An Energy-Aware Wireless Sensor Network for Data Acquisition in Smart Energy Efficient Building

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***Abstract*— extending the battery life-time of Internet of Things (IoT) devices is still a challenging research question. A lot of work has been done to optimize IoT wireless sensors in terms of hardware architecture, operating system, along with the usage of low power data acquisition techniques and energy aware routing protocols. In Smart Energy Efficient Building (SEEB), Energy Management System (EMS) uses WSN for data acquisition to monitor energy consumption and to track user behaviour. For EMS, context recognition is a key element for HVAC (Heating, Ventilation and Air Conditioning system) control. Therefore, the more the context is precise, the more the decision that will be taken, by the EMS, is accurate. In most SEEB, sensor nodes are configured to send data periodically. Thus, unnecessarily increasing battery-energy consumption as sensor nodes keep sending redundant data (e.g., when context did not change). To solve this issue, we propose an Energy Aware Context Recognition Algorithm (EACRA) that dynamically configures sensors to send specific data under specific conditions and at a specific time, thus avoiding redundant data transmissions. This algorithm uses SEEB declared knowledge, and forcing the sensor node to send data only when context changes. The experiment results shows the difference between the periodic sampling and sampling using EACRA in terms of energy consumption.**

Keywords—WSN, Context-recognition, smart building, HVAC, EMS, energy aware protocol, EEB, IoT.

I. INTRODUCTION

Nowadays, Wireless Sensor Network (WSN) [1] and Internet of Things (IoT) [2] are gaining more and more the interest of both academiaand industry. The emerging topic of Smart Energy Efficient Building (SEEB) [3] compel the adoption of policy based Energy Management System (EMS) [4]. Next generation EMS solutions will be based on Information and Communication Technologies (ICT) [5] and ICT will depend on WSN and IoT devices to track user behavior, monitor energy consumption and control Heating Ventilation and Air-Conditioning appliances (HVAC) [6].

In a cold area, like the city of Ifrane in Morocco, temperature degrees fluctuate between -10 C° and 22 C° during the whole year. Therefore, heating becomes necessary which dramatically increases the electricity consumption. To solve this issue, CASANET project [7] aims to develop a policy-based EMS which is dedicated to control heaters in a university campus. The CASANET EMS is developed based on the Plan-Do-Check–Act (PDCA) life cycle [8] and designed using the Context Based Reasoning Model (CBR) [9]. CASANET project adopts ICT-based solutions to establish SEEBs in a university campus. The data acquisition system used in this EMS project is a WSN based on Arduino programming boards and XBee radio frequency modules. In this WSN, sensor nodes send data to the EMS server via a gateway device. The role of this gateway is to connect the ZigBee [10] WSN to the TCP/IP network and forward data to the EMS server. Based on the WSN data and data about the building, the EMS server issues a command to switch ON or OFF the heaters. The next figure illustrates the general architecture of the CASANET EMS.

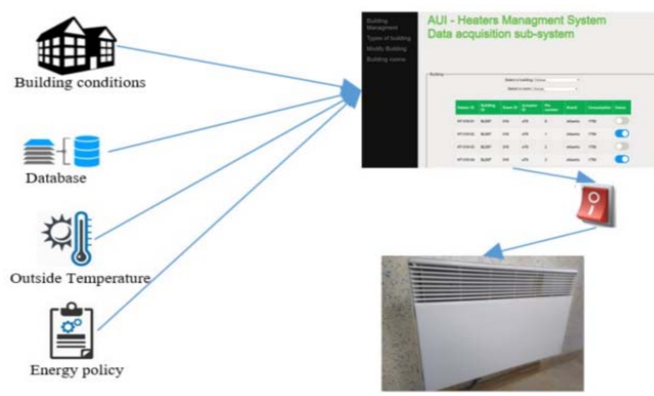

Figure 1 CASANET EMS general architecture [7].

