The Wireless Sensor Network and Local Computational Unit in the Neighbourhood Area Network of the Smart Grid

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Abstract: The Smart Grid intends to provide good power quality, energy cost reduction and improve the reliability of the electricity Grid. Electricity Grids exist across a wide hierarchy of voltages and spatial scales. In this paper we particularly investigate the deployment of monitoring systems in the urban environment, specifically in a university campus that is embedded in a city. Monitoring at this level of the Grid is very underdeveloped, since most current Grids are controlled centrally and the response of the neighbourhood area is not generally monitored or actively controlled. We develop a communications architecture that can integrate sensor network applications. We provide both for sensors that directly measure the electricity activity of the network and also sensors that measure the environment (e.g. temperature) since these provide information that can be used to anticipate demand and improve control actions. Energy efficiency is a major design driver for our architecture. Finally we analyse the optimal number of clusters in a wireless sensor network for collecting and transmitting data to the local control unit for applying finer-grained control.

1 INTRODUCTION

In planning for future electricity supply issues such as increased energy usage, urbanization, reduction in personnel, global warming and conservation of natural resources need to be considered. As the result some countries have investigated the transformation of their existing power grid to the so-called Smart Grid. A Smart Grid adds a communication network to the power network. Until now most research has focused mainly on wide area and home area communications networks. Contrariwise we have investigated communications in the neighbourhood area network (street level or local area network) in the distribution sub-Grid. At this level there is currently a lack of monitoring and predictive real-time system control. We have proposed an ICT architecture to integrate sensing, computation and decision-making to enable prediction of the future state of the sub-Grid in the real-time. A Wireless Sensor Network (WSN) is considered as an essential component of the monitoring function. The WSN is responsible for monitoring and collecting real-time data from the field. It will send live data to a Local Control Unit (LCU) to provide more accurate prediction. Since these sensors are envisaged to be battery powered our system design is aimed at investigating the energy constraint problem of WSNs.

In this paper we focus on an urban area (street level) of the Smart Grid, with the aim to support Smart Grid applications. The remainder of this paper is organized as follows: Section 2 demonstrates the abstract view of our proposed architecture, section 3 discusses the deployment view, section 4 quantifies the optimal number of clusters required in the neighbourhood area of the Smart Grid. Finally section 5 presents conclusions and future works.

2 THE COMMUNICATION ARCHITECTURE

Noticing that the predictive real-time system requires real-time information, our proposed architecture (Pourmirza and Brooke, 2012) intends to collect real-time data, analyse them, convert them to information and finally based its action up on them. It is a modular architecture that combines the peer-to-peer and hierarchical architectures, to utilize various communication technologies for transmitting

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data. It represents the integration of sensor networks and distributed computation.

The difference between our architecture and other communication architectures in the Smart Grid is that we are particularly linking it to the area in the sub-Grid, where we are concerning about the energy efficiency of the communication system. An example of the recommended communication network for the Smart Grid, bases itself on the Gossip algorithm (Krkoleva et al., 2011) that provides robust communication. It is believed to be a suitable candidate for sub-Grid applications in Smart Grid systems. However, since it does not take the energy efficiency of the system in to account, it is not the optimal solution for the WSN in our grid.

Our proposed architecture consists of six layers. The first three layers are responsible for sensing, measuring and collecting data. The other layers present the database layer and two control layers.

In this paper we focus on the first two layers of the architecture that are considered as a WSN. Due to the energy constraint drawback of wireless sensors, we intend to reduce their energy consumption. As a result the cluster based communication algorithm for WSN has been selected as a method of communication. Consequently, the first layer of the architecture which is composed of hundreds of sensors situated in the street areas are grouped into clusters, sending their data via Bluetooth directly to the more powerful sensor designed to be the Cluster Head (CH). Since Bluetooth with extended antenna can cover up to 100 meters, we believe it is a good candidate for providing communication within the clusters. These sensors sense attributes such as temperature, humidity, traffic, motion, occupancy and so on. The CHs, the second layer of the architecture, are responsible for transmitting the received data to the database via wireless LAN (e.g. IEEE 802.11b) or cellular technology.

The third layer consists of few sensing units located at the substation communicating via FTP and TCP for transmitting live data to the test and control unit using wired and wireless technologies such as GPRS. These units monitor three phase voltages, currents, frequency, and power factors and so on.

