A context-Aware Smart Home Control System based on ZigBee Sensor Network

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Abstract

The applications of Wireless Sensor Networks (WSN) are progressively adopting for various smart home services such as home automation, controlling smart home household appliances, constrained application services in a smart home, etc. However, enabling a seamless and ubiquitous WSN communication between the smart home appliances is still a challenging job. Therefore, in this paper, we propose a smart home control system using an Actuator based ZigBee networking (AZNET). The working of the proposed system is further divided into three phases, 1) an interference avoidance system is adopted to mitigate the effect of interference caused due to the co-existence of IEEE 802.11x based wireless local area networks (WLAN) and WSN, 2) a sensor-based smart light control system is used to fulfill the light requirement in the smart home using the sunlight with light source, and 3) an autonomous home management system is used to regulate the usage time of the electronic appliances in the smart home. The smart is tested in real time environment to use the sunlight with light sources in a various time of the day. Similarly, the performance of the proposed smart home is verified through simulation using C# programming language. The results and analysis revealed that the proposed smart home is less affected by the interference and efficient in reducing the energy consumption of the appliances available in the smart home scenario.

***Keywords*:** ZigBee, IEEE 802.11x, WLAN, Smart Home

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1. Introduction

The emergence of smart devices has boosted the concept of connecting everyday objects via the existing networks. The drastic increase of connected devices has outreached the boundaries of the conventional networks, resulting in the renaissance of the web as the third wave "Internet of Things (IoT)". IoT is rapidly growing a network of heterogeneous devices and objects, which are uniquely addressable within the network and capable of identifying and sharing information with or without human interaction. Consequent to the development of everyday objects embedded with minuscule and machine-readable identifiers i.e. Radio Frequency Identification (RFID), IoT has become a remarkable spotlight among diversified interest groups. The IoT concept is matured with the extensive attention, leading towards the innovation of novel applications i.e. smart home, smart transportation, smart healthcare, smart industry, etc. Initially, the smart home concept was coined for better management mechanisms with the rapid increase of using smart devices for domestic purposes [1]. However, this notion has revolutionized from switching on lights to security systems, heating control systems, remotely controllable devices, smart device management, enhance energy consumption, etc. [2].

The dramatic increase in energy consumption accelerates the demand, resulting in a relative increase in the monetary value of energy. Hence, it is crucial to implement smart home applications that focus on consuming energies efficiently in residential buildings. Consequently, it influences positively on energy consumption habits, meanwhile creating energy saving, demand reducing, and low carbon emission phenomenon [3]. Synthesizing new connections with home automation bring about more realistic and energy efficient smart home concepts. The home automation is widely used for central controlling of lighting, heating, ventilation, and air conditioning appliances (HVAC) and security locks. Regardless of the purpose, smart home applications extensively rely on WSN. Among multiple technologies, WIFI seems to be advantageous due to higher bandwidth, large coverage, easy expansion, etc. [4]. However, its power consumption is higher compared to Bluetooth and ZigBee, which are widely accepted as the ideal communication protocols for resource constrained sensor devices. In fact, the technologies operate on the same ISM band i.e. WIFI, ZigBee, and Bluetooth (2.4 GHz), cause network interference in the WSN leading to a massive data loss [5]. It is a compelling requirement to address this regard, to enhance the Quality of Service (QoS) provided by smart home applications.

However, implementing an efficient smart home control system under heterogeneous WSN is a challenging task. One of the major challenges in this regard is the standardization of IoT. Thus, making IoT as a standard can help the researchers in providing a common platform for producing products and services for smart home designing. Therefore, multiple attempts have made in order to overcome the technology and application demands, while adapting to dynamicity of service requests. A resource-aware smart home management system was proposed with an effective mechanism for managing home resources and presents a base architecture for autonomic services is presented in [1]. Similarly, the integration of ZigBee with IEEE 802.15.4 is capable of delivering effective solutions in multiple interest areas i.e. energy management and efficiency, building automation, industrial plant management, etc. [6]. For example, DOMotics and SECurity (DOMOSEC) home automation system proposes a novel communication protocol that connects the architecture's IP-based elements through

UDP employing ZigBee technology [2]. Moreover, the DOMOSEC has been evolved to adapt into multiple settings with regards to the contextual requirement i.e. greenhouse, e-health, elderly care, and energy efficiency. However, DOMOSEC does not provide any solution to avoid interference and control packet loss, which can ultimately affect the performance of the smart home automation system. Similarly, many other challenges are present in the current literature such as high-energy consumption, high packet loss due to the co-existence of heterogeneous technologies, smart light control systems, etc.

