Low Cost Wireless Sensors for Distribution Grid Intelligence and Resiliency[1]

Arnab Kundu, Asis Nasipuri, Badrul Chowdhury,
Darshan Prabhu, and Krupa Mahesh
Department of Electrical and Computer Engineering
University of North Carolina at Charlotte
Charlotte, NC 28223
Email: {akundu2, anasipur, b.chowdhury, dprabhu, kmahesh}@uncc.edu

Christopher Grafer, Divya Ravi, and K. R. Subramanian
Department of Computer Science
University of North Carolina at Charlotte
Charlotte, USA
Email: {cgrafer1, dravi, krs}@uncc.edu

***Abstract*— Extreme weather events have been known to cause massive disruptions in power leading to significant outages in the recent past. The main goal of this study is to improve situation intelligence in the distribution grid to determine the downed lines, impacted areas, location of healthy lines and nodes, and the amount of distributed generation available at customer locations to serve the critical loads (healthcare facilities, law enforcement, natural gas delivery network, gasoline pumping stations, water distribution facilities, etc.). A multi-tiered wireless sensor network is designed that has the ability to report to the substation with information on the attributes of an outage, including location, possible extent of the outage, and potential use of DER for backup power. An interactive visualization software is developed to display the sensor data.**

Keywords—Wireless sensors; sensor network; power system; MicaZ; Distributed Energy Resources

I. Introduction

The resilience of any infrastructure hinges on its ability to anticipate, absorb, and/or rapidly recover from a disruptive event. The power distribution infrastructure is inherently vulnerable to outages considering the fact that thousands of miles of critical current-carrying wires are exposed to the elements. This fact coupled with the realities of an aging infrastructure and continuously changing operating dynamics and constraints render the power grid fully exposed to the changes in weather conditions. The objective of this study is to improve the power distribution network resiliency, thereby decreasing the power grid recovery time. Modern networked data sensing and processing technologies offer unlimited potential for multimodal sensing, distributed processing, and dynamic adaptability to changing conditions. In particular, wireless sensor networking technologies can enable the development of systems that enhance the speed and accuracy of detecting emergency events and perform distributed computing to optimally deploy mobile power sources; reconfigure nearby available distributed energy resources (DER) to energize critical loads; and identify healthy power lines through which to deliver power from rooftop solar and community energy storage devices to critical loads. The key challenge is to quickly and efficiently solve this mobilization and reconfiguration problem using a diverse set of inputs. The research study presents a unified approach for designing the system architecture to handle such computation and communication intensive operations.

The fault response systems for the power lines require an effective fault detection sensor network that can automatically provide information on the attributes of the outage. The objective is to use this information for a number of tasks, including fault location, use of DERs for potentially serving affected critical loads, efficient dispatch of repair crew, and many others. The following tasks were completed:

- Development of a multi-tiered wireless network architecture for scalable deployment of the proposed outage monitoring wireless sensor network (WSN).
- Development of low cost solutions for tilt and current sensing.
- Development of software and hardware components for the integration of the wireless sensors into the multi-tiered network.
- Adaptations for sensor node deployment, which includes development of modifications of the interface circuits for current sensor to enable all node operations from a single 3V battery.
- Analysis of the current consumption in the wireless sensors and development of features for achieving low power operation.
- Development of interactive visualization tools to visually display the output of live sensors.

Details of the tasks are provided in the following sections.

II. Wireless Sensor Network Development

A. Current Sensor

Extensive research was done on the sensors to be used in this application. Current transformers (CT) are typically the most commonly used line sensors. Examples includes *Tollgrades*' MV sensors that use inductive powering and utilize wireless communication protocols like Wi-Fi or the cellular network [1]. They can measure the RMS current, as well as fault and surge currents. However, they are bulky and expensive. Another solution is to make use of optical current and voltage sensor [2].