CASANET EMS depends on the WSN for data acquisition and control. Hence, it suffers from the inherent problem of battery limitations in WSN. To solve this problem, a lot of work was done to optimize sensor components. The next table presents different optimization goals along with contributions that helped in making the WSN's life longer.

Table 1 Optimisation objectives in WSN[11].

Layer	Optimization goals	Contributions
Application	Minimize data generation and transmission	*Data Acquisition Techniques:* Directed diffusion, Chain construction, Probabilistic model, Cluster model using data correlation, Query model…
Network	Energy consumption balancing and packet size optimization.	*Routing Protocols:* LEACH, TEEN, SPIN, EAP, ODYSSE, SMAC, TMAC, DMAC
Operating system	Minimize software services.	*Operating Systems:* TinyOS, Contiki, Free RTOS, MANTIS, Nano-RK, LiteOS, RIOT.

Hardware	Minimize hardware architecture.	*Microcontrollers:* MSP, ATMEGA, and PIC

CASAET EMS differs from the previous work by taking in consideration the context of building. Context includes the types of building, occupant behavior and environment conditions. During the study phase of the CASANET EMS, we concluded that in some cases the occupant's behavior and room schedule can be defined without the need for WSN data. For example, a sensor node that is placed in a classroom, doesn't need to send data about motion in order to communicate the classroom's occupancy, because such piece of information can be triggered from the classroom's schedule on the university portal. Besides, some energy policy rules do not require data from the WSN in order to be applied. For instance, a heater placed in a classroom is switched OFF during the weekend regardless of the classroom's temperature, motion etc. Hence, no data is needed from the sensor nodes located in a classroom.

This paper contributes at the level of data acquisition technique by introducing an Energy Aware Context Recognition Algorithm which aims at minimizing the WSN's energy consumption. Such algorithm, takes advantage of both the declared knowledge and the energy policy rules in order to minimize data generation and transmission in the WSN. The rest of this paper is organized as follows: First, we present the CASANET EMS project's bbuilding modelling, data acquisition and heaters control. Second, we discuss how the CBR model and the declared knowledge can help minimize WSN energy consumption while maintaining a good context recognition. Third, we present EACRA algorithm and its optimization objectives. Fourth, we present the real world test results of a testbed experiment. Finally, we conclude the presented work along with future work.

II. CASANET EMS Project

The CASANET EMS decision making process takes into consideration the declared knowledge about the different buildings on campus, the dynamics inside the buildingthe outside temperature and the energy policy. This EMS is composed of two subsystems to build knowledge of each location: the data acquisition subsystem (Arduino/XBeeWSN) and the context recognition subsystem (Context Based Reasoning Model). In this part, we describe the way each subsystem was developed.

A. The Data acquisition subsystem:

After the investigation and the analysis of WSN technologies in smart building, we opted to use open platform hardware to implement our WSN nodes.

(A) (B)

Figure 2 WSN Sensor and actuator.

As illustrated in figure 2, the sensor nodes (figure2-A) we used are composed of three elements. First, the sensor modules: composed of passive infrared (PIR) for motion detection, DHT11 for temperature and humidity measurements, and MC38 to detect if the window/door is open or closed. Second, the processing unit which is Arduino Nano v3.0 board that samples and sends data. Third, the communication RF module: composed of an XBee Series 2 S2C communication unit to send and receive data.

The WSN is implemented as a mesh topology where sensor nodes route data towards the gateway device (figure 4). The gateway links the WSN and the TCP/IP network to which the application server is connected. The command coming from the application server is forwarded to the appropriate actuator (Figure2-B) also via the gateway. In this test, we used 9 sensor nodes indoor with a voltage supply of 5V. The sensor nodes are XBee Series 2 S2C with a wire antenna. All nodes can be both sensors and routers using AODV routing protocol [12]. All the nodes belong to the same Personal Area Network (PAN) ID BD07. The nodes forward sampled data to the ZigBee gateway which forwards it to the application server. The performance evaluation of the network includes delay, distance measurement, packet loss, and throughput. We tested the network in low, medium and high data rates. In the testing phase we created a full mesh network out of 10 nodes. Six sensor/router nodes are located inside rooms, offices, and laboratories. Three routers were installed in the hall to route data to the gateway. All the ten nodes are configured as routers. These XBee nodes runs the DigiMesh firmware that is based on ZigBee and AODV routing protocol. The DigiMesh firmware simplifies the network setup. Figure 3 below shows the network architecture inside the building's ground floor.

