.

Technologies that would mostly influence our lives in the future should visually disappear from our environments [11]. Their usage would be effective only if they become transparent to users but always prepared to interact. In such a case, indoor wireless sensor networks (IWSN) present an acceptable solution. The performances of IWSN depend on the radio wave propagation path between a transmitter and a receiver. Unlike wired interfaces that are stationary and predictable, radio

channels are extremely random. In addition, radio propagation characteristics vary significantly especially in indoor environments where the signal can be reflected or absorbed by walls, windows, doors and furniture. The transmitted signal often reaches the receiver through more than one path, resulting in a phenomenon known as "multi-path fading". Due to such a nature of the radio signal, an acceptable solution for human presence detection would be to use the impact of a person's presence on radio signals nearby, instead of processing data read from conventional sensors.

Radio irregularity is a common phenomenon in wireless networks. It can arise from multiple factors, such as different signal radiated powers caused by hardware imperfection and different path losses in different directions of a transmitted signal. The research presented in [12] explains that the radio irregularity is mainly caused by device properties and the propagation medium. Device properties include signal-to-noise ratio (SNR), the antenna gain and type, the receiver's sensitivity and threshold and the transmitter's radiated power. Medium properties include the background noise and the environmental factors such as obstacles within the propagation medium. The variations in signal path loss can also cause radio irregularity. When the signal travels through a medium, it may be diffracted, scattered or reflected. Diffraction occurs when the signal encounters an irregular surface, such as a sharp edge. Scattering occurs when the signal propagates through a medium which contains a large number of objects smaller than the signal's wavelength. Reflection occurs when the signal during its propagation through a medium encounters an object which is larger than the signal's wavelength.

The signal variations caused by radio irregularity are even more expressed when a human body encounters the signal in its propagation path. The human body comprises bones, flesh and body liquids which can additionally absorb, diffract or reflect the radio signal. The presence of a human in the radio network results in higher signal strength variations at the receiver's input. Several studies have already confirmed higher RSSI variations of radio signal caused by humans moving within the line-of-sight path between the transmitter and receiver. The research presented in [13] reports that the shadowing effect caused by a human entering the line-of-sight path can be used for outdoor people counting mechanism. In [14], the authors proposed an intrusion detection mechanism based on radio irregularity which translates signal variations into sufficient information that corresponds to a human activity. Intruder detection method enabled by exploiting RSSI considerations, proposed in [15], confirms that a link quality indicator (LQI) has a less significant relationship with the presence of a human than the RSSI.

III. METHOD FOR HUMAN PRESENCE DETECTION

A received signal strength indicator often varies in different environments with higher or smaller variations around the mean value. The RSSI variation over a period of time is even more expressed when a human is present

within the signal's propagation path. Inside a room, the initial RSSI variation defines the interval of the initial signal strength variation (ISV). This interval is set during the system initialization phase when wireless nodes communicate with each other by exchanging the messages and values of RSSI for each communication link, making the "radio image" of the environment. During the initial phase, there are no humans inside the sensing area and the RSSI is only obstructed by the environmental and device properties. Signal strength variation in initial conditions is used to define the high and the low bounds (thresholds) of ISV. The ISV bounds are calculated based on a set of RSSI samples taken for a minute. This time interval is not strictly defined. It is recommended to be one minute and verified by the number of experiments. At least two wireless nodes with the associated control unit have to be used for system realization. The number of nodes in this research is four and the polling time of each node is 100ms. In this way the system is able to detect even a human running with the fastest known speed without unnecessary frequent polling that can bring high processing loads to the system. After the set of one-minute samples is formed, the standard deviation and the expression given in (1), which calculates the ISV bounds $Bnd_{min/max}$, are executed. ISV bounds setting algorithm is based on a comparison of differences between the mean value (\overline{ISV}) of the set and the set's min and max values ($ISV_{min/max}$):

$$Bnd_{min} = \left| ISV_{min} - \overline{ISV} \right| / \overline{ISV} \cdot 100\% , \quad (1)$$

$$Bnd_{max} = \left| ISV_{max} - \overline{ISV} \right| / \overline{ISV} \cdot 100\% .$$