Therefore, in this paper, we proposed a smart home control system based on AZNET to mitigate the effect of interference and reduces the energy consumption of the smart home appliances. The proposed interference control system divides the wireless channels among the sensor nodes and the WIFI users based on Multi-Attribute Decision Modeling (MADM). Similarly, a smart light control system is used to tune the illumination level in a room by incorporating the natural light. A management station is designed to control the working time of the smart home appliances. The simulation results reveal that the proposed AZNET in integration with the management station delivered energy and interference aware solution than a relay and pure WSN based smart home systems.

2. Related Work

The quality of life is supposed to be better in urban locals than rural areas. The people migration rate from a rural area is considerably high in the last couple of years. The main reason for this increase is the availability of various services such as better life style smart communities, always connected systems, etc. Thus, the researchers divert their focus to designing smart services in homes and cities [7] [8] [9]. Several mechanisms are developed to make the smart homes autonomous and always connected based on IoT technologies. For example, a scheme based on smart WSN infrastructure has been proposed in [10]. The proposed mechanism operates in three levels i.e. 1) a smart WSN (S- WSN) level is used to form a base of proposed architecture, 2) a smart pervasive edifice level is used to provide a platform for various devices such as sensors, etc. to internet and process the data in a smart environment and 3) finally, a cloud service platform is designed to facilitate the queries generated by the user. The proposed architecture is theoretically represented with all requirements. However, a real-time implementation on test beds still needs to check the performance of the proposed scheme. Designing a completely new architecture for smart cities is a challenging job. However, the ICT based solutions can be employed to avail some of the basic services and requirement needed by the user [11]. A scheme based on deploying several hundred nodes in a cloud to provide in IoT environment is proposed in [12]. The proposed work discusses several different aspects such as cloud assisted remote sensing service by highlighting their main capabilities, etc. Similarly, various context-aware solutions are presented in the recent literature to present efficient solutions according to the users [13]. However, context-aware solutions are mostly based on the dedicated sharing of services among users. Therefore, several cognitive approaches are presented to efficiently address the problems of sharing resources [14].

The integration of WSN in smart home designing is widely studied in the near past [15] [16]. However, several challenges exist in using WSN with existing technologies. For example, high packet loss, deployment of sensors, energy consumption of the sensors, etc. the WSN, and WLAN both operates in 2.4 GHz bands and hence most of the problems exists because of the co- existence of both the technologies. Therefore, several methods have been proposed to address the co-existence of WSN and WLAN [17] [18]. For example, in [17], the authors presented an experimental model of analyzing the co- existence of WLAN and WIFI. The authors specifically calculate the packet loss in various scenario based on a test bed environment. However, specific scenarios are not helpful in such conditions where heterogeneous and dense sensors are present. Moreover, real-time decision systems are needed to perform decisions and improve the performance of the system. A scheme based on testing various channel selection mechanisms has been presented in [18]. The authors tested comparison of various channel selection and testbed simulations. Finally, the authors suggested the best channel selection metric among the existing channel selection algorithms. Several management systems are presented to control the household appliances functionality in a smart home [19] [20]. However, the functionality of these smart home management systems is significantly affected by the packet loss occur due to heterogeneous technologies. Moreover, the sensors do not operate in an appropriate way, and thus, the required information does not reach to the management system. However, several schemes are presented to deal with such situations. For example, in [21] the authors presented a model used to control the packet loss in the smart home. The author shows that the packet failure slows down the working of the smart home control system. Therefore, it is extremely important to consider the packet loss rate while designing the communication network for a smart home.

One of the major issue in smart home systems is the energy management of the household appliances. In order to address the aforementioned issue, is to develop an autonomous system for household appliances. However, it requires an intelligent system to control the autonomous system. Therefore, it increases the computation and processing time which ultimately consumes high energy. A scheme has been proposed based on intelligent management system in [22]. The proposed system computes the comfort level of the user based on the inputs from the user. However, the system mainly depends on the input from the user and therefore, it is possible that the system can perform poorly if the input to the system is not correct.