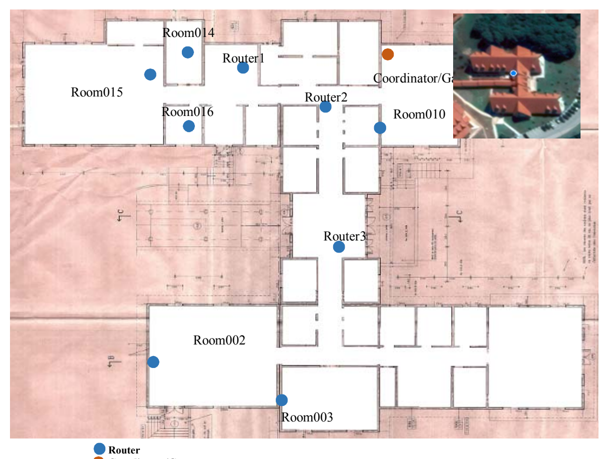

Figure 3 The Network test architecture in ground floor of building 7.

1) *Throughput measurement*

We measured the throughput from each sensor node to the gateway during one minute using the XCT-U software. Each sensor node sends packets of 20 bytes and waits for the ACK back from the receiving node. The data packet contains three information (temperature, motion and humidity). The test was performed in two different topologies: full mesh topology and a cluster tree topology. The next table presents the results in Kbps which was close to the values reported on the data sheet [13].

The red dot in figure 3 represents the gateway. As the distance from the sensors increases, the throughput decreases.

Table 2 Throughput test of sensor nodes in different topologies.

	Full mesh topology	Cluster Tree
Room010	7.42 kbps	8.39 kbps
Room014	6.53 kbps	7.67 kbps
Room016	6.85 kbps	7.9 kbps
Room015	4.38 kbps	5.38 kbps
Room003	3.21 kbps	4.35 kbps
Room002	2.33 kbps	3.51 kbps

2) Gateway testing

The goal of the test evaluate the gateway that has better performance for a given network topology and load. In this phase, we tested three different gateways: first, XBee Gateway (figure4-A), second, Raspberry Pi based gateway (figure4-B), third, Arduino Uno based gateway (figure4-C).

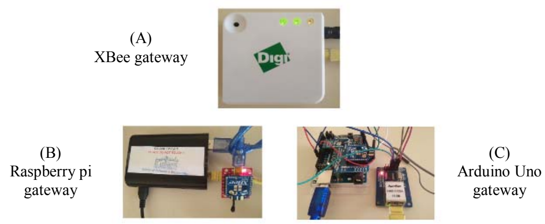

Figure 4 Three different gateway hardware.

These gateways have different CPUs, RAM capacity, operating systems and communication resources. These resources and theirconfiguration have an impact on the performance of the gateway. The following table 3 illustrates the hardware configuration of these different gateways.

Table 3 Gateways hardware configuration

	CPU	RAM	Operating System	Ethernet	Wi-Fi	XBee
XBee	Freescale i.MX28	68 Mb	Embedded Linux	✓	✓	✓
Raspberry-Pi	ARM	2 Gb	Raspbian	✓	✓	✓
Arduino	AVR	2 Kb	On-chip Boot	✓	✓	✓

The test we performed was about measuring the packet arrival rate under different packet time interval. This test took 60 rounds. Each round lasts for 1 minute. In the first round, we started by a packet time interval of 1 second, while in the last round, the packet time interval was 60 seconds. The test was also in two different network topologies: full mesh topology and cluster tree mesh topology.

