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Solar Powered SCADA Infrastructure Serving Different Smart Grid Applications

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Abstract— This paper deals with the design issues of a green Supervisory Control and Data Acquisition (SCADA) communication infrastructure. We suggest enhancing the reliability of the SCADA system using a self powered wireless ad-hoc network technology. The suggested SCADA infrastructure consists of various types of wireless nodes called Wireless SCADA Router (WSR). Here, we propose that WSRs can harvest the energy needed for their work from the surrounding environment, especially solar energy. In order to evaluate the power consumption of the proposed WSR under realistic SCADA traffic conditions, a simulation model is built using OPNET simulation package. Different scenarios are run to determine the effect of the different parameters on the network traffic and hence, the WSR power consumption. The different network traffic patterns generated from running the simulation model are used in an experimental network based mainly on UBICOM IP2022 network processor platform (as the implementation of the proposed WSR). In order to decrease the power consumption of the suggested WSR and to extend the life time of the batteries, a new power management scheme called "Controlled Duty Cycling (CDC)-Event Driven Duty Cycling (EDDC)" is suggested and implemented. According to this method, the WSR must follow Sleep/Active periods scheme and perform based on its available energy. The service rate of the WSR is determined as a function of the WSRs' power budget.

Keywords— Duty cycling, researchable batteries, smart grid, supervisory control and data acquisition (SCADA), solar energy harvesting, wireless SCADA router (WSR).

I. INTRODUCTION

Smart grid is a contemporary electric power grid infrastructure to enhance effectiveness, consistency and safety. It is a soft combination of renewable and alternative energy sources throughout automated control and modern communication technologies. In the smart grid, the reliable and real-time information exchange becomes the key factor for consistent delivery of power from the generating units to the end-users [1]-[4].

To support the management and control of the smart grid, automation processes like SCADA were developed and implemented. SCADA systems control and monitor the equipment necessary for power delivery. SCADA systems have a broad range of functions which are essential to the operation of the electrical power utility. These functions consist of identifying and isolating faults, and restoring service, circuit breaker and re-closer control, feeder switching and reconfiguration, line switching, voltage control, load management, automatic meter reading, automatic generation control, economic dispatch, simulation and emulation, capacitor bank switching, voltage regulator monitoring, transformer temperature, and metering [5]. The main element of the SCADA system is the SCADA master which is a computer system running proper SCADA software under a suitable operating system [6]. On the other hand, the SCADA system also consists of remote terminal units (RTUs) positioned in the different parts of the utility such as substations and power plants. They communicate their data with the SCADA master or with other RTUs through communication links such as optical fiber, radio, telephone line, microwave, satellite, or Ethernet [6]. SCADA systems can also be linked to the local area network (LAN). This enables anybody in the LAN with the

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approved authentication and applications software to be able to contact the SCADA system [7].

Communication network reliability is an essential concern in power systems. By means of reliability, we require that system faults take place with the minimum possibility; its impact on the entire power system is minimized; and the dysfunctional module is restored to the regular functioning status in the shortest time. In view of the fact that communication networks play a fundamental role in the intelligent and automated energy system management, their reliability issues are a significant part of the power system reliability. Thus these issues need to be addressed carefully. More importantly, given the time importance of some types of messages in power systems, it is not easy to find the reliability solutions that meet the firm delay necessities at the meantime [8].

Communication networks are not deployed widely in conventional power systems. As such, the existing research efforts on power system reliability have mostly focused on the identification of reliability problems [9]–[12], the definition of reliability metrics [13], and evaluation of reliability models [14], [15] for power devices. Communication network reliability [16]–[19] and the reliability of its connection to the power system [20]–[22] are still in a primitive research stage.

In this paper, we suggest enhancing the reliability of SCADA communication infrastructure by using a self powered wireless ad-hoc communication network. In this context, we are dealing with the different challenges resulting from the practical implementation of such systems by answering the following questions:

1. What are the different logistic requirements to build a self powered SCADA communication system?
2. What are the different factors governing the behavior of the system, its evaluation metrics and performance measurement?
3. Is it possible to use a power-managed network processor to act as the main player in such a green infrastructure?

II. THE SUGGESTED SELF POWERED SCADA COMMUNICATION INFRASTRUCTURE

Communication problems can be largely reduced if networks are carefully implemented and operated, but they can never be eliminated. Having backup communication solutions is always a good practice to improve network reliability further. For every important end-to-end connection path, one or more alternative routing paths should be planned ahead of failure occurrences. The original and alternative paths should have minimum intersections to enhance the robustness of each individual path. Automatic failure detections and path switching are needed to resume communications instantly at the time of disruption in the original path [8].

In this paper, we suggest enhancing the reliability of SCADA communication networks using the wireless ad-hoc network technology. We suggest the employment of a standby wireless network which is activated to carry out the data of the SCADA system in the event of traditional network failure or in response to a SCADA network extension. The suggested SCADA infrastructure consists of various types of wireless fixed (or even mobile) nodes performing different actions according to applications' demands. An important class of these nodes is the Wireless SCADA Router (WSR). Each WSR is responsible for providing different SCADA services to SCADA clients (e.g. RTUs) in a certain area of the network, ranging from transferring the data and control signals, SCADA masters’ remote access and even multimedia services. WSRs, as part of the SCADA infrastructure, receive different packets from the RTUs before they forward them to the SCADA master. These WSRs would create an ad-hoc network in order to assist each other to deliver data packets to their destinations. That is why a suitable ad-hoc routing protocol is needed (Fig. 1). As a member in the ad-hoc network, WSR also behaves as a router in order to deliver other WSRs traffic to their destinations. The adoption of an ad hoc networking to enhance SCADA system reliability is much superior over other wireless and wired methods. Ad hoc networks are established among the nodes without the use of a centralized infrastructure or administration. The ownership, installation and maintenance cost is lower than other networking methods.