The comparison of the mean value against the min/max values defines ISV bounds whereas a standard deviation is an additional control factor. These three elements together define the detection condition. Within the ISV, the RSSI can vary without a recognized detection. When a human enters the sensing area the RSSI starts to vary greatly by exceeding the ISV bounds and deviating from control factors, which results in detected presence. Two bounds are used, because the signal's nature is such that it can vary below and above its mean value. The signal deviation can vary significantly across different environments, making the definition of universal bounds difficult. That is the main argument why the bounds definition is necessary during the initial phase. Bounds are also recalculated periodically for the case of room layout change, such as positioning the furniture. During the initial phase, the RSSI deviation is very small. When a subject enters the room and obstructs one of the propagation paths, the RSSI deviation on that radio link is increased. After the subject exits the room, the recalculated signal deviation value is restored to the initial. If the subject changes the furniture layout before leaving a room, the new layout also affects the RSSI deviation. The additional software mechanism monitors the signal deviation over a period of environment changes (PEC). If the signal deviation is constant during the PEC interval but considerably higher compared to the initial phase, the system detects a room layout change and

new ISV bounds are recalculated based on the last minute of samples. The proposed concept is illustrated in Fig. 1.

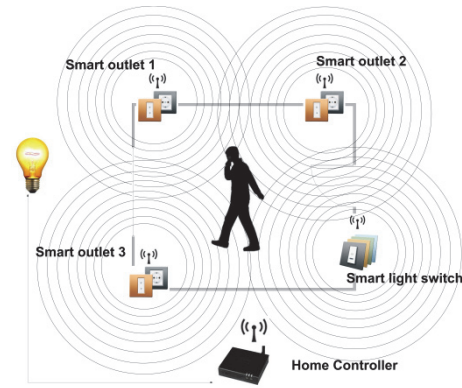


Fig. 1. Presence detection method in smart energy residential ecosystem based on radio irregularity.

IV. EXPERIMENTAL ENVIRONMENT

Implementation of the proposed method requires at least two smart wireless nodes (smart outlets or in combination with a smart light switch). The communication control, polling and the ISV analysis are implemented as modules which are part of the home controller software device (HC), explained in detail in [1]. The home controller tends to be platform independent, and currently it can easily be installed on both Windows and Linux OS platforms. HC and smart nodes communicate with each other and monitor the radio signal strength variations between smart nodes during a periodic polling. The system units preserve the main functionality, which is the energy consumption management. As the final result, the system senses the environment and enables the automatic control of plugged devices (e.g. switch off an oven or a light if a house is empty and send an SMS notification). ESH design is shown in Fig. 2.

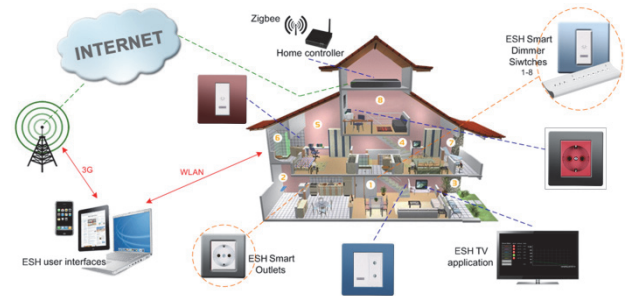


Fig. 2. Design of Ecosystem for Smart Home.

Smart outlets and smart light switches, described in detail in [1], fit into existing electrical installations, standard power sockets on the wall. The outlet provides power to electrical devices with a standard flat, two-pole AC power plug - Europlug (CEE 7/16) which is designed for voltages up to 250 V and currents up to 2.5 A. ZigBee RF transceiver CC2530 is used for the communication with HC. The transceiver comprises an RSSI status register whose value contains the signal strength in 8bit form of representation. Conversion to dBm is given by expression:

$$RSSI[dBm] = \overline{RSSI[8bit]} - 1 . \quad (2)$$

With an average current of 35 mA and an operational voltage of 3.3 V for an outlet and 2.4 V for a switch, the power consumption is 0.12 W per outlet and 0.08 W per switch. The HC software runs on a Linux based PC, using CPU Intel Atom Z530 1.6 GHz with 2 GB DDR2 RAM.

V. EXPERIMENTAL RESULTS

The system described in the previous section has been installed in two buildings whose walls were made of different materials: (a) a combination of concrete and gypsum walls with fiberglass isolation, (b) aluminum with plastic covers and fiberglass isolation. The RSSI variations in such environments and processing results are shown in the following subsections. Four nodes have been used for each experiment, three outlets and one light switch, which is the most often room electrical installations layout. In both environments, the nodes were placed at an elevation of 40 cm above the floor, whereas the light switch has been placed at an elevation of 120 cm above the floor. The results of each experiment are presented in 8-bit form and can be translated into dBm by using (2).

A. Concrete and Gypsum Walls Building

The layout of the first testing room is illustrated in Fig. 3. Red squares illustrate smart outlets positions, blue circles illustrate the subject's positions and a yellow point illustrates the central (0,0) position.