3. Proposed smart home architecture

The proposed smart home control system is further divided into a three-tier model i.e. 1) Interference Avoidance System (IAS), 2) sensor based Smart Light Control System (SSLCS), and 3) Autonomous Home Management System (AHMS). A brief overview of the proposed smart home control system is provided followed by the proposed three-tier model in following sections.

3.1. Overview

In order to clearly elaborate the architecture of the proposed smart home control system, a scenario is shown in **Fig. 1**. The proposed smart home consists of four rooms and one kitchen. Each appliance in the smart home scenario is connected with a ZigBee sensor. Similarly, the sensor is further attached with a coordinator, and the coordinator is further connected with the AHMS system. In addition, a light sensor is placed in each room and kitchen to control the intensity of the light using the SSLCS. The ZigBee coordinator helps each sensor in channel assignment using the IAS. The channel allocation significantly controls the interference level in the entire smart home. Moreover, the AHMS perform various functions such as, gathering the information from each coordinator, store the information in a database, sending commands to the sensors, and generates daily and monthly reports of the energy consumption by the appliances, sensors, gas, etc.

3.2. Interference Avoidance System

The WLAN always affect the performance of the WSN and vice versa, if both the technology operating on the same band (2.4Ghz). In order to mitigate the interference caused due to the coexistence of WLAN and WSN, the coordinators are placed in each room and kitchen. The sensors in the entire smart home scenario are divided into n number of groups based on the physical distance between the sensors and WIFI Access Point (AP). The first group (G_1) consists of all those sensors that are present very closer to the WIFI AP, and their physical distance is less than the pre-defined distance threshold ($d[Th_1]$). Similarly, the rest of the groups i.e. G_2… G_n has lesser distance than the distance thresholds $d[Th_2]$… $d[Th_n]$, respectively. The sensors available in the first group suffered from high interference due to the closer physical distance of the sensors to the WIFI AP.