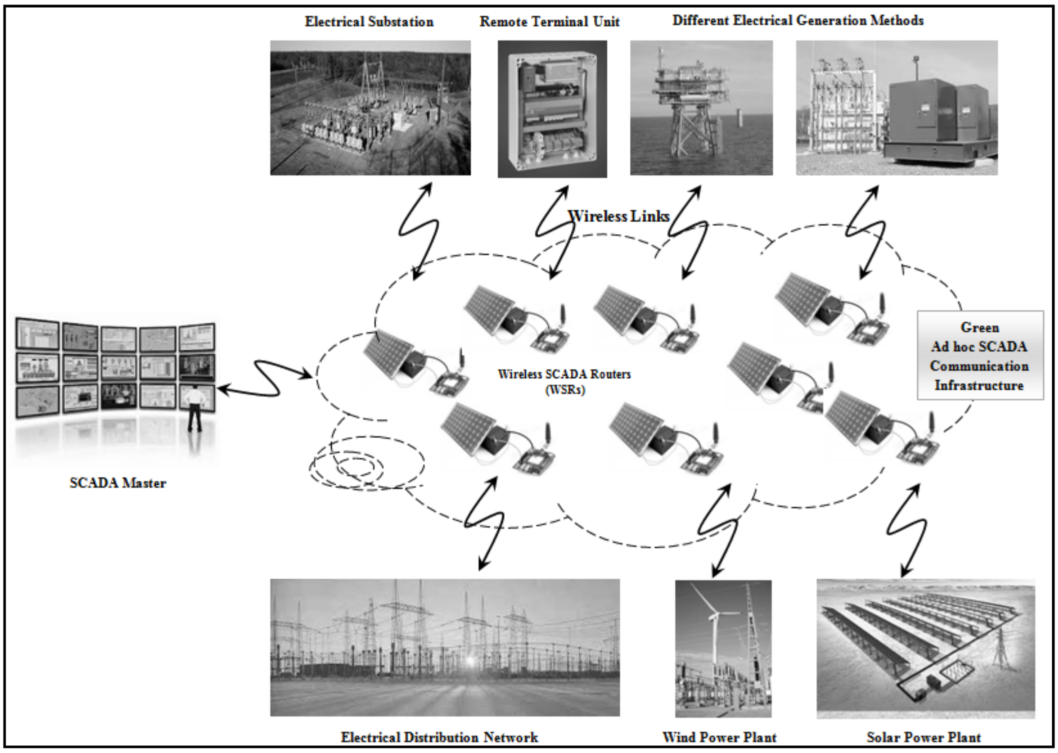


Fig. 1. Green ad-hoc SCADA communication infrastructure

Due to power supply requirements, the WSRs should be localized near to wired electricity sources. However, such a placement limits the area covered by the suggested SCADA infrastructure and its services. In order to overcome this restriction, it is required to establish self powered WSRs. Here, we suggest that WSRs can harvest and store the energy needed for their work from the surrounding environment, especially the solar energy, (Fig. 1). Such a suggestion permits to install WSRs in any place without considering the power supply availability. Hence, the extensive area is covered by the SCADA infrastructure.

It is expected that WSRs are subjected to different network traffic conditions which significantly affect their power consumption and hence their running period. In this paper we are focusing on prolonging the service time of the WSRs using a suitable power management scheme. Many power management methods were developed throughout the past few years [23]; one of the most successful approaches is duty cycling. Duty cycling is an approach intended to save energy; hereby, the embedded nodes regularly change between an energy demanding status (active) and a low energy (sleep) status [23]. In energy demanding states, nodes can do all the normal duties of an embedded node, whilst nodes in the low energy states are limited to specific tasks in order to save energy [24]. Traditionally, the duty cycling protocols used for embedded systems can be implemented either as an independent sleep/wakeup protocol running on the top of a MAC protocol (typically at the network or application layer), or strictly integrated with the MAC protocol itself [24]. In this paper, we adopt the first approach and suggest a new methodology in order to reduce the consumed power to the lower possible limits with a minimum effect on the performance. This methodology, we called "Controlled Duty Cycling (CDC)–Event Driven Duty Cycling (EDDC)", involves two steps: dynamic duty cycle estimation and the governance of the WSR behavior during active periods.

A. Controlled Duty Cycling (CDC) Algorithm

In this paper, we suggest that a WSR should perform according to its available energy. The service rate of the WSR is determined as a function of the WSRs' power budget. In this algorithm, sleep periods are chosen dynamically (in each day) according to many factors such as the WSR power consumption, weather conditions and amount of the stored energy.

In this context, we need to derive a relation among Duty Cycling periods, Average Service Rate (ASR) and the Available Energy (AE). We firstly start by defining the following terms:

- Average Service Rate (ASR) is the average of the total traffic (in bps) transmitted and received from/to the WSR.
- Duty Cycling Periods: this paper divides time into time slots. Hence, the Duty Cycle is the ratio of the active period to the total slot time.
- Available Energy (AE) is the summation of the residual energy in the batteries from the last day plus the expected energy in the next day.

Our approach involves the following steps:

At the beginning of each working day, a WSR calculates the Available Energy (AE) as follows:

$$AE = RE + EE \tag{1}$$

where:

RE is the residual energy from the last day; *EE* is the expected harvested energy in the present day. *RE* of the batteries can be found as:

$$RE = (\text{Initial Energy} + I_{in} \cdot \text{Effective Charging Time}) - I_{out} \cdot 24 \tag{2}$$

It is obvious that in order to calculate the RE, WSR needs to measure the current flowing to/from the batteries (I_{in} and I_{out} respectively) during the whole working day. Our measurement process involves taking a sample every one second, and calculating average current values in each hour. The Effective Charging Time represents the number of hours in which the current drained from solar panels is greater than zero.

In order to estimate the value of EE, we suggest that the SCADA Master should broadcast (to all WSRs) weather forecasts and the effective charging time for this particular day. This weather report includes the expected weather (Sunny, Cloudy or Rainy) and the number of useful charging hours. Our measurements indicate that the highest current could be acquired on sunny days, 70% of this value in cloudy weather and about 50% of the maximum current on rainy days. As a function of the current measurement procedure mentioned earlier, the WSR can determine the expected current value according to its historically recorded current values in similar weather conditions. Hence, EE could be calculated as:

$$EE = \text{Average Expected Current} \ . \ \text{Effective Charging Time} \tag{3}$$

The next step is to calculate the Average Service Rate (ASR) of the WSR on this particular day according to the value of the *AE*. The relation between Service Rate (SR) and AE could be derived by determining the power consumed according to the WSR activities as follows:

$$AE = ETX + ERX + E_{Proc.} + E_{Sleep} \tag{4}$$

ETX is the energy consumed during data transmission. It can be expressed as:

$$ETX = I_{TX} \ . \ \text{bit time during transmission} = SR\left(\frac{I_{TX}}{n.\text{Data Rate}}\right) \tag{5}$$