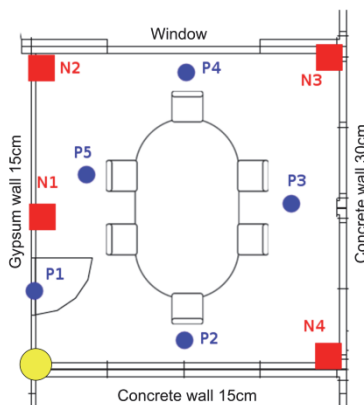


Fig. 3. The layout of the testing room (conference room) with combination of concrete and gypsum walls.

The room dimensions were 536×530 cm. The distance (in cm) of each smart node from the central position and positions of a subject are given in Table 1.

TABLE 1: NODES AND SUBJECTS COORDINATES – ROOM1.

Node	Coordinates	Subject	Coordinates
N1	(73, 211)	P1	(0, 78)
N2	(54, 477)	P2	(270, 75)
N3	(474, 428)	P3	(424, 254)
N4	(519, 66)	P4	(306, 420)
-	-	P5	(120, 255)

In Fig. 4, raw samples that present RSSI variations in the testing room obtained from smart nodes are logged and shown. Each chart shows a set of RSSI samples between one wireless outlet and others inside the room.

During the first one and a half minute, corresponding to approximately 250 samples, the room was empty. During

that period the ISV bounds were set. As it can be seen from Fig. 4 the RSSI variations on all links during the initial phase were very low, maximally $\pm 1\%$ around the mean value. After ISV bounds were set, a human was walking inside the room for one minute. From Fig. 4 it can be observed that during human's walking the RSSI varied greatly by exceeding the ISV bounds at least on one link, what was enough to detect human presence.

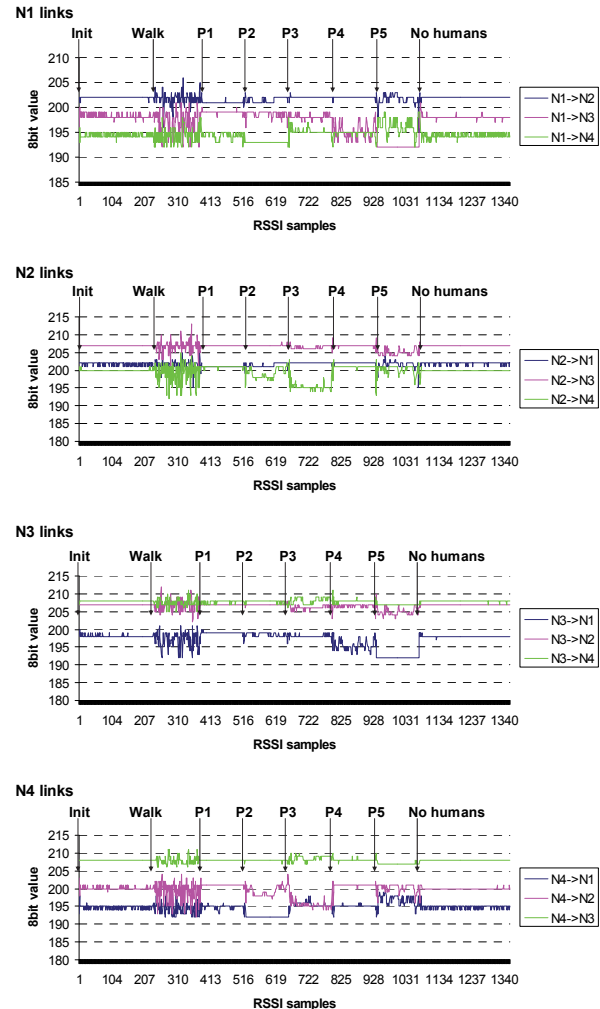


Fig. 4. RSSI variations obtained in the first testing room.

After one minute of walking around the positions $P1$ - $P5$, denoted in Fig. 4, human was standing in each position for one minute, without movements. From Fig. 4 it can be observed that in the position $P1$ the RSSI variation was the highest on the link $N1 \rightarrow N4$ in both directions. This is explained as a result of signal reflection by the human body which was very close to the line-of-sight between outlets $N1$ and $N4$. In the position $P2$, the human body shadowed the links $N1 \rightarrow N4$ and $N4 \rightarrow N1$, so the radio signal was absorbed by the human body what is the main reason for low RSSI values. In the position $P2$, the links $N2 \rightarrow N4$ and $N4 \rightarrow N2$ were distorted with the reflection by the human body; therefore the high RSSI variation in the position $P2$ for links between outlets $N2$ and $N4$ can be noticed. Also, the position $P2$ had slight influence on the links $N1 \rightarrow N3$ and $N3 \rightarrow N1$, which were distorted by the vicinity of human body that slightly reflected the signal. The human body position $P3$ mostly