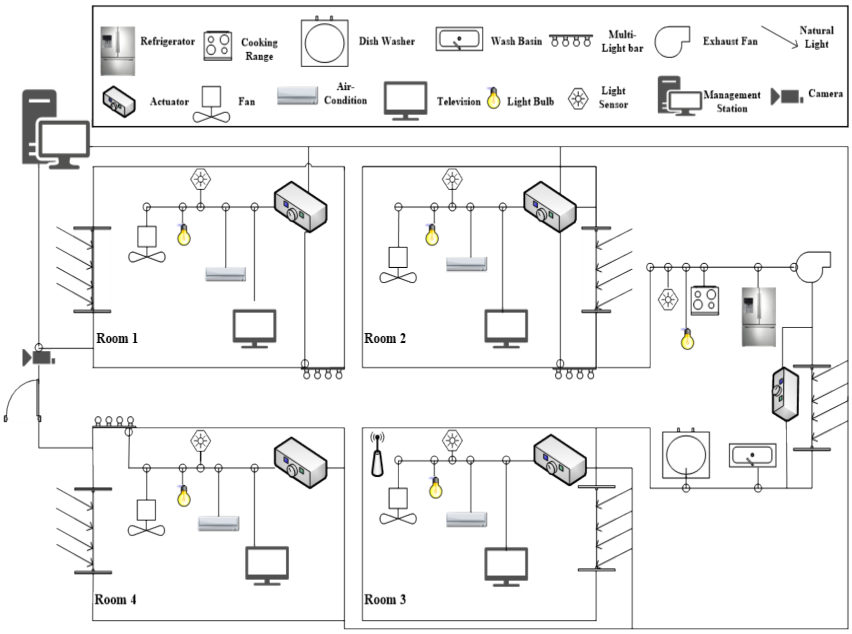


Fig. 1. Proposed smart home scenario

In the traditional WSN, the sensor nodes are directly communicating with the management node or via a relay node. Therefore, the packet loss is significantly high due to the interference resulting in lowering the performance of smart home devices and sensors. Keeping the physical distance in mind, the coordinators are always placed in the locations where the chances of interference are less. Similarly, the coordinator reduces the number of hops to the destination, as there are greater chances of packet loss by transferring the data to the far destination using relay nodes or sensors. Moreover, if one of the ZigBee channels is occupied by the WLAN signal, then there is a high possibility that the adjacent channels are also occupied by it. In order to reduce the effect of interference, each group G is assigned with a specific set of channels. The rest of the IAS mechanism is two-fold, 1) the division of the wireless channels into overlapping and non-overlapping channels, 2) the first group G_1 is assigned with the non-overlapping channel and the rest of the channels are assigned based on the MADM technique. Four different parameters (P) are used to select a channel using MADM technique i.e. bandwidth, occupancy, Signal-to-Interference-plus-Noise-Ratio

(SINR), and quality. The entire MADM technique used to rank the channels is given in **Algorithm 1.**

Algorithm 1. Working of channel selection based on MADM

1: Initialization of decision-making Matrix M_{rc} (r = rows, c = cols)

$$M_{rc} = P_{ij} \Big/ \sqrt{\sum_{r=1}^{m} {P_{rc}}^2 \; r = 1, 2, \cdots, m; c = 1, \cdots, n}$$

2. Computing the Normalizing Matrix M'

$$M'_{rc} = \begin{cases} P_c^* = max_{1 \le r \le m}(p_{rc}) \\ P_c^{\circ} = min_{1 \le r \le m}(p_{rc}) \end{cases}$$

3. Computing the Weighted Normalized Matrix M''

$$M''_{rc} = w_c * M'_{rc}, r = 1, 2, \cdots, m; c = 1, \cdots, n$$

$$w_c = {p} \Big/ {\sum_{c=1}^{4} p_c}$$

4. Computing the Ideal Situation I

$$I^+ = (\max M''_{rc}\; c \in C \mid r = 1, \cdots, m = [z_r^+, z_{r+1}^+, \cdots, z_m^+]$$

$$I^- = (\min M''_{rc}\; c \in C \mid r = 1, \cdots, m = [z_r^-, z_{r+1}^-, \cdots, z_m^-]$$

5. Distance with Hypothetical Ideal Situation D

$$D_i^+ = \sqrt{\sum_{k=1}^{n} \left(m''_{kc} - m''^{+}_{k} \right)^2}, k = 1, 2, \cdots, m$$

$$D_i^- = \sqrt{\sum_{k=1}^{n} (m''_{kc} - m''^{-}_{k})^2}, k = 1, 2, \cdots, m$$

6. Computing the Ranks of the channels

$$R_i^* = \frac{D_i^-}{D_i^+ + D_i^-} = 0 \le R_i^* \le 1\,; i = 1, \cdots, m$$

After computing the ranks of the available channels, they are arranged in ascending order. The channels with higher ranks are assigned to groups available at a closer distance to the WIFI AP and vice versa.

3.3. Sensor based Smart Light Control System

In order to save the energy of the proposed smart home, the SSLCS works in two parts i.e. 1) sending the switching on and off time to the AHMS and 2) balancing the natural light and light source intensity in a particular location. Each electronic appliance in the smart home required a different amount of electrical energy. However, the consumption of electrical energy directly depends on the user activities in a smart home. Therefore, the SSLCS is operating in a semi-automatic mode. The user manually switches on an electronic device, but the SSLCS is responsible for turning it off based on the command from the AHMS. Each time the user switches on a device, the SSLCS sends the switching on time to the AHMS. Similarly, the SSLCS periodically checking the presence of the user in that particular location. Once, the user leaves a location, the SSLCS switched off the device and sent the switching-off time to the AHMS. Each sensor deployed in the smart home scenario is assigned with a unique identification number, which helps in distinguishing the home appliances from each other. The AHMS keeps track of the record of the user activities, appliances, and sensor active time. The SSLCS also checks the intensity of the sunlight by considering the area covered by the sunlight in a room etc. as shown in **Fig. 2**. Four different cases are identified based on the angle of sunlight (θ) falling on the window of a room or any other place. In all the cases, the SSLCS directs the light sensor to check the light intensity in the room and adjust the light source intensity (I) using following relation.