ERX is the energy consumed during data reception. It can be expressed as:

$$ERX = I_{RX} \ . \ \text{bit time during reception} = SR\left(\frac{I_{RX}.(n-1)}{n.\text{Data Rate}}\right) \tag{6}$$

$E_{Proc.}$ is the energy consumed during data processing. It can be expressed as:

$$E_{Proc.} = SR\left(\frac{I_{Proc.}}{\text{WSR Processing Speed}}\right) \tag{7}$$

E_{Sleep} is the energy consumed during the Sleep mode. It can be expressed as:

$$E_{Sleep} = SR\left(\frac{I_{Sleep}.\text{WSR Processing Speed} - I_{Sleep}}{\text{WSR Processing Speed}}\right) \tag{8}$$

Now, the final relation between *AE* and the Service Rate (SR) can be expressed as:

$$SR = \left(\frac{AE-d}{a+b+c-e}\right) \tag{9}$$

where:

$$a = \left(\frac{I_{TX}}{n.\text{Data Rate}}\right)$$

$$b = \left(\frac{I_{RX}.(n-1)}{n.\text{Data Rate}}\right)$$

$$c = \left(\frac{I_{Proc.}}{\text{WSR Processing Speed}}\right)$$

$$d = 24\, I_{Sleep}$$

$$e = \left(\frac{I_{Sleep.}}{\text{WSR Processing Speed}}\right)$$

Finally, ASR could be calculated as:

$$ASR = 0.5\, SR \tag{10}$$

The next step is the mapping procedure of the ASR value to suit different rates of the applied load. ASR represents the service rate for the average number of vehicles. Mapping is necessary in order to afford a variable service rate according to the variation in the number of vehicles. This step requires that WSR has the ability to predict the future load according to its historical behavior. We have developed an Artificial Neural Network (ANN) based predictor and performed experiments to prove its accurate prediction ability with low overhead suitability for dynamic real time settings similar to this system model. Our three layers network with a learning rate of 0.25 has reduced the mean and standard deviation of prediction errors by approximately 65% and 73%, respectively. The network needs 30 minutes to be trained with 2016 samples, and designed to predict the traffic volume given the past four values of the time series. A set of 2016 consecutive 5-minute samples were extracted from the data available. This is the volume of 7 days. The set was divided into a training set (5/7 days of week) and a test set (2/7 days of week). The model generates a forecast for the next 24 hour period from the daily traffic profile. The evaluation of the model performance can be done by the Mean Square Error, calculated as the difference between the forecasted and actual demand. The average errors for the forecasting up to 24 hours are about 0.007.
The last step is to calculate the sleep period in each time slot. Average Sleep Period (ASP) can be found easily using the following equation:

$$Average\ Sleep\ Period = 1 - \left(\frac{ASR}{Data\ Rate}\right) \tag{11}$$

The same mapping procedure mentioned earlier is applied to calculate different values of sleep periods according to the variation in the applied network load.

B. Event Driven Duty Cycling (EDDC)

In this paper, we suggest that the behavior of the WSRs during active periods is governed by two factors: WSRs' scheduled tasks or in response to a packet reception event targeted to this WSR. The suggested Event Driven Duty Cycling (EDDC) technique makes use of the important feature of "Clock Stop Mode", in which the system clock may be disabled. This results in disabling the CPU core clock and the WSRs' motherboard. When the system clock is disabled, the interrupt logic continues to function, and a sleep timer is enabled to keep running. Recovery from the clock stop mode (sleep mode) to the normal execution is possible using the sleep timer interrupts or in response to an external interrupt from the WLAN NIC. This method does not reset the chip, so the program execution continues from where it was stopped. This mode sends the WSR motherboard only (WLAN NIC is still ON) to the power saving mode in which its circuitry (except the external interrupt circuits, sleep timer and program memory) goes OFF. Whenever an interrupt occurs (due to the reception of a packet by the WLAN NIC or when sleep timer expires), the board wakes up within a few clock cycles to perform the necessary actions, see Fig. 2.