[1] The authors gratefully acknowledge the financial assistance of the Center for Advanced Power Engineering Research (CAPER) and the Energy Production & Infrastructure Center at UNC Charlotte

978-1-5386-1539-3/17/$31.00 ©2017 IEEE

It uses a hollow core composite silicone polymer insulator to support a high voltage conductor. It makes use of an optical fiber to carry digitized current and voltage data and a collimated light source to pass an optical beam through one or more optical crystals located along the length of the hollow core insulator. Electro-optic crystal modulates the state of polarization of the light in direct proportion to the voltage drop across that crystal. These sensors are very bulky and very expensive as well. Several other papers show the usage of CTs for current measurement like Cooper power systems by Eaton [3], Schneider Electric [4] and so on. However, these have their own disadvantages which can be overcome by using a different sensor.

Hall sensors are small, low cost sensors which can be used to measure very high currents [5]. It has its own drawbacks – the output from Hall Effect sensor has a large temperature drift and usually requires a stable external current source. The giant magneto resistor (GMR) current sensor shows excellent performance and is cost effective, making it suitable for applications such as steady-state and transient-state monitoring [6]. With the advantages of having a high sensitivity, high linearity, small volume, low cost, and simple structure, the GMR current sensor is promising for the measurement and monitoring of smart grids, except for its temperature drift as in the case of Hall sensors. Also the drift can go up to 0.3% which is high.

Compared to the aforementioned alternatives, the Rogowski Coil was the most appropriate current sensor for this project as can be observed in Table I. The Rogowski Coil is an air–core conductor which is wrapped around the Transmission lines. It captures the change of flow in current through the conductor and provides a proportional output voltage on the basis of electromagnetic induction. Use of Rogowski coils as the current sensor provides advantages over regular current transformers in terms that it has an air – core, which leaves no scope for saturation. It is also compact and comparatively cost effective.

B. The Multi-tiered WSN Model

Our objective is to sense the current in the power lines and the angle of tilt in the power poles. Two kinds of sensors are used for this purpose: Rogowski coil and Tilt sensor. The sensors collect data and send them to the wireless communication modules. This data is then sent to the visualization system where it is updated. If there is any abnormal functioning of the power grid, the visualization system shows alerts using color codes. The optimization system then makes use of this data and optimizes the way DERs and PVs can be used to power up critical nodes. To break this down, we use a three tier system as explained below.

The proposed network model is shown in Fig. 1. Tier I includes a set of low-power wireless sensor nodes for capturing line current and tilt values from each pole. The sensor node for tilt sensing uses a MEMs sensor that is attached onto the top of each of the poles. Three current sensor nodes equipped with Rogowski coils are installed on power lines that are intended to be monitored. Each of these four sensor nodes were developed using low-cost off-the-shelf wireless sensor nodes manufactured by MEMSIC (MicaZ motes). The Micaz is a low power Wireless Sensor Board based on the IEEE 802.15.4 standard and is used to create a Wireless Personal Area (WPAN) Network in this implementation. A MicaZ coordinator at each pole interfaces with a ZigBee PRO module on the pole, which has a longer transmission range and is used to communicate across multiple poles.

TABLE I: A COMPARISON OF CURRENT SENSORS

Sensors	Optical Current Sensors	Fluxgate	Shunt	FOCT
Volume	Bulky	Bulky	Small	Small
Cost	High	High	Low	Extra High
Voltage Range	< 37kV	--	< 4kV	< 1600kV
Current Range	200A ~ 10kA	1A ~ 10kA	mA ~ kA	< 600kA
Accuracy	0.3%	0.5%	0.5%	0.5%
Temperature Range	-20ºC to +60ºC	-50ºC to +80ºC	-40ºC to +125ºC	--
Ease of Installation	Clamp On	Medium	Complex	Medium

Sensors	Hall Sensor	GMR	CT	Rogowski Coils
Volume	Small	Small	Bulky	**Small**
Cost	Low	Low	High	**Low**
Voltage Range	--	--	< 25 kV	**7.5kV - 500kV**
Current Range	10mA ~ 35kA	1mA ~ 10kA	1A ~ 100kA	**< 400kA**
Accuracy	0.2%	0.3%	0.4-0.5%	**0.15%**
Temperature Range	-40ºC to +150ºC	-40ºC to +150ºC	--	**-40ºC to +150ºC**
Ease of Installation	Medium	Clamp On	Clamp On	**Easy (Clamp On)**

The tilt sensor measures the angle of tilt of the pole it is attached to. If a pole tilts more than what can be considered safe or until the power line almost snaps, then the sensor alerts the substation with the help of the visualization system. Tier I communication steps are shown in Figs. 2, 3 and 4. The three current sensors and the tilt sensor periodically transmits sensor data to the MicaZ coordinators on each pole, which forwards the data to a ZigBee Pro Module located on respective poles. These are considered to be end-device ZigBee Pro modules.