$$I_{\theta_i} = \begin{cases} \varphi\left[\frac{1}{2}(b1 \times h1) + (b2 \times x)\right] \pm \delta & 0^{\circ} \le \theta_1 < 15^{\circ} \\ \frac{\varphi}{2}[(b3 \times h2) + (b4 \times h3)] \pm \delta & 15^{\circ} \le \theta_2 < 30^{\circ} \\ \varphi\left[\frac{1}{2}(b6 \times x) + (b5 \times x)\right] \pm \delta & 30^{\circ} \le \theta_3 < 45^{\circ} \\ \varphi\left[\frac{1}{2}(b6 \times x) + (b5 \times x)\right] \pm \delta & 45^{\circ} \le \theta_4 < 60^{\circ} \\ \varphi x^2 & Otherwise \end{cases} \quad (1)$$

Where δ is a tuning factor to adjust the light source intensity with different environmental conditions and φ is the intensity of luminous flax by a unit length light source and it computed as follows.

$$\varphi = \frac{F_L \times L_M \times R_f}{\Gamma} \quad (2)$$

Where F_L is the total luminous flux by a light source, L_M is the lumen maintenance of the light source, R_f is the lampshade reflection coefficient, and Γ is the length of the light source.

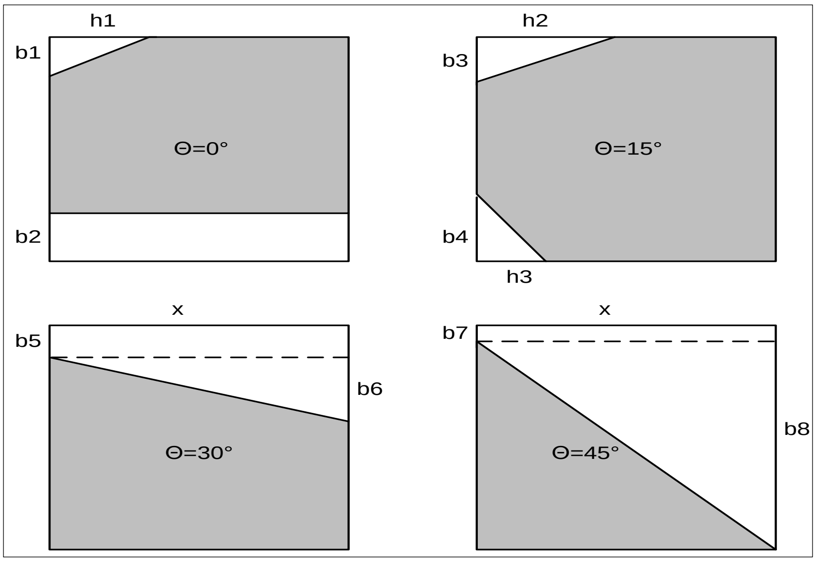


Fig. 2. Area covered by sunlight

3.4. Autonomous Home Management System

The data collected from sensors and coordinators are sent to the AHMS for further processing. The AHMS consists of different modules 1) organizing the data in the database, 2) performing necessary actions, 3) decision making, 4) event generation, etc. The data from the sensors are organized in the database, and a threshold is defined for each service (Gas, Water, and Electricity). The AHMS is periodically checking the consumption of these services. If the data from any service elevates from the normal threshold, an event is generated by the AHMS and sends it to the smart home user. The smart home user can perform a necessary action by connecting to the AHMS using the remote access functionality. Upon receiving the instruction from the smart home user, the respective event is generated and send it to the sensor. For example, if the electricity consumption elevates from the normal threshold the event sends to each sensor attached to the electronic appliance. Furthermore, the sensor first checks the availability of the user at that particular location. If a user is available, the sensor waits until the user leaves. The AHMS also manages the consumption of all the services present in the smart home, and a monthly record is generated. This monthly record shows the consumption of each appliance present in the smart home. The smart home user can use these statistics and perform necessary management for the next month. Thus, using the AHMS, the consumption of the smart home is set to a normal level. Following the experience of the smart home user, a Human-Machine Interface (HMI) is designed for future adjustment and automation of the AHMS. Thus, based on the user data, the AHMS is made intelligent for future decisions or when the user is busy or unavailable. The automation system helps the user to adjust different tasks in the smart home such as a refrigerator and air-condition cooling, surveillance system i.e. locking the doors, etc. These functionalities help the user in reducing the energy consumption of the devices and ultimately helps in low bills, etc.