As presented in Figure 5, the Raspberry Pi gateway performs the best in both full mesh and cluster tree topologies. It reaches 100% packet successful arrival rate at around 5 second interpacket interval time for full mesh. The packet loss start is at 6 second interpacket interval time in the cluster tree because there are less number of routers the network is congested at the gateway. Arduino Uno gateway does not perform well in low interpacket interval time. It achieves 20% and 30% successful packet delivery rate in cluster tree and full mesh topologies. The packet delivery rate increases as the interpacket interval time increases, reaching 100% between 10 and 15 second.. XBee gateways performed well in both network topologies with performance little lower but comparable to RaspberryPI.

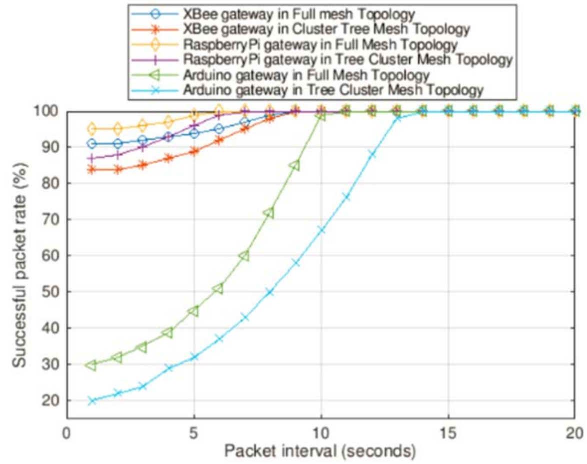

Figure 5 Successful packet rate in different packet time interval of the three gateways in different network topologies.

3) Power consumption evaluation in WSN nodes

The power consumption includes power consumed during computation (i.e. data acquisition) and communication. We measured both of them separately to assess the impact of each. In the WSN data acquisition, we used different sensor node configurations. In each configuration we used specific sensor modules. The next table presents these five different configurations.

Table 4 Different WSN node configuration used in the experiments.

	Arduino Nano	Humidity Temperature module	Sound module	Ambient Light module	PIR module	Door/Windo w module
Configuration 1	✓	✓				
Configuration 2	✓	✓	✓			
Configuration 3	✓	✓	✓	✓		
Configuration 4	✓	✓	✓	✓	✓	
Configuration 5	✓	✓	✓	✓	✓	✓

For each configuration we measured the energy consumed as function of sampling rate.

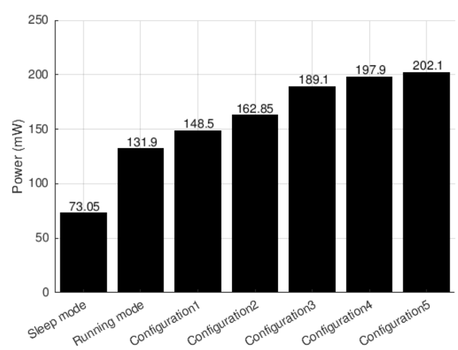

Figure 6 WSN node energy consumption of different configurations.

Figure 6 presents the computational energy consumed of the different configurations during the sampling process. It does not include the energy consumed in the network setup or during the data transmission.

Figure 7 presents the power consumed by the XBee RF during the sleep mode, networking setup, standby mode and the transmission mode.

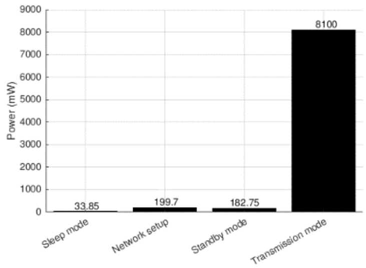

Figure 7 XBee RF power consumption in different modes.

At this level, we measured the WSN node energy consumption using periodic sampling without scheduling the tasks of the WSN sensor node using the EACRA algorithm that we will present later in this paper.

B. *The Context recognition subsystem:*

The context recognition in the EMS is based on two different types of parameters (figure 8). First, parameters with static values that describe the building type, room type, season, current day and the part of the current day. These parameters are fetched from the database of the EMS. Second, parameters with dynamic values which describe the temperature value, humidity, occupancy etc. such values are obtained using the WSN data acquisition of the EMS.

