A Human Detection Method for Residential Smart Energy Systems Based on Zigbee RSSI Changes

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Abstract — *In this article, the device-free human presence detection method based on radio signal strength variations is proposed. The method exploits the known fact that human body interferes with radio signals by causing fading and shadowing effects. Introduced irregularities in the radio propagation pattern indicate possible presence of a human. The proposed method is incorporated into the existing platform for intelligent residential energy management. As opposed to conventional solutions which utilize a complex set of sensors for human detection, the proposed approach achieves the same only by analyzing and quantifying radio signal strength variations incorporated in messages exchanged between 2.4 GHz radio transceivers. One of the key benefits of the proposed solution is the integration of the detection algorithm into the smart power outlets and smart light switches. Such an approach improves interactions in smart home systems, enables intelligent power consumption management and low installation cost*[1].

Index Terms — Object detection, RF signals, sensorless control, wireless sensor networks.

I. INTRODUCTION

Radio signal propagation characteristics are significantly versatile across different environments, especially indoors, where the signal can be absorbed, reflected, scattered or diffracted by many objects in its propagation path, as explained by Ababneh [1] and Zhou *et al*. [2]. At microwave frequencies, absorption by molecular resonance is a major factor affecting the radio propagation (Youssef *et al*. [3]). Therefore, the presence of a human subject within the wireless network range results in significant signal strength variations at the receiver input, whereas the degree of variations is correlated with the level of human motion. Due to the nature of radio signals, an approach for human presence detection would be to use the impact of a human body on radio signal's propagation characteristics.

Wireless sensor networks play an important role in smart home environmental challenges. Some of the smart home systems, such as [4]-[7], combine human presence detection sensors with power outlets, in order to provide the interactivity and energy savings in smart homes. The authors of this paper extended the existing smart energy setup to detect irregularities in the radio propagation patterns for the purpose of human presence detection. The proposed method was motivated by a need to decrease the installation complexity and development costs of a system which incorporates specific human detection sensors. As opposed to conventional smart home solutions, the proposed presence detection is performed without additional sensors, only by analyzing and quantifying Received Signal Strength Indicator's (*RSSI*) variations at the inputs of 2.4 GHz (*Zigbee*) radio transceivers embedded in wireless nodes. RSSI is the most commonly used signal characteristic, as it is much easier to estimate by the receiver than Time of Arrival (*ToA*) or Angle of Arrival (*AoA*) which require specialized hardware.

Wireless smart power outlets and light switches from the pre-installed residential electrical installations, used in the proposed solution, are described in the previous work [7]. The firmware of the power outlets and light switches is extended for providing the RSSI values on demand, which enables them to be used as invisible sensors in many applications for smart homes, from surveillance to energy saving. By incorporating the proposed algorithm, smart outlets and light switches detect human presence without decreasing the quality of the regular communication used for energy-monitoring related operations.

The paper is structured as follows. In Section II an overview of device-free methods for human presence detection is given. The proposed method is explained in Section III. In Section IV, the ecosystem for smart home (*ESH*) which applies the proposed method is described. Experimental results are given in Section V. The paper concludes with Section VI.

II. RELATED WORK

The use of the shadowing effect, caused by a human subject moving within the line-of-sight path between the transmitter and the receiver, for human presence detection is proposed by Woyach *et al*. [8]. That approach, mainly based on RSSI variations monitoring at the receiver, has been extended by Puccinelli *et al*. [9] for outdoor people counting mechanism. The feasibility of intrusion detection based on the signal strength variations in wireless sensor networks (*WSN*) has been investigated by Lee *et al*. [10]. The authors have succeeded to characterize the signal strength variations and to translate them into sufficient information that corresponds to human activity. Significant signal strength variations based on

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a human's movement are confirmed experimentally and the presented idea is extended for an indoor automated people counting mechanism [11]. Intruder detection method [12], enabled by exploiting RSSI measurements, confirms the hypothesis that irregularities in the RSSI signature can be used as human presence indication. Through distributed processing of RSSI samples, nodes deployed in an indoor environment can also detect human presence and possibly help in localization and tracking of moving individuals, as shown by Kaltiokallio *et al*. [13]. The use of RSSI variations due to radio irregularity for security threats detection alongside a roadway demonstrates the ability of applying passive WSN for the outdoor surveillance (Puzo *et al*. [14]). Patwari and Wilson [15] explained how multi-path fading can be used in device-free localization systems. In such systems, a human position can be inferred by measuring the absorption, reflection, scattering and diffraction of electromagnetic waves, intersected by a human body. Device-free human localization in indoor environments using "RF sensor networks" is the topic of several researches [16]-[19]. The phrase "RF sensor network" comes from the fact that the wireless network itself is the sensor, using RF signals to probe the environment. Device-free localization is a method in which a human does not need to carry any form of wireless transceiver to be detected.