The fourth layer is a test and control unit that is responsible for applying control over the substations only. The fifth layer is the DB layer that will store the aggregated data received from layers below, and feed the LCU with collected data. The LCU, that is the top layer will apply control over the entire neighbourhood area. It can access sensing units directly in emergency situations, or indirectly through the DB layer in normal conditions.

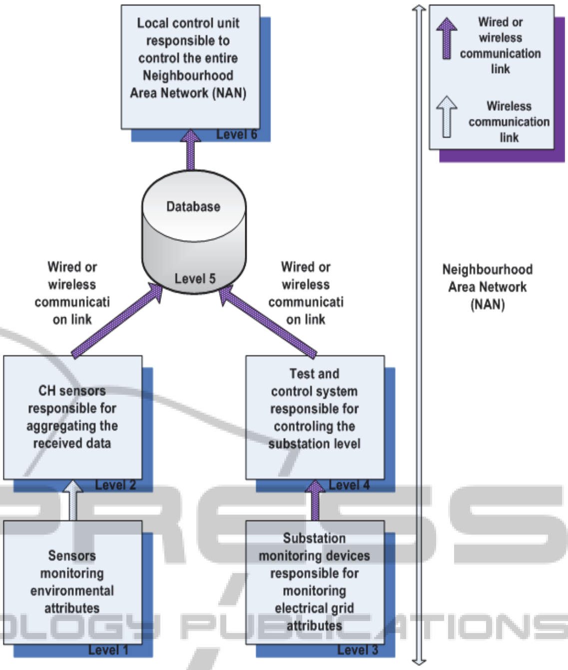


Figure 1: Abstract view of the proposed architecture.

We present evidence (Section 4) that the proposed architecture will bring energy efficiency to the communication network. Given that the energy for data transmission is higher than energy for data computation (Heinzelman et al., 2000), by reducing the transmission range and adding more computation unit we may achieve an energy efficient architecture.

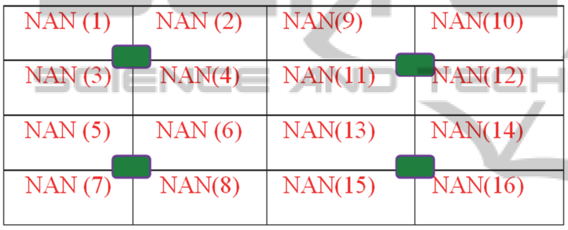
3 DEPLOYMENT AND ASSUMPTIONS

This architecture is going to be deployed in the university sub-Grid. The university campus is embedded in a city, containing streets and road. The whole campus is connected by rectangular grid.

The relevant WSN would be the streets connecting the campus buildings (first and second layer of the architecture). The relevant electrical sensing would be the substations (third layer) that are equipped with monitoring systems. In this project the sensors cannot be deployed anywhere in the grid. Since we are dealing with an urban area the sensors are located at fixed locations. We choose to put the sensors on the street level, which means we are dealing with a rectangular grid.

The proposed environment is a heterogeneous WSN in which the CHs are more powerful sensors than the cluster members. Since the sensors and CHs are static and the CHs are predefined there is no need to establish a connection between the sensors and the CHs at the beginning of each round of transmission. Establishing a connection happens only once during the network lifetime, thus we ignore the energy spent for handshaking in our analysis.

For modelling the energy consumption of the neighbourhood area network (NAN), we could locate the LCU either in the centre or corner of each area. Since neighbourhood areas need to talk together, we have located the LCU at the corner of the area to make their communication easier. Moreover, having the LCU at the corner of one neighbourhood area makes it at the centre of four neighbourhood areas (figure 2). Thus by having one LCU we can serve four neighbourhood areas, which is efficient for installation costs and maintenance.



NAN (1)	NAN (2)	NAN(9)	NAN(10)
NAN (3)	NAN(4)	NAN(11)	NAN(12)
NAN (5)	NAN (6)	NAN(13)	NAN(14)
NAN (7)	NAN(8)	NAN(15)	NAN(16)

Figure 2: Each LCU (shown as a green rectangle) serves four Neighbourhood Area Networks (NANs).