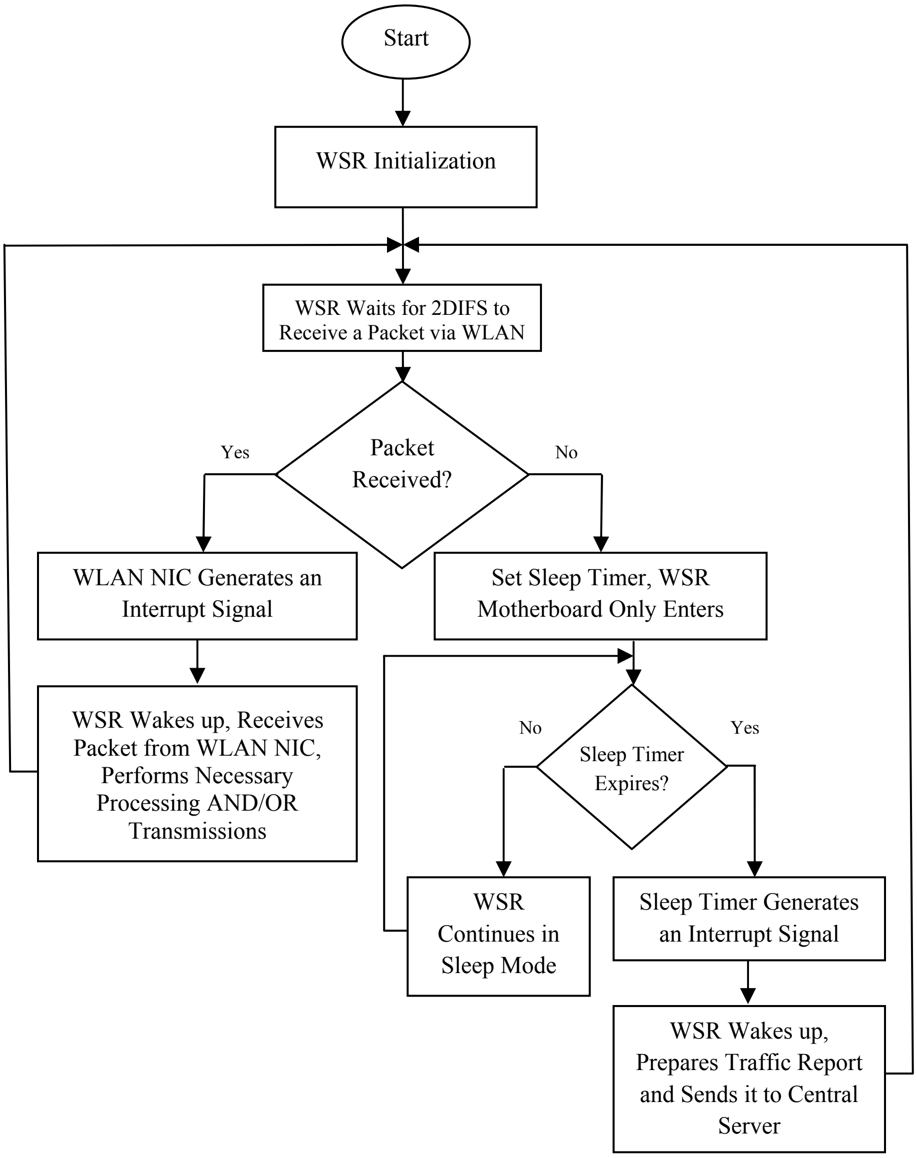


Fig. 2. Functionality of EDDC algorithm

III. PRACTICAL IMPLEMENTATION OF THE SUGGESTED (CDC-EDDC) METHOD

This paper focuses on using solar energy harvesting in providing an alternative power source to supply the WSRs. This paper seeks to employ a simple, efficient and adaptable energy harvesting module which can be used with diverse categories of embedded WSRs. Even though UBICOM IP2022 [25] was chosen to be the proposed WSR, the recommended energy harvesting circuit can be slightly customized to suit other embedded devices. The central part of the harvesting module is Texas Instruments TPS63000 low power boost-buck DC-DC Converter [26], see Fig. 3. The electrical energy produced by the solar panels is routed by the harvesting circuit before it is stored in two parallel AA battery cells with voltage varying between 2.9V and 3.1V [26].

Ubicom IP2022 network processor provides the whole solution as a fully integrated platform: the RTOS (Real Time Operating System), the protocol stack and the necessary hardware. Ubicom's IP2022 chip embeds some basic hardware, but it permits combining it with on-chip software to support the most prevalent protocols. The same device can support Ethernet, Bluetooth wireless technology, IEEE 802.11, and so on. Ubicom's hardware includes the following components [25], see Fig. 4:

- 64kB (32k x 16) Flash program memory
- 16kB (8k x 16) SRAM data/program memory
- 4kB (4k x 8) SRAM data memory (can be extended to 2MB)
- Two SerDes communication blocks supporting common PHYs (Ethernet, USB, UARTs, etc.) and bridging applications
- Advanced 120MHz RISC processor
- High speed packet processing
- Instruction set optimized for communication functions
- Support software implementation of traditional hardware functions
- In-system reprogrammable for the highest flexibility
- Run time self-programmable

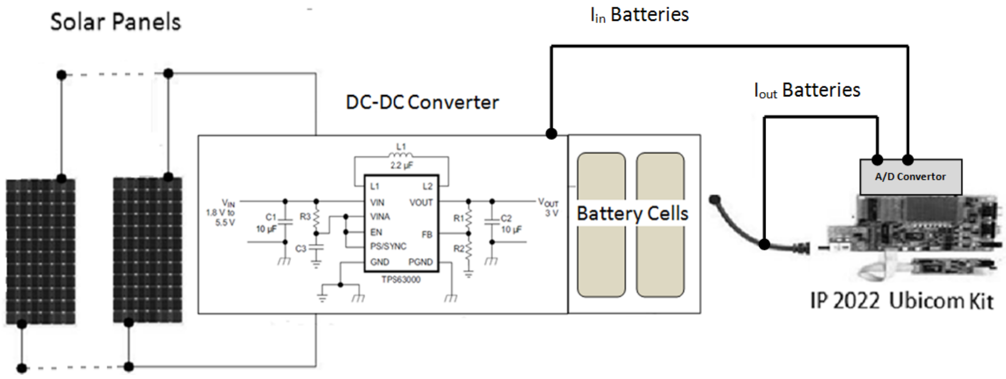


Fig. 3. Application circuit for solar energy harvesting module

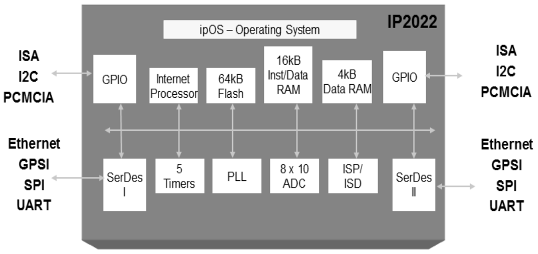
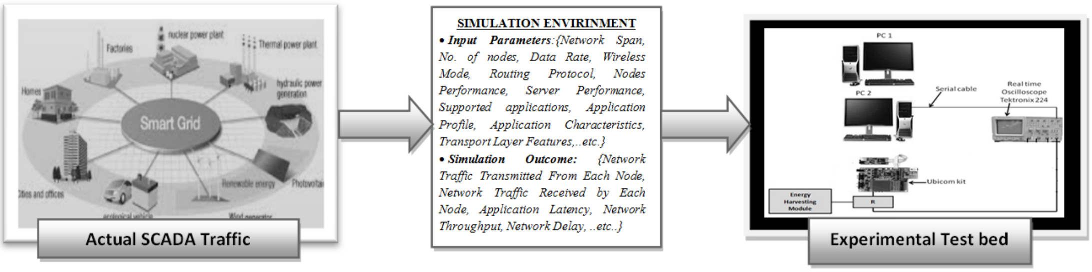


Fig. 4. IP2022 block diagram [25]

In order to evaluate the power consumption of the proposed Ubicom WSR under realistic SCADA network traffic conditions, an experimental framework was built as shown in Fig. 5. According to this model, real SCADA traffic statistics were fed into an OPNET 14.5 modeler in order to generate the required network traffic used by an experimental test bed to emulate a WSR behavior under an actual SCADA traffic.