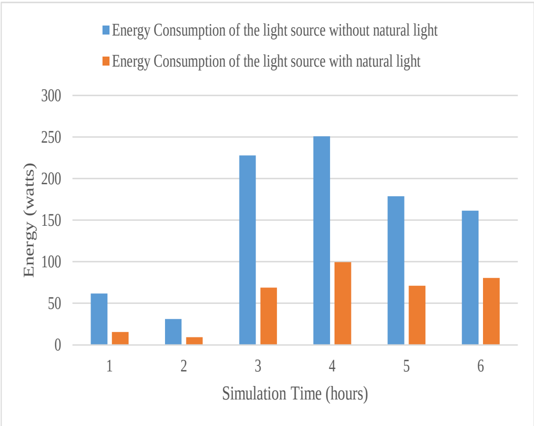
4. Simulation and Results

The proposed smart home architecture as shown in **Fig. 1** is simulated in C# programming language. The entire smart home is tested for all the electronic appliances for a duration of 6 hours. Both the energy consumption by sensors and appliances is computed by taking the user activity as a random variable between 5 to 30 seconds except for the burner in the kitchen. In order to be more realistic, the simulation time for the gas burner is changed to 5 to 15 minutes. A total of four users is considered in the smart home scenario. Initially, a single user is injected into the smart home. In addition, the rest of the users are injected within the first two hours of the simulation. All the four users are continuously using WIFI AP. Similarly, all the four users are continuously generating a traffic of eight Mbytes randomly on any WIFI channel. The rest of the simulation parameters are listed in **Table 1**.

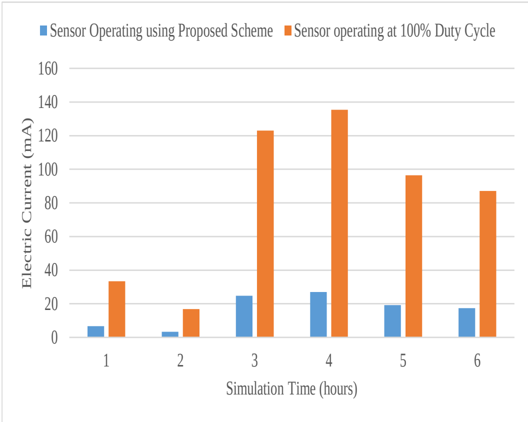
Table 1. Simulation parameters

Parameter	**value**
Simulation Time	6 hours
Sensor Transmit current	15 mA
Room Size	3000 mm x 3000 mm
F_L	1700 lm
L_M (20000 h)	65%
R_f	2.16
Γ	330 mm
Number of sensor groups (n)	4
$d[Th_1]$, $d[Th_2]$, $d[Th_3]$, and $d[Th_4]$	3, 6, 9, and 13 m