absorbed the signal in links $N2 \rightarrow N4$ and $N4 \rightarrow N2$, but also reflected signals in links $N3 \rightarrow N4$, $N4 \rightarrow N3$ and $N1 \rightarrow N4$, $N4 \rightarrow N1$. Position $P4$ shadowed the links $N1 \rightarrow N3$ and $N3 \rightarrow N1$, and absorbed the signal. The position $P5$ also shadowed the links $N1 \rightarrow N3$ and $N3 \rightarrow N1$, and reflected the signal in all other links except $N3 \rightarrow N4$ and $N4 \rightarrow N3$, which were far from the human body. At the end of the experiment the room was empty again for two minutes and no strong signal variations were reported.

From the results obtained in the first testing room, the following conclusion can be derived: RSSI values for all nodes that communicate far from the human's position vary slightly or have constant values. When a human is close to a node, but not in the line-of-sight, RSSI varies greatly because of the signal reflection which is shown to be the most powerful radio irregularity feature that can report presence in this environment. When a human shadows the line-of-sight, the RSSI deviation is decreased, and the signal strength does not exceed the ISV. But, the other links whose line-of-sight is near are distorted with the reflection. It is enough that RSSI exceeds the ISV only at one link and the detection would be reported.

B. Aluminum Walls with Combination of Plastic

The second set of measurements was performed in a building whose walls were made of aluminum and plastic slices with fiberglass isolation. Room dimensions were 960×580 cm and the wall thickness was 30 cm from all sides. Red squares illustrate nodes positions, blue points the subject's positions and a yellow point illustrates the central position. The room layout is shown in Fig. 5.



Fig. 5. The layout of the testing room (classroom) with combination of plastic slices and aluminum walls.

The distance (in cm) of each node from the central position and subject's positions are given in Table 2.

TABLE 2: NODES AND SUBJECTS COORDINATES – ROOM2.

Node	Coordinates	Subject	Coordinates
N1	(410,530)	P1	(220,305)
N2	(600,530)	P2	(410,305)
N3	(795,40)	P3	(500,150)
N4	(410,40)	P4	(690,150)
-	-	P5	(945,305)
-	-	P6	(955, 500)

This environment is interesting because of the wall's structure, which forms a Faraday's cage; therefore the signal is strongly reflected by the wall. From the initial samples shown in Fig. 6 it can be noticed that the signal strength varies even in an empty room, so values for ISV bounds are higher than bounds in the previous building.

The test scenario was slightly different from the previous scenario. The room was empty for a period of two minutes, and no detection was reported. Once a subject entered the room, he was standing in each position $P1$ - $P6$ from Fig. 5 for one minute without movements. After samples from all positions were collected, the subject performed one minute walking within the room by passing the positions $P1$ - $P6$. The logged samples of RSSI variations retrieved from each node are shown in Fig. 6.

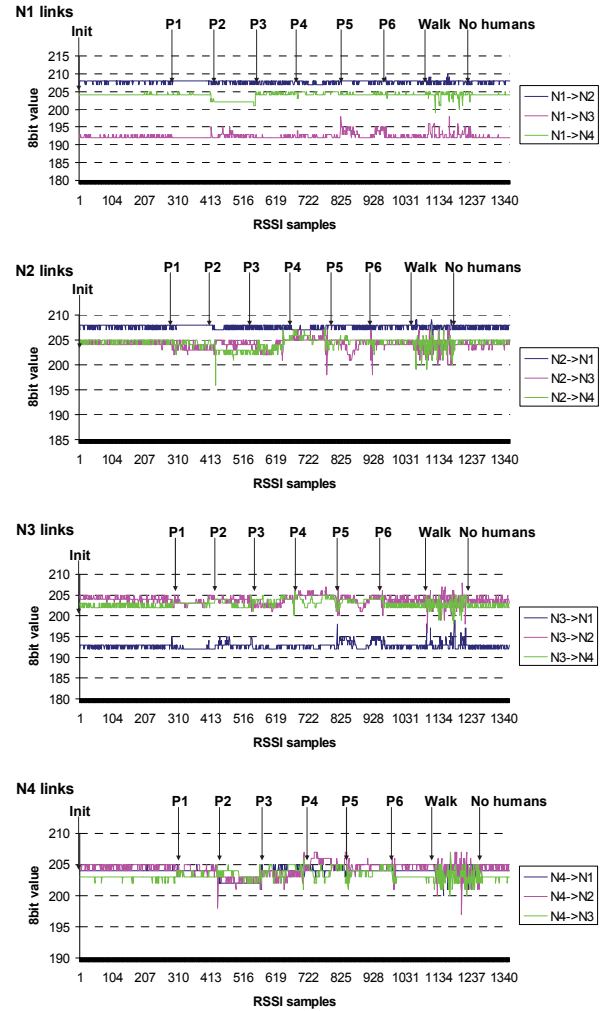


Fig. 6. RSSI variations obtained in the second testing room.