Compared to existing work, this paper focuses on a device-free human presence detection algorithm designed for the residential smart energy system, based of smart power outlets and light switches (smart nodes). In order to make the system reliable and cost-effective, solution-specific human detection algorithm and the smart nodes firmware have been implemented, as described in the following sections.

III. Human Presence Detection Method

The proposed algorithm for human presence detection enables the ESH to be always aware of human presence or motion. ESH is based on wireless 2.4GHz (*IEEE 802.15.4*) smart outlets and light switches which are controlled by the home controller device. Main advantages of the presented solution are: (1) the reduction of required number of physical devices and the elimination of additional sensors solutions (such as presence sensors or RFID tags); (2) the RSSI monitoring algorithm applied solely to the smart electrical installations is used to increase the interaction with the environment. By analyzing RSSI variations of the messages exchanged between nodes, the system can generate a functional status, dependent on people entering or leaving the room. The proposed method is mainly based on the shadowing effect between stationary wireless nodes which line-of-sight is obstructed by a human body, as illustrated in Fig. 1.

RSSI often fluctuates in different environments with higher or smaller variations around its mean value. However, RSSI variations over a period of time significantly increase in the presence of a human. When nobody is present in a room, the initial RSSI variations enable the definition of the interval of initial signal strength variations (*ISV*). ISV is set during the system initialization by analyzing the exchanged messages and RSSI samples for each communication link that create environmental "radio image". During the initialization, there are no humans in the room and the RSSI is affected only by environmental and device's properties.

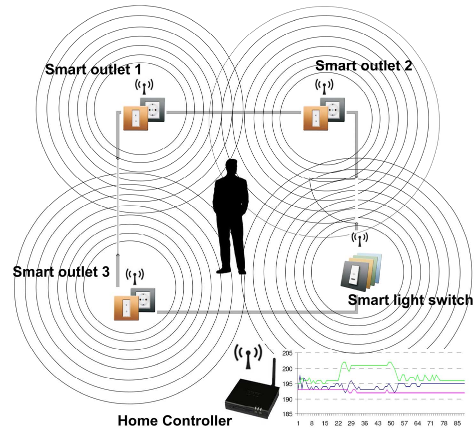

Fig. 1. Human presence detection concept based on wireless smart outlets and light switches utilization, supported by the analysis of RSSI variations within the exchanged communication messages.

The RSSI variations analyzed during initial conditions are used to define the high and low ISV thresholds. The thresholds are defined by using a set of RSSI samples taken within a predefined time interval. The duration of the interval is empirically defined and verified by a number of experiments to be one minute. At least two wireless nodes with the associated control unit are used for the system realization. The home control unit (*HC*) is implemented as a software module for managing the control message flow and monitoring the RSSI variations between the nodes. As the final result, the HC is able to control any appliance connected to smart outlets through on/off switching. The number of nodes used for this research was 4 and the polling time of each node was 100ms. This way the system was able to detect a human which runs at the fastest running speed without unnecessary frequent polling that increases the system processing load.

Smart outlets, smart light switches and the HC incorporate specific software for initial signal strength measurements *Po* in order to define thresholds *Th1* and *Th2*. The initial signal strength measurements for each node and thresholds setting for the time period *t* are calculated during the start-up phase. Taking into account the attenuation factors of distance *Pd* and spatial obstacles *Pa*, the signal strength variation *ΔRSSI* can be calculated as:

$$\begin{aligned} \Delta RSSI &= P(t+1) - P(t) \ , \\ P(t) &= Po - Pd\,(t) - Pa\,(t) \ , \\ P(t+1) &= Po - Pd\,(t+1) - Pa\,(t+1) \ , \\ \Delta RSSI &= \begin{Bmatrix} presence & , \Delta RSSI > Th2 \vee \Delta RSSI < Th1 \\ nopresence & , Th1 < \Delta RSSI < Th2 \end{Bmatrix}. \end{aligned} \tag{1}$$