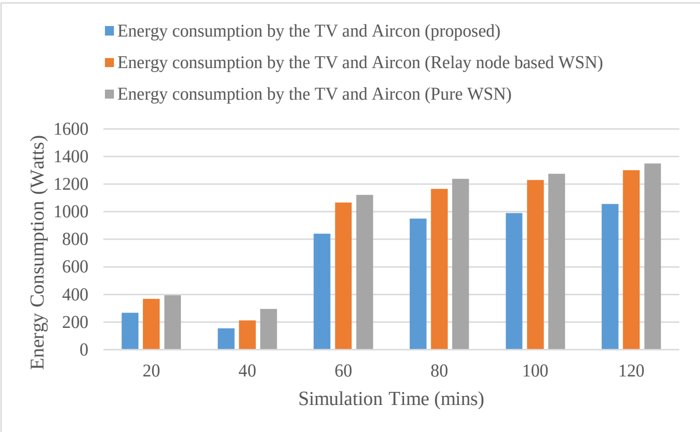
The values of the parameters used for ranking the channels are assigned randomly between 0 and 1 to adjust the pairwise relationship between the parameters. However, the group of sensors near to the WIFI AP are assigned with higher SINR and bandwidth values comparing to the other groups. The light source in room 1 is tested with and without the natural light. In order to ensure a real time scenario, we performed an intuitive test in our laboratory for the sunlight falling on the window at a different time of the day. The intensity of the natural light falling on the window is computed at different times starting from 8:00 AM to 2:00 PM. Initially, the natural light covers the maximum portion of the room. However, after 12 PM, the sunlight reduces and covers almost half of the room. This experiment reveals that the natural light can be used with the light source to save the energy as shown in **Fig. 3(a)**. Moreover, the usage of natural light significantly reduces the energy consumption of the light source. Furthermore, the electrical energy required by the light sensor comparing with the 100% duty cycle of the sensor is also shown in **Fig. 3(b)**. Both the light sensor and the light source required significantly low energy. Similarly, the energy consumption by the rest of the devices i.e. television and air-conditioning system in room 3 is also computed for a duration of two-hour time for proposed AZNET, relay node based WSN, and pure WSN as shown in **Fig. 3(c).** The results reveal that the proposed AZNET with the AHMS system save much energy. In addition, the simulation shows that the interference is highly affected the relay and pure WSN communication. Thus, the proposed AZNET helps in controlling the unnecessary energy consumption of the smart home devices.



(a). Energy consumption of light source

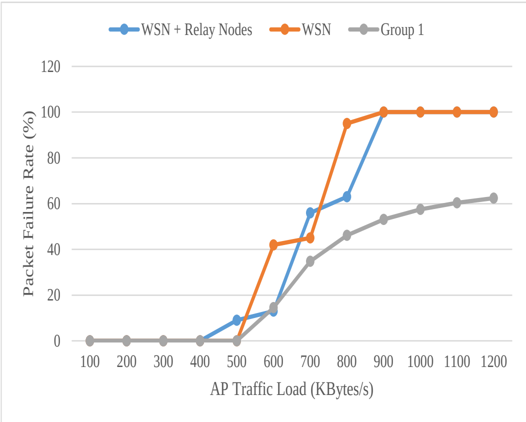


(b). Energy consumption of the light sensor

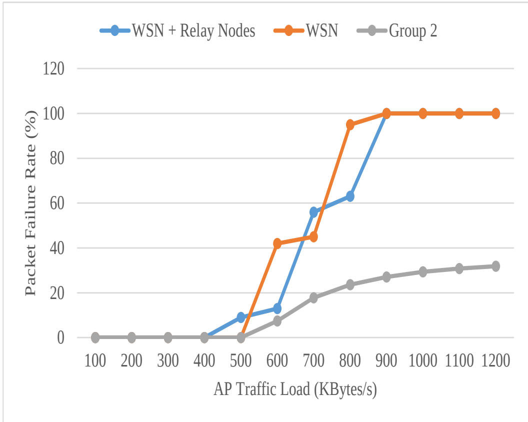


(c). Energy consumption of TV and Air conditioning system

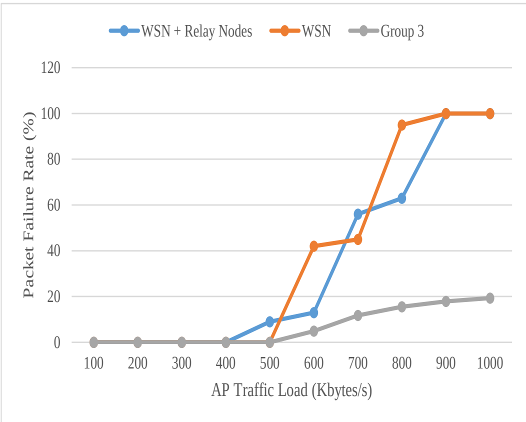
Fig. 3. Energy consumption of various appliances



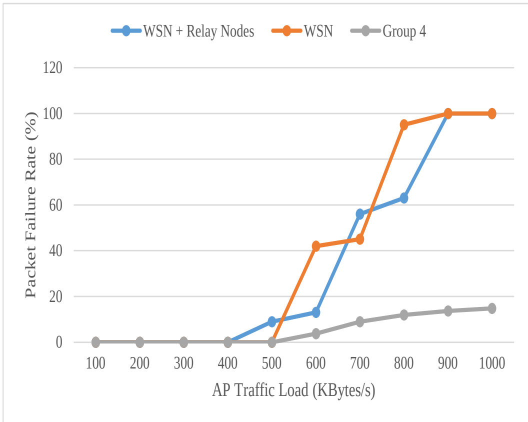
(a). Packet loss rate in Group 1 sensors