4 COMMUNICATION ENERGY CONSUMPTION COST

The WSN suffers from the lack of resources such as shortage of power and processing capabilities. Difficulties arise when the deployed sensors in the Smart Grid are short on power, thus a specific area of the grid is no longer being monitored at a sufficient rate. Given that real- time data is being used in the control layer, this may result in wrong decision making in the grid. In order to reduce the energy limitation drawback of the wireless sensor, we examine the energy consumption cost of a network, and identify the optimal topology of the WSN for the specific applications. Depending on the purpose of the sensor network, the networking topology, communication protocol and Quality of Service (QOS) requirements may vary. This will affect the design of the WSN architecture.

We create two scenarios. The first scenario is direct communication where each sensor transmits its data to the database layer in our architecture to be controlled by LCU. The second scenario is cluster-based communication, where a number of sensors are grouped in to clusters and CHs are responsible for compressing and transmitting the collected data to the database. The result shows that cluster based communication is more energy efficient than direct communication in our specific network. A study on the WSN (Prakash et al., 2009), also confirms our result that the cluster-based networks provide more energy efficiency. Their result allows the sensors to be placed anywhere in a 2-D region, here we show that the result also applies when the sensors are constrained to be on a rectangular grid.

In the WSN each sensor consists of the sensing unit, processor unit, and transmission unit. Each of these units consumes energy while sensor is running. In our analysis we have used a first order radio model described in (Heinzelman et al., 2000) for analysing the energy spent in transceiving the data, energy used for sensing, and energy consumed for data computation. First the sensors will spend the energy on sensing the K bits of data (E_{se}). In order to send the sensed data, the sensor will spent energy for running the transmitter circuitry (E_{stt}) and energy for transmitting k-bit messages to destination located at the distance d (E_T). Although the energy spent during the communication does not quite scale with the distance, but using the sensor coordinates for analysing the distance is an approximation of how much energy will be spent during the communication (Heinzelman et al., 2002).

Moreover in the sensors which are responsible for receiving, compressing and sending the data to the next destination, the energy is used for running the reception circuitry (E_{str}) plus the energy for receiving the data (E_R) and energy for computation (E_C). Given that the energy spent for a single transmission is n times bigger than the energy spent for single instruction execution (Hingne et al., 2003), we assume the energy spent in computation is $E_C = E_T/n$. Table 1 demonstrates the energy calculations used in our analysis and table 2 define the parameters used in our calculations.

With the aim to achieve the most energy efficient topology of a grid we should find the optimal number of cluster in our specific network. As such we divide the network in to different number of clusters. We kept the number of sensors in the NAN fixed and created networks with 4 clusters, 6 clusters, and so on, ending with 16 clusters. We assumed that the CHs consume two times more energy than the normal sensors. Then we simulate each network by varying the number of nodes in the clusters, cluster shapes and locations for 12 different configurations, all of which preserve the number of clusters, to estimate the variance. Since in reality we are not always able to deploy the sensors in the most optimal topology, we consider the average of these 12 configurations.

Table 1: Energy consumption for each section.

Energy calculation	Definition
$E_{se} = E_{elec} \times K$	Energy for sensing data
$E_{stt} = P_t \times T$	Energy for starting up the transmitter circuitry
$E_T = E_{elec}k + E_{amp}Kd^2$	Energy for transmitting data
$E_C = \frac{E_{elec}k}{n}$	Energy for computation
$E_{str} = P_r \times T$	Energy for starting up the reception circuitry
$E_R = E_{elec}K$	Energy for receiving data

Table 2: Parameter definition and representative values.

Parameter	Value	Definition
E_{elec}	$5 * 10^{-8}(^J/_b)$	Energy disseminated by the radio per bit to run the transceiver and sensor circuitry
E_{amp}	10^{-10} (J/b/m^{2})	Energy spent per bit per m^2 for the transmit amplifier
P_t	0.66 watt	Power used in transmitter circuitry
P_r	0.395 watt	Power used in receiver circuitry
T	0.001 second	Start up time
K	2000 bits	Number of bits of data
d	variable	Distance between sending sensor and receiving sensor
N	variable	Number of nodes in each cluster
c	variable	Number of clusters
n	3	Computation to communication ratio
r	2	Compression ratio(e.g. *K* bits of data are compressed to *k/2*)

In this analysis we consider a rectangular grid in which the LCU is located at the corner of the network. Given these network assumptions, we analyzed the total energy consumption in each scenario. The total energy spent in the system is the sum of energy spent by each individual sensor for sensing and sending data to its CH called $E_{sensors}$, plus the energy spent by the CHs to receive the sensed data, compress them and send the compressed data to the LCU called E_{CHs}.