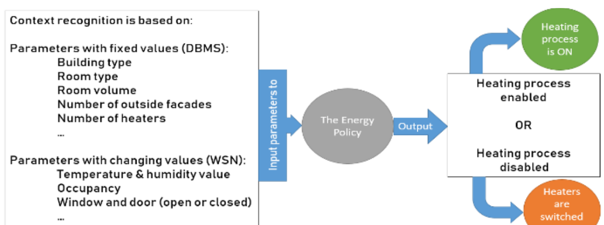

Figure 8 Context recognition parameters that enable/disable the heating process.

Both static information and dynamic information are input parameters to the energy policy in order to decide whether to enable the heating process or not.

Based on the CBR model [9], we have developed a set of groups. Each group contains one type of entity, for example, building types, room types, seasons etc. This information represents the static type of knowledge needed to infer the context. This static knowledge can be drawn by selecting an element from each group following the order from G_1 to G_5. G_1: Building type. G_2: Location type. G_3: Current season. G_4: Current day. G_5: Current part of the day (see figure 9).

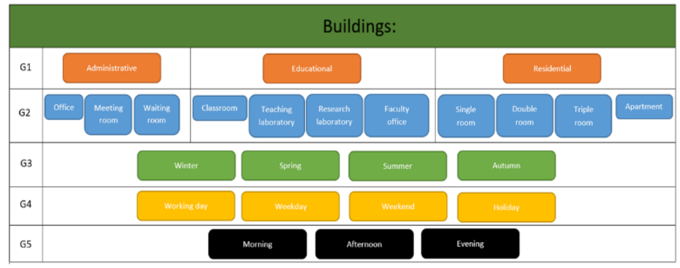

Figure 9 the hierarchy groups of the CBR model applied on the university campus.

In administrative building for example, there are 144 possible context combinations. In this building, there are three active contexts depending on the room type, for each room type, there four possible seasons, for each season there four possible day type and for each day there three possible part of the day. Thus, all possible combination is equal to1*3*4*4*3 =144). As an eexample of context C_1: {Administrative, Office, Season, Current day, and current part of the day}. In educational building, there are four possible contexts (depending on the room type) at each moment among the 192 possible ones in all time and here is an eexample of context C_1: {Educational, Classroom, Season, Current day, current part of the day}. In residential building, there are four possible contexts (depending on the room type) at each moment among the 192 possible ones in all time. An Example of context C_1: {Residential, Single room, Season, Current day, current part of the day}.After we draw the context, using the CBR model for each location, there comes the role of the WSN data. The EMS builds knowledge about air quality, temperature, and occupancy based on data coming from different sensor modules. The next table presents the different sensor modules that are used to build the knowledge. Each sensor node present a specific data which deem as the building block of knowledge.

Table 5 Sensor modules used to build diffrent types of knowledge.

Knowledge	Data	Data type	Sensor Module	Sampling time interval
Occupancy	Motion	Digital	PIR	Low
	Pressure	Analog	MPX4115A	High
	Sound	Analog	2PCS	High
	Gas	Analog	MQ-4	Medium
	Camera	Analog	OV2640	High
Air quality	Temperature	Digital	DHT11	High
	Humidity	Digital	DHT22	High
Appliance status	Light	Digital	MSE004LSM	High
	Relay	Digital	SRD-05VDC-SL-C 5V	High
	Power consumption	Analog	YHDC 30A	High

III. Energy-Aware Context Recognition Algorithm for Data Acquisition

Energy consumption in the deployed WSN nodes can be optimized at the level of the following three components: XBee RF, Arduino Nano programming board, and the attached modules. The XBee RF can consume less energy in the transmission mode if it sends a minimum number of packets with less data payload.

A. Energy-Aware Context-Recognition Algorithm (EACRA)

The EACRA algorithm identifies the building type and the room's type of usage based on room ID. Then, it generates the sensor schedule and configuration that will be valid during an amount of time (lease). This configuration is then sent to the sensor node. The lease schedule is updated twice a day; first schedule is attributed on the morning at 6 AM, and the second schedule updated at 7:00 PM.