The received power (Pr) is directly affected by the transmitted power (Pt). According to Friis' free space transmission equation, the signal power at the receiver input is decreased quadratically with the distance from the transmitter. Therefore, the distance attenuation factor Pd can be approximated with:

$$\Pr = \left(\frac{1}{d}\right)^2 \cdot Pt \cdot Gt \cdot Gr \cdot \left(\frac{\lambda}{4\pi}\right)^2, \qquad (2)$$

where Gt and Gr denote gains of the transmitter's and the receiver's antenna, λ is the wavelength and d denotes the distance between the transmitter and the receiver.

The obstacles attenuation factor Pa can be calculated as signal losses introduced by walls, when traversing the direct propagation path:

$$Pa = \sum_{i=1}^{N} k_i \cdot l_i \ , \qquad (3)$$

where k_i denotes the number of penetrated walls of type i and l_i denotes the attenuation due to the wall of type i.

During the start-up phase, the ISV high and low thresholds are determined as:

$$\begin{aligned} Th1 &= \left(\left|\Delta RSSI_{\min} - \overline{\Delta RSSI}\right| / \Delta RSSI_{\min}\right) \cdot 100\,\% \ , \\ Th2 &= \left(\left|\Delta RSSI_{\max} - \overline{\Delta RSSI}\right| / \Delta RSSI_{\max}\right) \cdot 100\,\% \ , \end{aligned} \qquad (4)$$

where $\Delta RSSI_{min}$ and $\Delta RSSI_{max}$ denote minimal and maximal values from the set of samples, and $\overline{\Delta RSSI}$ denotes the mean value of the $\Delta RSSI$. Within the ISV, the $\Delta RSSI$ can vary, but the presence of a human subject will not be reported. When the human subject enters into the sensing area $\Delta RSSI$ variations are stimulated to exceed the predefined ISV thresholds, resulting in the detected presence. $\Delta RSSI$ varies significantly across different environments, making the definition of universal thresholds difficult. Therefore, the adaptive ISV thresholds definition is necessary during the initial phase.

Thresholds are recalculated periodically, after the layout of objects (such as furniture) in the room is changed. The signal strength deviation δ is calculated over a set of one minute sliding window of RSSI samples by:

$$\delta = \sqrt{\frac{1}{n}\sum_{i=i}^{n} (RSSI_i - \overline{RSSI})^2}\,, \quad \overline{RSSI} = \frac{1}{n}\sum_{i=1}^{n} RSSI_i \ . \qquad (5)$$

During the initial phase, the signal strength deviation is very low. When a human enters the room and obstructs one of the propagation paths the RSSI deviation on that radio link is increased. After the human leaves the room, RSSI variations are decreased to minimal values. If the human moves an object (such as a chair) before leaving a room, the signal deviation becomes slightly increased. The additional software mechanism is implemented to monitor the dynamic of the signal strength deviation over a period of environmental updates (*PEU*). If the signal deviation is constant during the PEU interval, regardless of the initial value, the room layout change is recognized and new ISV bounds are automatically recalculated, based on the last sampling minute.

IV. System Design for Human Presence Detection

The proposed method for human detection is applied to the smart energy residential system [7], shown in Fig. 2.

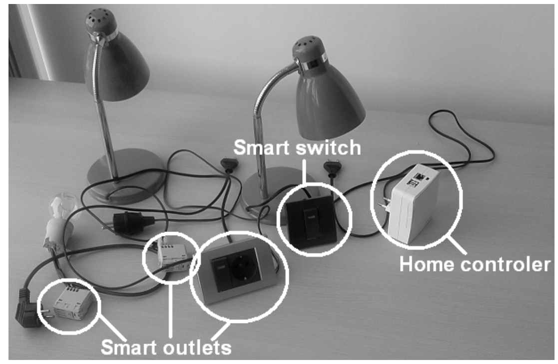

Fig. 2. ESH smart outlets, smart light switch and the home controller.

The ESH is composed of the home controller and a number or smart power outlets and light switches. The communication control, periodic polling mechanism and the RSSI data sets analysis are implemented within the core modules of the home controller. HC (illustrated in Fig. 3) is made as the software module based on POSIX/C open standards which provide scalability. The software is platform independent and can be easily ported to various POSIX-based target controllers.