$$E_{sensors} = N(E_{se} + E_{stt} + E_T) \tag{1}$$

$$E_{CHs} = c\,(E_{se} + E_{str} + NE_R + (N+1)E_C + E_{stt} + (N+1)/rE_T) \tag{2}$$

Figure 3 plots total energy consumption against the number of clusters. The curve shows a minimum at 8 clusters. It also shows that the variation between 6 and 14 clusters is very small, i.e. the shape of the minimum is asymmetric. The result that the minimum occurs at 8 clusters is a function of the total size of our grid (10x10) and the amount of energy consumed by the CHs; however, the methods could be used on grids of arbitrary size and CHs.

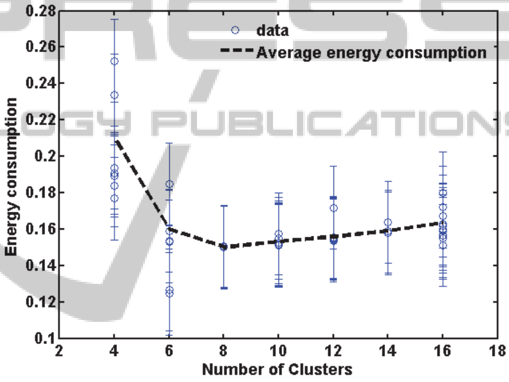


Figure 3: Energy cost analysis of a grid with different number of clusters.

Additionally it has been concluded that the shape and location of the clusters are also determining factors for energy consumption. The results show that if the clusters are rectangular, then the best result is when the rectangle is square. Also we observed that if we allow cluster sizes to be different, then if smaller clusters are near the LCU, and bigger clusters are located farther from the LCU, this improves energy efficiency. Figure 4 compares the total energy consumption of a grid with 12 clusters, with different topologies. It shows how the different arrangement of the sensors offers optimal energy efficiency.

5 CONCLUSIONS

This paper has considered the neighbourhood sub-Grid level of the electrical network where monitoring has not previously been deployed. We

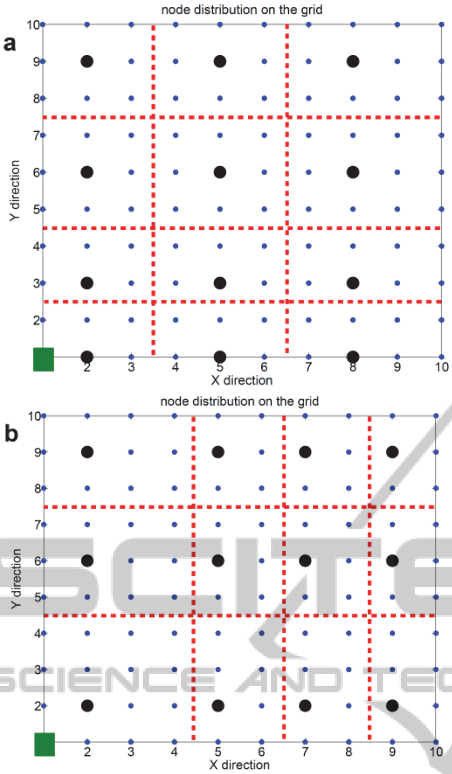


Figure 4: The effect of clustering location (CH is the black circle) on the total energy consumption. In the first topology E=0.1551, while in the second one E=0.1781.

have proposed a communication network architecture and analysed its design in terms of offering energy efficiency for a local control system. We evaluated experimentally a WSN placed on a rectangular grid representing a city environment. The results confirm, for this environment, previous results that cluster based communications are more energy efficient than direct communications. By varying the number of clusters we established that there exists an optimal number of clusters in terms of energy efficiency, for a given size of rectangular grid. For a given number of clusters there are particular arrangements of the clusters that give a deeper minimum. Thus the number of clusters, their shapes and the way the clusters are geographically grouped are important in energy efficiency of the system.

Finally a further study needs to investigate the optimal data reduction algorithm to be used in the WSN. The final stage of our work is to use the collected data from the sensors to calibrate a simulation that then can be used to test strategies for control of the campus grid, providing a pattern for control of local Smart Grids.

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