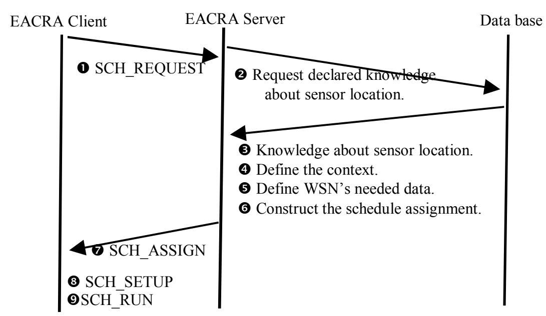

Figure 10 ECRA Client/Server communication process.

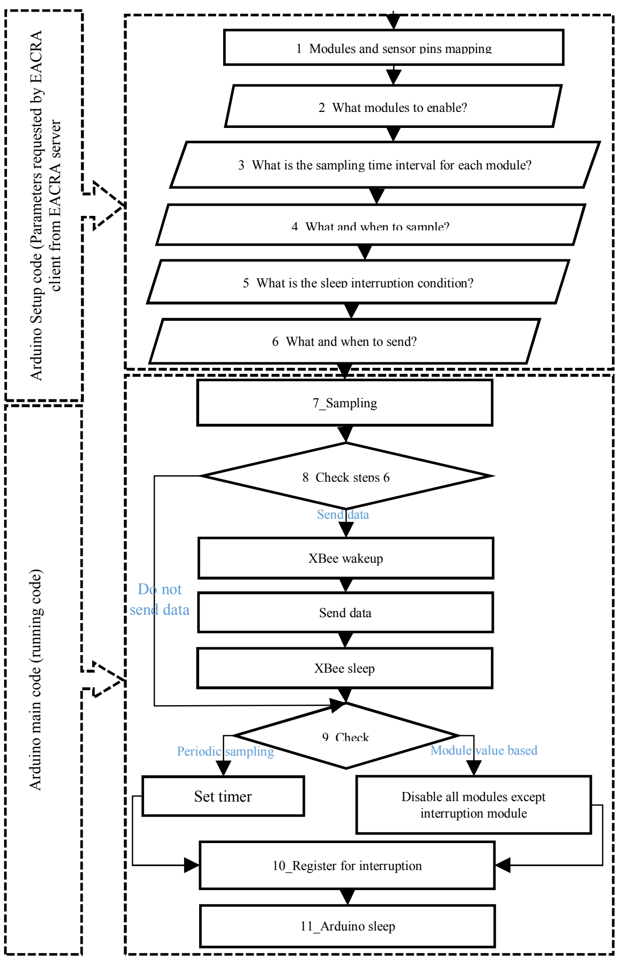

Figure 11 EACRA Client algorithm.

Table 6 Optimization objectives of sensor node components.

	Optimization objective
XBee RF	Using sleep mode, while in transmission mode, minimize the packet size and the number of packets as well.
Arduino Nano	Using sleep mode and minimize the processing code in sampling
Modules	No sampling and while sampling minimize the sampling rate

As stated in table6, there are many optimization opportunities at the level of the sensor components.The proposed Energy-Aware Context Recognition Algorithm for data acquisition minimizes the WSN node's energy consumption by using a minimum number of sensor modules with a low sampling rate. As a result, this technique will also minimize the data packet size and while it will increase the sleep mode time of both Arduino Nano programming board and XBee RF module. For this reason, we started by describing the different room types in an educational building as well as their usage and schedule. The following table describes the usage of these different rooms in a weekday, during the day (working hours) and at evening.

Table 7 Types of room usage in an educational building.