SIMULATION ENVIRINMENT

- ***Input Parameters***:*{Network Span, No. of nodes, Data Rate, Wireless Mode, Routing Protocol, Nodes Performance, Server Performance, Supported applications, Application Profile, Application Characteristics, Transport Layer Features,..etc.}*
- ***Simulation Outcome:*** *{Network Traffic Transmitted From Each Node, Network Traffic Received by Each Node, Application Latency, Network Throughput, Network Delay, ..etc..}*

Fig. 5. The experimental framework

A. The Simulation Model

Our simulated network represents a typical SCADA infrastructure of 50 WSRs covering ($100km^2$) area. The data traffic generated by the WSRs (resulting from their interaction with the RTUs and other WSRs) is forwarded to the SCADA master using a suitable routing protocol. It was assumed that RTUs broadcast their 200 byte status packets every two seconds [3], while WSRs generate their 1000 byte measurement report 10 times per minute and forward them to the SCADA master [3]. As a result of our earlier analysis in [27], Optimized Link State Routing (OLSR) gives the best performance (it shows less packet delay, less data dropping rate, higher throughput and moderate routing overhead) as compared to other ad hoc routing protocols when working in a non-stationary ad-hoc topology. This is why it was adopted in our simulation model. OLSR is a proactive link-State routing protocol designed for ad hoc networks which show both low bandwidth utilization and low packet delay. OLSR is a type of classical link-state routing protocol, which relies on employing an efficient periodic flooding of control information using special nodes that act as multipoint relays (MPRs). The use of MPRs (WSRs in our case) reduces the number of required transmissions [28]. OLSR daemons periodically exchange different messages in order to maintain the topology information of the entire network. The core functionality is performed mainly by using three different types of messages: HELLO, TC (topology control), and MID (multiple interface declaration) messages. The OLSR mechanisms are regulated by a set of parameters predefined in the OLSR RFC 3626 [28] which was used in our simulation model, see Table 1.

TABLE 1
SIMULATION MODEL PARAMETERS

Simulation Time (minute)	60
No. of WSR nodes	50
Network Span Area (km^2)	100 (10km x 10km)
WSR Modeling Parameters	Packets Processing Rate (Packet/sec.)= 2000 Memory= 2MB
WLAN settings	Data Rate: 18Mbps for IEEE 802.11a
OLSR settings	Hello Interval= 2 sec. TC Interval= 5 sec. Neighbor Hold Time= 6 sec. Topology Hold Time= 15 sec. Duplicate Message Hold Time= 30 sec.

In order to simplify our simulation model, WSRs were assumed to be identical and subjected to the same distribution of the Online SCADA clients shown in Fig. 6. As illustrated in [29]-[32], the clients served by the SCADA system could be either sensor or control devices (such as RTUs or PLCs) which generate data and control signals, a remote access to the SCADA Master by an operator or even much more sophisticated services [29]-[32]. The number and actions of these clients vary with the time as shown in Fig. 6 which shows an illustration case [29]-[32].

Our simulated network was tested with the presence of different SCADA services as listed in Table 2. These services create different network traffic profiles according to users' demands. Here, we assume that SCADA services are not limited to conventional data acquisition and control signals, but they include more sophisticated services such as web page access of the SCADA master made by an operator or even a video conferencing between the control center and a remote unit [29]-[32].

Different scenarios were built to determine the effect of different network parameters on the network traffic and hence, WSR power consumption. In the first simulation scenario, we will determine the most appropriate data rate which gives the best network performance. It was assumed that Application Profile 1 (as listed in Table 2) was the relevance service; and the maximum number of RTUs served by each WSR was 100. Table 3 lists the results obtained from running this scenario. Based on the measured statistics, the 18 Mbps clearly give the best network performance in terms of bandwidth-delay metrics. It will be our choice for the rest of this paper (higher data rates were also tested but gave unstable performance in the nominated TX power, so that their results were discarded).

The effect of varying the number of the served SCADA clients (by each WSR) on the WSR network traffic was studied. The three traffic profiles were tested with the presence and absence of different network applications. According to the users' behavior recorded by [20], it was assumed that 35% of the total SCADA clients were Online and involved in acquiring the various SCADA services. Table 4 shows that increasing the number of SCADA clients adds more traffic to the system (especially the received traffic). Also, multiple applications SCADA consume much higher bandwidth. The listed network traffic was originated from different protocols in the TCP/IP stack. The major contributor was the application layer traffic in both directions (send & receive) while the other traffic sources, such as layer2 and OLSR related traffic, have much less effects. It is useful to mention that the WSR location in the network topology affects seriously its network traffic; and the highest traffic (higher power consumption) was observed in the WSRs nearer to the SCADA master. These WSRs were selected in our experimental model as they represent the worst possible case (from power consumption point of view).