From Fig. 6 it can be observed that in the position $P1$ the RSSI variation was low or similar to the initial state (empty room) for all links. This is explained as a result of strong signal reflection by the wall combined with the human body which was close to the $N1$ and $N4$. In the position $P2$, the human body shadowed links $N1 \rightarrow N4$ and $N4 \rightarrow N1$, so the most of the radio signal was absorbed by the body which was the main reason for lower RSSI values. The position $P2$ had a slight influence on links $N1 \rightarrow N3$, $N3 \rightarrow N1$, $N2 \rightarrow N4$ and $N4 \rightarrow N2$, which were distorted by the vicinity of the body which slightly reflected the signal. The human position $P3$ reflected signals between nodes $N2$ and $N4$ and also reflected signals from links $N2 \rightarrow N3$, and $N3 \rightarrow N4$ in both directions. Position $P4$ strongly reflected signals from links between nodes $N2$ and $N4$, and also $N3$ and $N4$. The

position $P4$ slightly absorbed signals between nodes $N2$ and $N3$. The position $P5$ showed RSSI variations on links between nodes $N1$ and $N3$, which is most probably because of the signal reflection by the wall and the human body which were close to each other. A strongest impact on the signal strength in the position $P5$ was noticed for the links between nodes $N2$ and $N3$. The position $P5$ reflected the signal, and combined with the wall's reflection, increased the RSSI variation. The position $P6$ which was the furthest position from all nodes, showed very low signal strength variations. The system did not detect a subject standing in the position $P6$ - "blind position". Since the room was large, during nodes positioning installers did not keep in mind to cover all "blind positions". Therefore, for larger rooms the installers should consider installing more outlets for better radio coverage, which is usually the case for larger rooms. At the end of the experiment the subject was walking around the room, trying to pass closer to nodes $N2$, $N3$ and $N4$, and radio links therein, without obstructing the line-of-sight between nodes $N1$ and $N2$. After one minute of walking, the room was empty. From Fig. 6 it can be observed that the wall reflection and human body reflection mostly affected signals in this environment.

C. Smart Power Management

The presented human detection method implemented for residential smart energy management was analyzed in the experiment of controlling 5 bulbs of 100 Watts in a house. The regular control included the worst case when a user left a light on, after leaving a room. The presented solution applied to ESH switched off the light automatically after 10 seconds if no humans were detected within a room. In Fig. 7 the achieved power savings in the testing house (110m²) applied to lighting control are shown. The test has been performed during one working day with a four-member family. Test subjects performed normal activities at home, trying to manually save the electric energy by manually switching off the lights in empty rooms. In each room one lamp was plugged to a smart power outlet and another one to a standard power outlet. Smart power outlets were under ESH switch control, whereas standard power outlets were under manual control. Lamps plugged into smart outlets were initially dimmed by 10%, which was imperceptible for family members, but had an impact on overall power consumption. These two approaches have been compared and the energy consumption used for lights was lower by 1280 Watts to 690 Watts.

VI. CONCLUSION

The proposed human presence detection method is based on radio irregularity caused by the shadowing effect between stationary wireless power outlets where radio signal's propagation line-of-sight is obstructed by a human body. The usage of radio irregularity as a reliable method for human presence and motion detection extends the network of smart outlets with the sensorial intelligence which can be used to make the system able to respond automatically. The authors also showed that a smart home

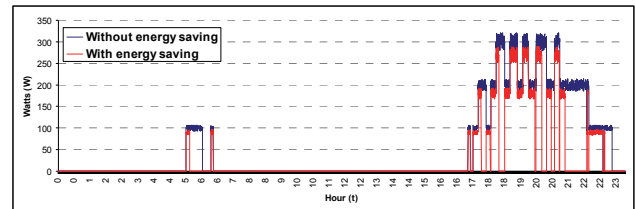


Fig. 7. Energy savings in the household - lights control.

system can be extended with the level of sensorial intelligence without additional sensors and complex processing algorithms. Presented solution utilizes existing electrical installations elements and radio communication signals among them to reduce energy wasting. Authors believe that this idea will encourage other manufacturers to apply the presented approach to their smart meters and help the global awareness on energy saving.

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