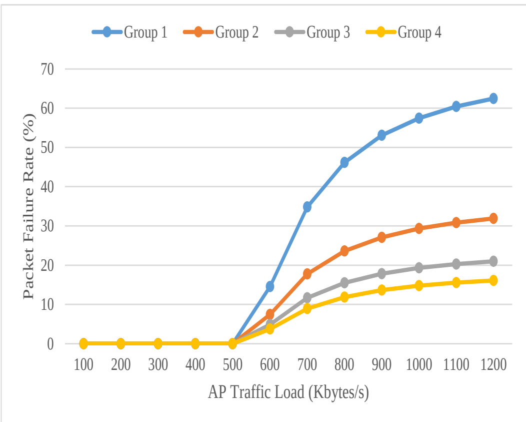
(b). Packet loss rate in Group 2 sensors



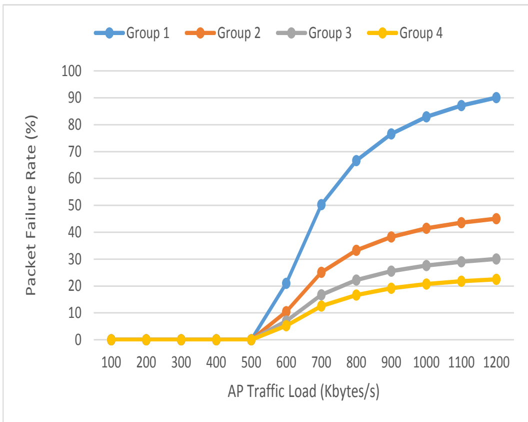
(c). Packet loss rate in Group 3 sensors



(d). Packet loss rate in Group 4 sensors



(e). Avg. Packet loss rate in all four groups



(f). Max-Packet loss rate in all four group

Fig. 4. Packet Loss in various sensor groups

The packet loss rate among G_1, G_2, G_3, and G_4 is computed and compared with the pure WSN and relay based sensor networks as shown in **Fig.s 4(a) ~ 4(d)**. The packet loss rate in pure and relay based WSN is measured by calculating the number of failed packets divided by the total number of packets under different WLAN scenarios. The group of sensors that is present near to the WIFI AP i.e. G_1 has a relatively high interference than the rest of the groups. The simulation reveals that as the physical distance between the sensors and WIFI AP increases, the interference level decreases. However, in the case of the pure WSN and relay based WSN, the packet loss rate is high than the proposed AZNET technique. The division of channels among the group of sensors helps the sensors to connect to a particular channel set. Thus, significantly reduces the probability of interference. Moreover, the average and maximum packet loss rate are computed to check the accuracy of the proposed AZNET in the proposed smart home scenario as shown in **Fig.s 4(e)** and **4(f)**, respectively. The packet loss rate in all of the above cases is significantly less than the pure WSN and relay based WSN. Thus, the AZNET is an accurate solution for reducing the effect of radio interference in a smart home scenario. Moreover, the proposed smart home control system can help in placing the WSN nodes in appropriate locations that further helps in efficient communication with the AHMS system.

5. Conclusion

This paper presented an architecture of energy and interference aware smart home design. The proposed smart home system employed a AZNET mechanism to mitigate the effect of interference caused due to the co-existence of WSN and WIFI networks. The proposed architecture also used the sunlight in addition to the light source to reduce the energy consumption of the light source. The proposed smart home architecture is tested for both energy consumption by the devices and the interference caused due to the co-existence of WIFI and WSN networks. The simulation results show that the proposed AZNET mechanism is significantly less affected by the interference. Similarly, the devices in the smart home required less energy comparing to the pure WSN and relay based WSN.

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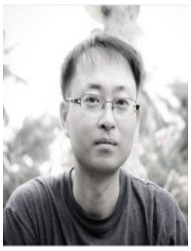

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