Room type	Type of usage	During the day	At evening
Classroom	Scheduled	Schedule	Not in use
Faculty Office	Hybrid	Schedule	Occupancy
Teaching laboratory	Scheduled	Schedule	Not in use
Research laboratory	Hybrid	Schedule	Occupancy
Open laboratory	Hybrid	Schedule	Occupancy
Conference room	Scheduled	Schedule	Schedule

The EACRA algorithm minimizes the need for WSN data in order to identify the context of each room in the building. Figure10 presents the EACRA Client/Server communication process and figure11 presents the EACRA client algorithm that runs in the sensor node. Table 8 presents sensor modules that should be involved during each part of the day. $S_i=(C_{OT}* T_r)/Time_{d\rightarrow d+1}$ Where S_i is the sampling interval time to increase the current room temperature to the requited threshold. C_{OT} is the current outside temperature. T_r is the temperature value reference and $Time_{d\rightarrow d+1}$ is the time reference required to increase temperature from degree d to $d+1$.

Table 8 what modules to sample and when to sample.

	During the da			At the evening		
Room type	DHT11	PIR	MC38	DHT11	PIR	MC38
Classroom	✓, S_i		✓			
Faculty Office	✓, S_i		✓	✓, S_i	✓	✓
Teaching laboratory	✓, S_i		✓	✓, S_i		✓
Research laboratory	✓, S_i		✓	✓, S_i	✓	✓
Open laboratory	✓, S_i			✓, S_i	✓	
Conference room	✓, S_i			✓, S_i		

The next table presents what data to send and when to send it. The current temperature TC is only sent if it is out of the tolerated range $(T_C>T_{max}$ *or* $T_C < T_{min})$. While the door sensor value DW_R and the motion sensor value M_R are sent only when their values are reset $(0\rightarrow 1$ *or* $1\rightarrow 0)$.

Table 9 what data to send and when to send it.

	During the day			At the evening		
	DHT11	PIR	MC38	DHT11	PIR	MC38
Classroom	✓, T_c		✓,DW_R			
Faculty Office	✓, T_c		✓,DW_R	✓, T_c	✓,M_R	✓,DW_R
Teaching laboratory	✓, T_c		✓,DW_R			✓,DW_R
Research laboratory	✓, T_c		✓,DW_R	✓, T_c	✓,M_R	✓,DW_R
Open laboratory	✓, T_c		✓,DW_R	✓, T_c	✓,M_R	✓,DW_R

Conference room	✓,T_c			✓, T_c		

When a sensor node sends data, it goes through a sleep period of time. However, there must an interrupter parameter to wakes it up. During the day, the sensor node wake up only when the sleep period of time S_i expires. While during the night, the sensor node does not wake up till it detects a motion reset M_R first and then it behaves like if it is operating during the day.

Table 10 Sleep time and wake-up condition.

Room type	During the day			At the evening		
	DHT11	PIR	MC38	DHT11	PIR	MC38
Classroom	S_i					
Faculty Office	S_i			^2S_i	^1M_R	DW_R
Teaching laboratory	S_i					DW_R
Research laboratory	S_i			^2S_i	^1M_R	DW_R
Open laboratory	S_i			^2S_i	^1M_R	DW_R
Conference room	S_i			S_i		

Figure 12 presents the results of WSN sensor node's power consumption using the EACRA in different room types in an educational building. These results are compared with a sensor node that is operating using periodic environment sampling without the EACRA algorithm. The results show that the power consumption dropped when using EACRA.

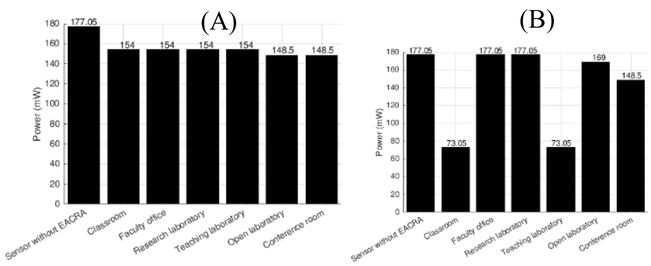

Figure 12 Energy optimization, during the day (A) and night (B) using the EACRA algorithm.