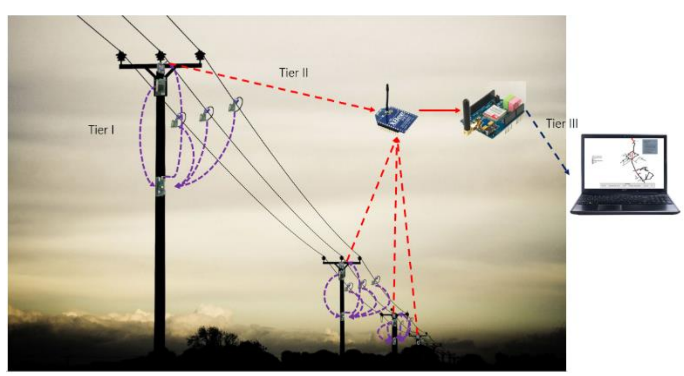


Fig. 1. The proposed WSN

Tier II consists of the communication network of the ZigBee PRO devices, conveying sensor data from each pole to a ZigBee coordinator that is also equipped with a SIM900 GSM data module. Tier II communication is shown in Fig. 5. The ZigBee Pro Modules use the IEEE 802.15.4 communication protocol and support the needs of low-cost, low-power wireless sensor networks. The ZigBee Pro modules provide reliable delivery of data between devices. The modules operate within the ISM 2.4 GHz frequency band. The outdoor range of ZigBee Pro is up to 2 miles (line of sight) and indoor range up to 90 meters.

The SIM900 GSM module is a quad band GSM/GPRS module that works on 850MHz, EGSM 900MHz, DCS 1800 MHz and PCS 1900MHz. The frequency bands can be set using AT commands. The current consumption is as low as 1.0 mA in sleep mode. The GSM module is interfaced with Arduino UNO microcontroller. The software used to program these modules is the Arduino IDE.

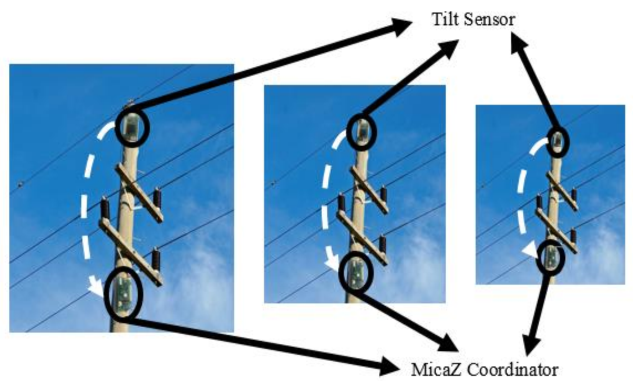


Fig. 2. Tier I Communication: Step 1.