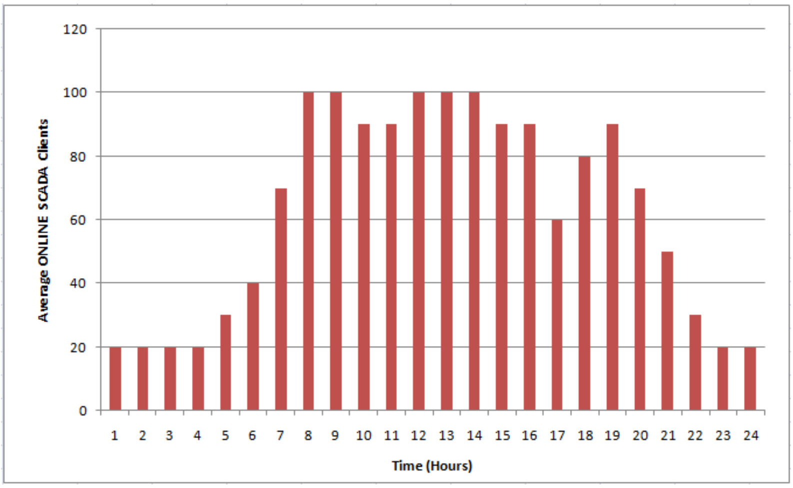


Fig. 6. Daily online SCADA client distribution

TABLE 2
TRAFFIC PROFILES OF THE SIMULATED SCADA NETWORK

Traffic Profile	Applications	Description
1	SCADA Traffic	RTUs to WSR packet length= 200 Byte RTUs to WSR packet rate= 0.5 Packet/sec. WSR to SCADA master packet length= 1000 Byte WSR to SCADA master packet rate= 10 Packet/Minute
	Browsing of SCADA Master Pages	HTTP Protocol Page Inter-request interval= 30 sec. No. of Objects/page= 8 Object Size= (2000 to 10000) Byte, Uniformly Distributed
2	SCADA Traffic	RTUs to WSR packet length= 200 Byte RTUs to WSR packet rate= 0.5 Packet/sec. WSR to SCADA master packet length= 1000 Byte WSR to SCADA master packet rate= 10 Packet/Minute
	Browsing of SCADA Master Pages	HTTP Protocol Page Inter-request interval= 30 sec. No. of Objects/page= 8 Object Size= (2000 to 10000) Byte, Uniformly Distributed
	File Transfer	File Transfer Protocol (FTP) File Size= 1MB Inter-request Interval= 60 sec.
3	SCADA Traffic	RTUs to WSR packet length= 200 Byte RTUs to WSR packet rate= 0.5 Packet/sec. WSR to SCADA master packet length= 1000 Byte WSR to SCADA master packet rate= 10 Packet/Minute
	Browsing of SCADA Master Pages	HTTP Protocol Page Inter-request interval= 30 sec. No. of Objects/page= 8 Object Size= (2000 to 10000) Byte, Uniformly Distributed
	File Transfer	File Transfer Protocol (FTP) File Size= 1MB Inter-request Interval= 60 sec.
	Video Streaming	128 kbps Constant Bit Ratio (CBR)-Compressed Video.

TABLE 3
NETWORK TRAFFIC AS A FUNCTION OF DATA RATE

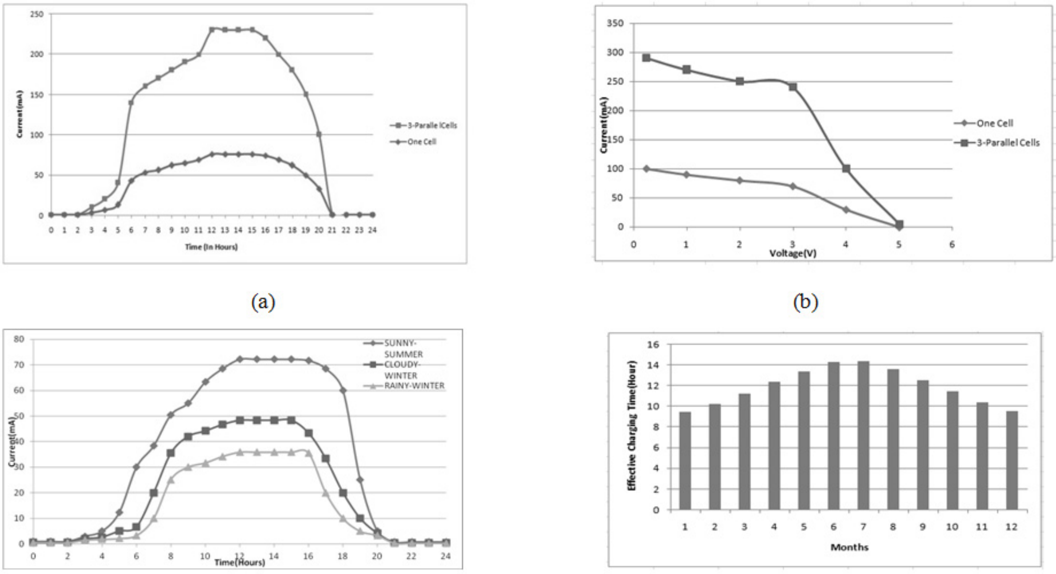
Data Rate (Mbps)	Traffic Sent From each WSR (kbps)	Traffic Received By each WSR (kbps)	Total Traffic (kbps)	WLAN Delay (Sec.)	Measurement Report Transfer Latency (Sec.)
6	55	320	372	0.0005	0.015
12	77	364	441	0.00026	0.012
18	78.7	401	479.7	0.00018	0.01

TABLE 4
SCADA TRAFFIC STATISTICS

No. of SCADA Clients	Traffic Profile 1			Traffic Profile 2			Traffic Profile 3		
	TX Traffic (kbps)	RX Traffic (kbps)	Total Traffic (kbps)	TX Traffic (kbps)	RX Traffic (kbps)	Total Traffic (kbps)	TX Traffic (kbps)	RX Traffic (kbps)	Total Traffic (kbps)
20	53.2	646.8	700	68.4	831.6	900	79.8	970.2	1050
30	205.8	2646	2851.8	264.6	3402	3666.6	308.7	3969	4277.7
60	385	3640	4025	495	4680	5175	577.5	5460	6037.5
80	672	7000	7672	864	9000	9864	1008	10500	11508
100	1869	8120	9989	2403	10440	12843	2803.5	12180	14983.5

B. The Results of the Experimental Test Bed

Different practical experiments were performed to investigate the characteristics of the suggested solar powered WSR under various working conditions. First of all, there is a need to determine the characteristics of the 4-4.0-100 solar panels (from Solar World Inc.), which were adopted in this work. Several tests were performed at different times in the year with a panel that measured 4.25"x2.5", see Fig. 7. The results obtained from these tests show the behavior of solar panels (as an electrical energy source) in terms of their voltage-current relation and the influence of weather conditions and other factors on the amount of the current produced by these panels [26].



(a) (b)

(c) (d)

Fig. 7. Measured characteristics of the Solar World 4-4.0-100 solar panel, a) produced current variation during one day, b) *V-I* curve**,** c) **p**roduced current variation of a solar panel in different weather conditions, d) effective charging time/month

The different network traffic patterns generated from running the previous simulation model were used in an experimental network. The experimental network consists of 2 ordinary PCs (PC1 and PC2) supplied with Belkin Dual-Band Wireless PCMCIA Network Card F6D3010 working at IEEE 802.11a, the IP2022 Ubicom platform with the same WLAN NIC, an energy harvesting module and a real time storage oscilloscope. The roles played by each member of the experimental network can be explained as follows:

- PC1 takes the responsibility of a traffic generator to emulate the behavior of the RTUs and the other WSRs, which forward their traffic packets to the Ubicom platform. The (RX) network traffic pattern shown earlier in Table 4 was taken as the reference to generate the network traffic (bit/s); meanwhile, Ubicom generates the (TX) traffic of the same Table 4.
- PC2 is considered as the master SCADA master and represents the destination to which all the Ubicom traffic is forwarded.
- The real time oscilloscope Tektronix 224 was used to measure the drained current from batteries according to different network traffic conditions.
- Ubicom platform collects different packets from PC1, stores them temporally in its 2MByte external memory. After performing the necessary processing, it sends them out to PC2 as a transmitted traffic.