IV. Conclusion

In this paper, we presented an Energy Aware WSN for data acquisition in Smart Energy Efficient Building. In this WSN, we tested the network performance in terms of hardware, packet loss, and throughput, in different network topologies. We presented the context recognition approach using the Context Based Reasoning model. In addition, we emphasized on how this CBR model can be used to optimize energy consumption in WSN without missing to sample important event. At this level, we presented energy optimization in Wireless Sensor Network using the proposed Energy Aware Context Recognition Algorithm. These results are obtained during a weekday in both parts of the day (day time and evening). This proposed algorithm takes into consideration the weekend, holiday, weekday, building type etc. the objective behind this developed algorithm is to avoid redundant data that has no impact on the context change or applied control. Moreover, the sensor node operates only when the heating process can be enabled, while it sleeps when the heating process is disabled. The paper set the stage for future work on how to formally model the CBR for more heterogenous building setting.

V. Future work

In this paper, we only presented the results obtained from applying the EACRA in an educational building during w weekday. In future work, we will expand the WSN network in terms of the number of sensor node, develop the context recognition approach, and finally, develop an Energy Aware Context Recognition Protocol which is based on the EACRA. This protocol will be applied on all different building types (educational, administrative, and residential) in the university campus.

VI. Acknowledgment

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VII. References

[1] Najem, Naji, et al. "Context-Aware Wireless Sensors for IoT-Centeric Energy-Efficient Campuses." 2017 IEEE International Conference on Smart Computing (SMARTCOMP). IEEE, 2017.

[2] Khalil, N., Abid, M. R., Benhaddou, D., & Gerndt, M. (2014, April). Wireless sensors networks for Internet of Things. In 2014 IEEE ninth international conference on Intelligent sensors, sensor networks and information processing (ISSNIP) (pp. 1-6). IEEE.

[3] Wang, Z., Yang, R., & Wang, L. (2010, November). Multi-agent control system with intelligent optimization for smart and energy-efficient buildings. In IECON 2010-36th Annual Conference on IEEE Industrial Electronics Society (pp. 1144-1149). IEEE.

[4] Rocha, P., Siddiqui, A., & Stadler, M. (2015). Improving energy efficiency via smart building energy management systems: A comparison with policy measures. Energy and Buildings, 88, 203-213.

[5] Abid, M. R., Lghoul, R., & Benhaddou, D. (2017, September). ICT for renewable energy integration into smart buildings: IoT and big data approach. In AFRICON, 2017 IEEE (pp. 856-861). IEEE.

[6] EHLERS, Gregory A. et BEAUDET, Joseph. System and method of controlling an HVAC system. U.S. Patent No 7,130,719, 31 oct. 2006.

[7] Naji, N., Abid, M. R., Krami, N., & Ben Haddou, D. (2018, October). CASANET Energy Management System: a Wireless Sensors based solution for Heaters Control. In Proceedings of the 2nd International Conference on Smart Digital Environment(pp. 148-153). ACM.

[8] Moen, R., & Norman, C. (2006). Evolution of the PDCA cycle.

[9] Bikakis, A., Patkos, T., Antoniou, G., & Plexousakis, D. (2007, November). A survey of semantics-based approaches for context reasoning in ambient intelligence. In European Conference on Ambient Intelligence (pp. 14-23). Springer, Berlin, Heidelberg.

[10] Kinney, P. (2003, October). Zigbee technology: Wireless control that simply works. In Communications design conference (Vol. 2, pp. 1-7).

[11] Dhand, G., & Tyagi, S. S. (2016). Data aggregation techniques in WSN: Survey. Procedia Computer Science, 92, 378-384.

[12] Perkins, C., Belding-Royer, E., & Das, S. (2003). Ad hoc on-demand distance vector (AODV) routing (No. RFC 3561).

[13] "Digi XBee Series 2 S2C data sheet", [online] Available: https://www.digi.com/resources/documentation/Digidocs/90001506/reference/r_dm_throughput.htm?TocPath=Networkingv