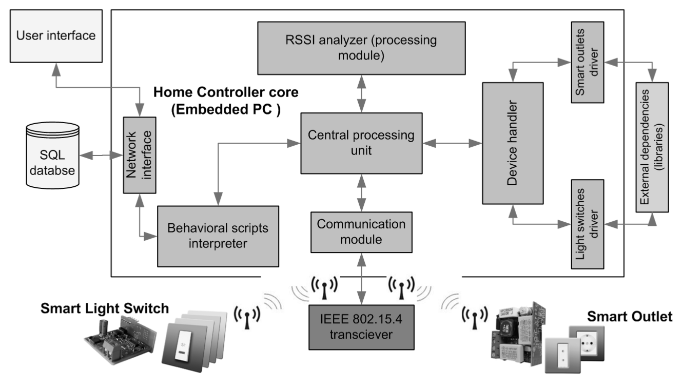

Fig. 3. Home controller software design overview.

The device handler is connected to device drivers units, providing a communication mechanism with the nodes via the central processing unit. The communication module is in charge of sending control messages as responses to detection events. The RSSI analyzer is used for periodic polling of the smart nodes, in order to retrieve the current RSSI values. The list of nodes' addresses is accessible by the RSSI analyzer. The nodes are polled every 100ms, whereas the received values are stored in the local database.

After the node receives the polling command from the HC, its RSSI vector is sent as a broadcast message. The message contains a set of RSSI samples toward all other nodes. When one node is polled, other nodes are in the "listening" mode. Therefore, there is no interference or superposition between their radio signals. The broadcasted message is received by the controller and other nodes, enabling them to update their RSSI vectors with the values of signal strength from that link. After the message is received, the values are stored in the local database, whereas the RSSI analyzer is suspended to wait another 100ms for the subsequent node polling. The procedure is repeated until all nodes provide their RSSI values corresponding to all links. After the RSSI matrix is completed, $\Delta RSSI$ and the signal strength deviation δ are calculated by (1) and (5) respectively. After the thresholds are defined, the polling procedure continues obtaining new samples which are compared with the ISV thresholds. If resulting samples exceed the ISV thresholds, the presence of a human is recognized. Otherwise, no human is detected.

The concept of behavioral patterns, proposed by Bjelica *et al*. [20], enables the ESH to be used for various setups related to the environment. Behavioral patterns are given in the form of XML scripts which define timely actions and reactions to external events, such as human detection, with the primary goal to achieve desired interactive environment. The script interpreter module (depicted as a block in Fig. 3) is responsible for the script execution and interpretation. The proposed algorithm can be easily integrated into wireless home power management systems and other similar solutions, by extending their original purpose with the detection capability.

Smart power outlets and light switches fit into existing electrical installations on the wall. Smart power outlet provides power to electrical devices with standard flat, two-pole AC power plug (*CEE 7/16*) which is designed for voltages up to 250V and currents up to 2.5A. Besides simple on/off switching, smart sockets are able to pass any percentage of power to the consuming electrical device (e.g. light dimmer). *IEEE 802.15.4* transceiver (2.4GHz) is used as the communication module. Smart outlets are powered from 220-240Vac (±10%), 50Hz current electric power supply. It is an inexpensive and the safest way to provide full compatibility with the regulatory requirements. With an average current of 35mA and operational voltage of 3.3V for an outlet and 2.4V for a switch, the power supply consumption is 0.12W per outlet and 0.08W per switch.

The smart outlets and light switches incorporate specific firmware which is implemented to enable: (1) the access to the consumption overview on demand, (2) switching the plugged devices on or off, and (3) the probe of the environment by broadcasting RF messages to the neighboring nodes. The firmware modules are illustrated in Fig. 4.

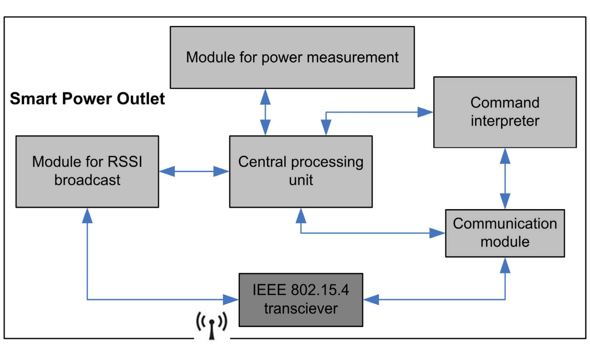

Fig. 4. Smart power outlet and light switch firmware design overview.