The objective of the first experiment is to record the current drained by a WSR according to its different modes of operation: Transmission, Reception, IDLE, CPU full load and SLEEP. PC1 was programmed to be a traffic generator to send and receive a 1Mbps streamed UDP traffic to and from the IP2022 Ubicom platform. The real time oscilloscope (Tektronix 224) was used to measure the drained current by measuring the voltage across a 0.1-Ω resistor, which is proportional to the drained current. Table 5 summarizes the settings of this experiment while Table 6 lists the average values obtained for different data rates.

TABLE 5
NETWORK SETUP

Experiment duration in each Case	5 minutes
WLAN NIC	Belkin (a/b/g) Dual-Band WLAN PCMCIA Card
Supply Voltage	3V
RF power	1dBm
WLAN Packet length	1500 Byte
Packet/sec.	84

TABLE 6
MEASURED CURRENT VALUES

Current drained in TX mode	150mA (for IEEE 802.11a)
Current drained in RX mode	120mA (for IEEE 802.11a)
Current drained in IDLE mode (WLAN NIC disconnected)	100mA
Current drained in CPU full load mode (WLAN NIC disconnected)	150mA
Current drained in SLEEP mode (for the Ubicom board only)	1mA

Our tests in the next experiments include measuring two quantities:

- The current drained in the normal mode: In this mode, the Ubicom board and its accessories work without any power management.
- The current drained in the sleep mode: In this mode, the power consumption of the Ubicom board and its accessories is governed by the EDDC power management scheme.

The first results of these experiments are listed in Table 7, which records the current drained from the WSR as a function of changing data rate. It was assumed that 100 RTUs with Traffic

Profile 1 was the initial settings of this experiment. Table 7 indicates that the current drained when working in the sleep mode is much lower than the normal mode for the reason of excluding the current drained during the IDLE state as the motherboard circuitry consumes the power without performing any action. The second extracted remark from Table 7 is that the value of the drained current proportions inversely with the increment in the data rate because the time needed (in Bit time) to achieve the transmission or reception task decreases as the data rate increases; and hence, the WSR consumes less power. Again, a 18Mbps data rate gives the best performance in terms of its efficient power consumption metrics (which supports our earlier choice).

TABLE 7
DRAINED CURRENT AS A FUNCTION OF DATA RATE

Data Rate (Mbps)	Drained Current (mA) Normal Mode	Drained Current (mA) SLEEP Mode
6	114	26.5
12	110	22.67
18	109	21

In order to investigate the power consumption of WSR, we make use of the statistics of Fig. 6 to generate network traffic as a function of the number of the served RTUs and the SCADA applications. Fig. 8 shows that the amount of the average current drained from the WSR varies as network traffic volume changes over time. Also, multiple SCADA applications have a great influence on the drained current because (more network traffic-more WSR processing) is required in order to respond to the user's needs. The effectiveness of the proposed EDDC technique is shown in Fig. 8. The WSR works according to the sleep mode and consumes much less power than the normal mode.

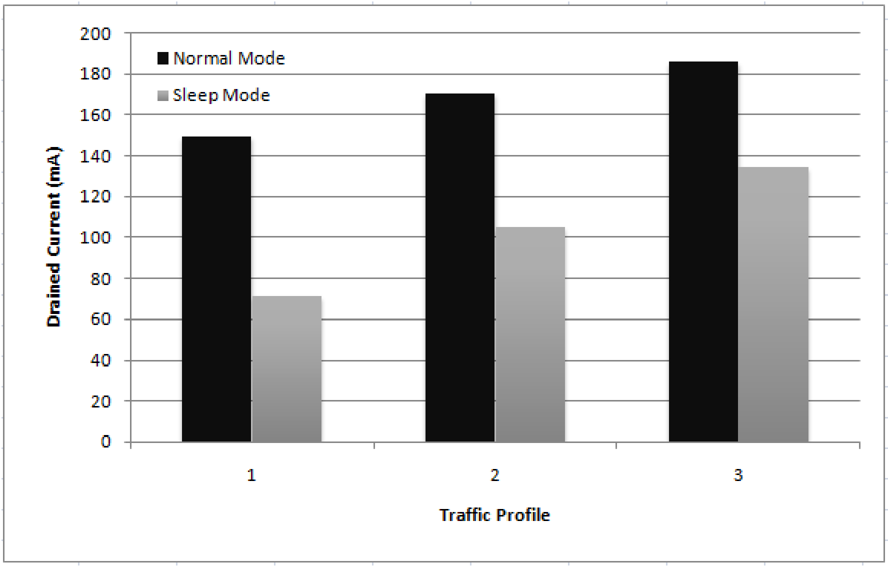


Fig. 8. Average current drained from Ubicom platform according to different traffic profiles

In the next experiment, the CDC technique was implemented in different scenarios. The initial settings of these experiments are shown in Table 8. The purpose of these experiments is to examine the ability of the suggested CDC method to adapt against the different working conditions wherein different available energy (AE) levels were assumed.

TABLE 8
INITIAL SETTINGS OF CDC EXPERIMENTS

Data Rate	18Mbps (IEEE 802.11a)
Traffic Characteristics	Traffic Profile 3 $n= (\frac{RX\ Traffic}{TX\ Traffic})= 4$
Data Processing Speed of the WSR	24Mbps
I_{TX}	150mA
I_{RX}	120mA
$I_{Proc.}$	150mA
I_{Sleep}	1mA
Battery Characteristics	3V, 2800mAh
Solar Panel Dimensions	4.25"x2.5"
Average Current Produced in a Sunny Day Effective Charging Time	34mA 15 Hours
Average Current Produced in a Cloudy Day Effective Charging Time	20.5mA 13 Hours
Average Current Produced in a Rainy Day Effective Charging Time	14.4mA 11 Hours

Fig. 9 shows the daily behavior of the WSR while tracking the load offered by its associated RTUs and other WSRs (for a sample case of 50% RE). Fig. 9 was plotted by mapping the ASR (the service rate for an average number of RTUs) in response to the number of the daily served RTUs as shown earlier in Fig. 6. It is noted that the suggested CDC technique was able to adapt its performance according to the available energy levels. It continues to function in a pre-managed and planned manner.

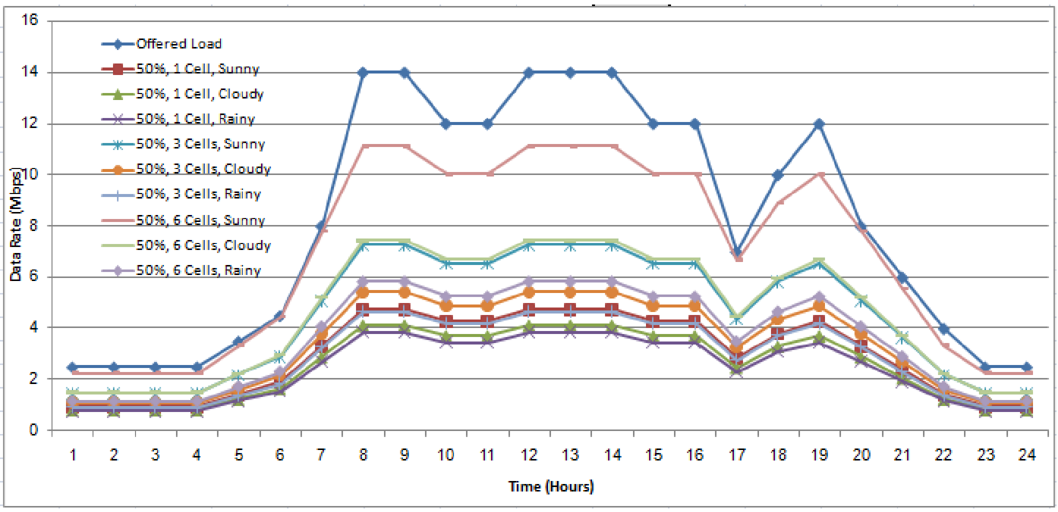


Fig. 9. The daily behavior of the WSR working under CDC technique

The purpose of the last experiment is to examine the ability of the suggested (CDC-EDDC) power management method to defend against unmanaged network traffic conditions, such as those resulting from the energy exhaustive Denial of Service (DoS) attack [21]. Different network traffic rates were sent to the WSR which can work with and without the presence of the suggested power management method. Fig. 10 shows that the battery life of the properly managed WSR was kept the same in spite of the variation in the incoming traffic rates. On the other hand, the battery life was significantly reduced due to the unmanaged power consumption which results from the different received traffic rates.

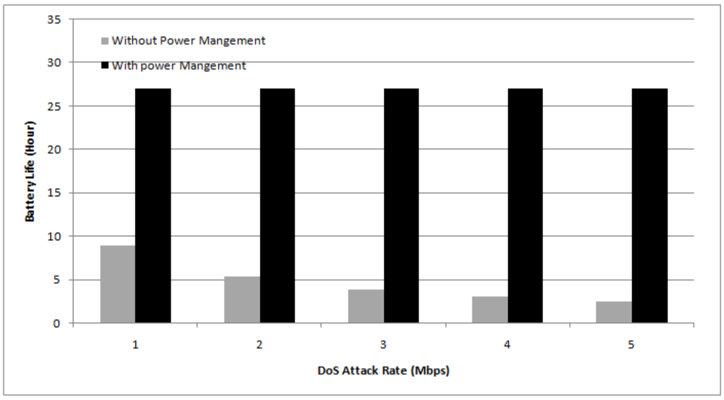


Fig. 10. WSR battery life according to different DoS attack rates

In order to finalize our design procedure, we need to estimate the required number of paralleled solar panels, the number of parallel AA battery pairs and their capacities in order to meet the WSR power requirement under different network traffic conditions. Our analysis was performed using the statistics obtained from running our earlier experiments as shown in Fig. 7 and 8, and Table 4. Table 9 declares that the WSR (when working in SLEEP mode) needs less number of paralleled solar panels and lower battery capacity to run various applications. The results prove the effectiveness of the suggested power management scheme to extend the life of the solar energy harvested-battery based WSRs and their serviceability which will be reflected positively on building a reliable and available green SCADA infrastructure.

TABLE 9
SOLAR PANELS & BATTERY CELLS REQUIRED FOR VARIOUS CONDITIONS

Normal mode Traffic Profile 1	No. of Parallel Solar Cells	5
	Battery Capacity, One AA Pair	1500mAh
Sleep mode Traffic Profile 1	No. of Parallel Solar Cells	2
	Battery Capacity, One AA Pair	100mAh
Normal mode Traffic Profile 2	No. of Parallel Solar Cells	6
	Battery Capacity, One AA Pair	1800mAh
Sleep mode Traffic Profile 2	No. of Parallel Solar Cells	3
	Battery Capacity, One AA Pair	500mAh
Normal mode Traffic Profile 3	No. of Parallel Solar Cells	7
	Battery Capacity, One AA Pair	2800mAh
Sleep mode Traffic Profile 3	No. of Parallel Solar Cells	4
	Battery Capacity, One AA Pair	1500mAh

IV. CONCLUSIONS

This paper suggests the adoption of a self powered communication infrastructure to enhance SCADA systems reliability. The proposed Ad hoc infrastructure consists of self powered wireless nodes called wireless SCADA routers (WSRs). These WSRs were realized using the IP2022 network processor platform which functions according to a novel power management method called duty cycling (CDC)-event driven duty cycling (EDDC). This method can be run locally and independently in each WSR to adapt its power consumption dynamically according to traffic demands, weather conditions and network status in which WSR was installed. The adoption of this method has many benefits in terms of the implementation simplicity, optimum utilization of energy resources and the enhanced network performance. Also, the adoption of this method has a remarkable economic effect because it needs less number of solar panels with an adequate battery capacity. The different experiments, performed in this paper, prove the expediency of adopting this method in order to build a green and self powered SCADA infrastructure.

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