The module for power measurement periodically provides its current RSSI samples to the HC. The power consumption on daily, weekly and monthly basis are calculated by the HC, and stored into its local database. The module for RSSI broadcast, which is the extension of the original firmware, waits for an event from the HC which actuates the message broadcasting. The same module receives broadcasted messages from other nodes during the polling cycle. Command interpreter executes commands received from the HC, such as dimming control, switching the plugged device on or of, etc.

V. Experimental Results

The system described in Section IV was installed in two buildings, with walls built of different materials: (a) a combination of concrete and gypsum walls with fiberglass isolation, (b) aluminum walls with plastic covers and fiberglass isolation. Four nodes were used for each experiment, three outlets and one light switch, placed at an elevation of 40 cm (outlets) and 120 cm (switch) above the floor.

The testing room built of concrete and gypsum walls (further referred to as *R1*) was 536×530cm, whereas the room built of aluminum and plastic walls (further referred to as *R2*) was 960×580cm large. Layouts of test rooms and the positions of a human subject (shown as points *P1-P5* in *R1*, apropos *P1-P6* in *R2*) and nodes positions (shown as squares *N1-N4*) are illustrated in the Fig. 5.

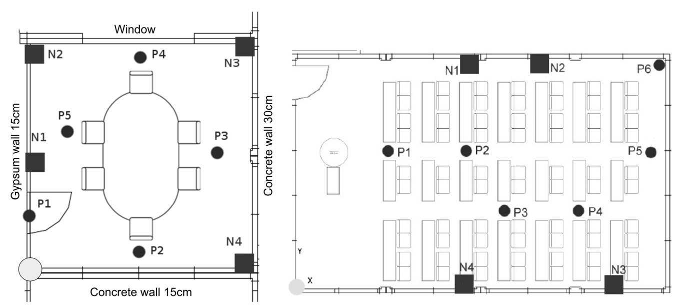

Fig. 5. Layouts of the test rooms. Left – the room *R1* is made as a combination of concrete and gypsum walls. Right – the room *R2* is made of aluminum-plastic walls. Points (marked with *Pn*) show human's positions, whereas nodes are marked with symbols *N1-N4*.

The test scenario for *R1* was the following: no humans were present in the room for a period of two minutes, therefore no detection was reported. Once a human subject entered the room, he walked around the room, passing the positions *P1-P5*, shown in the Fig. 5 - left. After a minute of walking, the human subject was standing in each position for a minute, without movements. The scenario was defined to investigate the hypothesis whether is possible to detect and distinguish between human motion, human presence and human absence in the room.

An example of RSSI variations pattern in *R1* is shown in the Fig. 6 for the links *N3→N1*, *N3→N2* and *N3→N4*. Mainly because of the human body's absorption and reflection effects, the variations in RSSI patterns were quite satisfactory for accurate human presence detection.

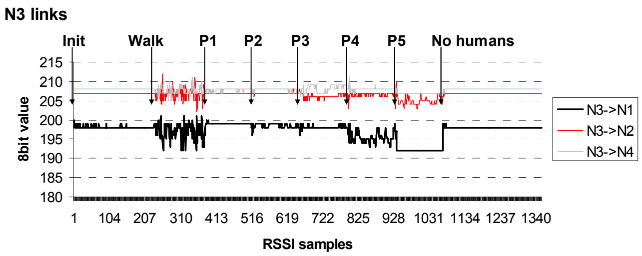

Fig. 6. RSSI samples observed in the first experimental room (*R1*).

The conclusions from the first experiment are as follows: (1) RSSI for wireless nodes which communicate far from the human, varies slightly or has a constant value; (2) when the human is positioned closer to a node without obstructing the line-of-sight, RSSI varies significantly (the larger variation is the consequence of signal reflections); (3) when the human obstructs the line-of-sight, the RSSI is attenuated and the lower ISV threshold is exceeded. It is sufficient to exceed the ISV only on one link and the detection would be reported.

The second experiment was performed in a building whose walls were built of aluminum and plastic slices isolated with fiberglass. The layout of *R2* is illustrated in Fig. 5 - right. The squares indicate nodes (counting from *N1* to *N4*), whereas the points (*P1* to *P6*) indicate human subject's positions.

The test scenario was slightly different from the scenario explained in the previous experiment. Initially, no humans were present in the room for a period of two minutes, and no detection was reported. Once a human entered the room, he was standing in each position *P1-P6* for a minute without movements. After the RSSI samples were collected, the human walked for a minute, passing the positions *P1-P6*. An example of the collected RSSI samples that correspond to links *N3→N1*, *N3→N2* and *N3→N4* is shown in the Fig. 7.

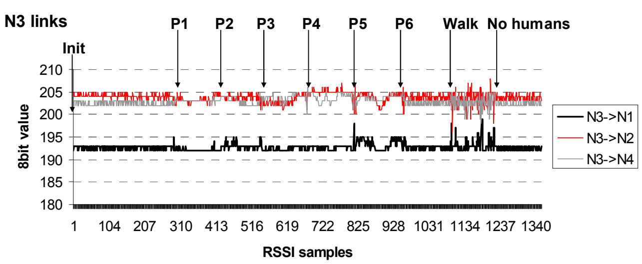

Fig. 7. RSSI samples observed in the second experimental room (*R2*).

Starting from the initial samples it can be noticed that the signal strength varies even if no human is present. The wall structure in *R2* formed a Faraday's cage and the signal was reflected by the walls. Therefore, the signal strength deviation is higher than the deviation measured in the previous experiment, but is adequate to detect and differentiate between human presence and human motion from the empty room. At the end of the experiment the human subject was walking around the room, causing higher RSSI variations. After one minute of walking, the human subject left the room. The room was empty again, as it was at the beginning of the experiment, but only for a minute.

The conclusion from the second experiment is slightly different from the previous one. Although the initial radio map was disturbed in this environment, because the wall reflections were interfered with the reflections caused by the human body, human presence and motion were successfully detected for most of the positions. Human absence was also recognized.

The experiments confirmed that certain positions in large rooms, such as the *R2*, can be out of the detection range (*P6*). The detection accuracy of the proposed method was around 84%, in total. For standard room dimensions, such as the *R1*, the detection accuracy was around 98%, in total. The detection accuracy for both experiments is shown in Fig. 8.

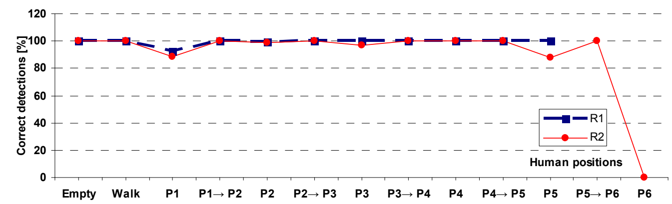

Fig. 8. Human presence detection accuracy for both experimental scenarios presented for each subject's position and transition.

As shown in Fig. 8, the detection accuracy is high, more than 99% particularly for human walking, empty room detection and transitions from one position to another. Each received RSSI sample is compared with the predefined ISV thresholds in order to distinguish the detection. The presence of a subject in the positions which are slightly away from the direct RF links, such as *P1* in both experiments, is recognized with approximately 5% of false detections. Human presence in the position *P5* in *R2* is detected with approximately 10% of false detections. The position *P6* in *R2* which was the farthest position from all nodes induced very low signal strength variations. The algorithm did not detect a human standing in the position *P6*, which was marked as the "*blind spot*". The solution to improve the detection accuracy in larger rooms is to install additional nodes for a better radio coverage.

VI. Conclusion

The proposed device-free RF based human detection method is incorporated in the network of smart power outlets and light switches. The outlets and light switches are extended to detect human presence in order to increase user awareness and to improve human-computer interaction in smart homes. For certain applications in smart homes the proposed method is even more reliable and robust than other conventional presence sensor technologies. In contrary to PIR sensor, which is mainly dependant on ambient temperature, the RF based detection accuracy is not disturbed with the typical temperature changes. When the subject is stationary for a period of time, the PIR sensor is unable to detect human presence. The RF based human detection successfully detects the presence even in such demanding cases. The authors believe that this idea will encourage other manufacturers to apply the presented method to their smart outlets in order to improve the user awareness in smart homes.

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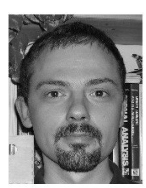

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