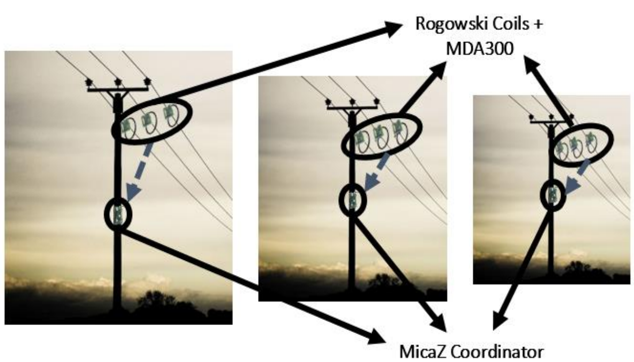


Fig. 3. Tier I Communication: Step 2

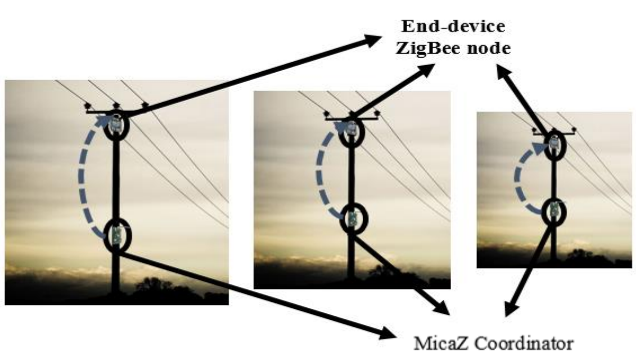


Fig. 4. Tier I Communication: Step 3.

Tier III is the communication between the GSM module and the GSM tower and network. 3G and HTTP together help us send sensor data wirelessly to the visualization software and update periodically. The multi-tiered wireless network is designed for robustness and resiliency for efficiently transmitting the sensor information to the substation for appropriate reconfigurations during disruptive events. Tier III communication is shown in Fig. 6.

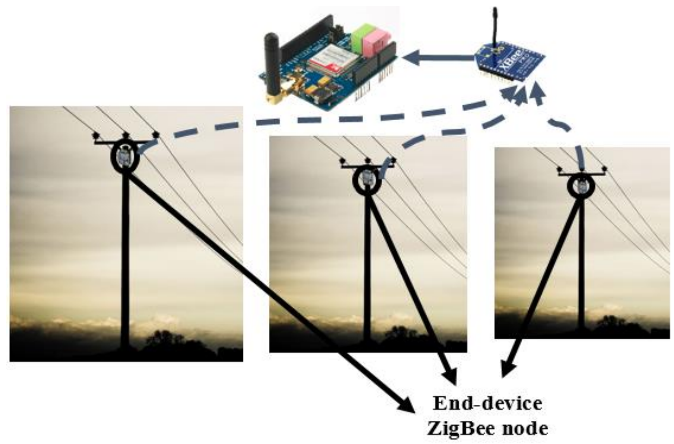


Fig. 5. Tier II Communication

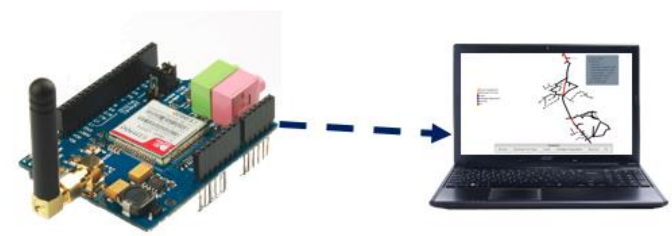


Fig. 6. Tier III Communication

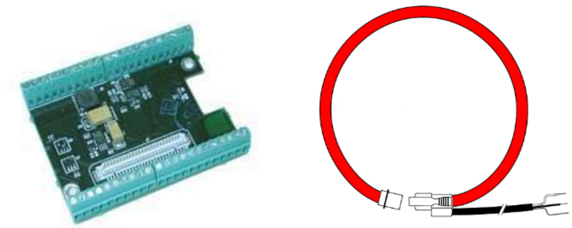
C. Sensor Node Development

MicaZ Sensor nodes enable users to use various sensors that are integrated in a customized sensor board MTS 300CA [7]. These include the 2-axis accelerometer ADXL202JE that has been used for tilt sensing in this project. It has acceptable accuracy, sensitivity and also has a 10-bit ADC providing a decent resolution. Fig. 7 show images of the sensor board and the sensor nodes.

The data acquisition board MDA 300CA, shown in Fig. 8.a can be used to connect a variety of external sensors to the MicaZ mote through its analog inputs, and also provide actuation signals. Here, we use the actuation signal of the MDA300 for providing the supply voltage to the combination circuit and simultaneously retrieve the sensor signal from the Rogowski coil (Fig. 8.b). Both the MTS300CA and MDA300CA are peripherals that allow additive features to the Micaz Sensor nodes. The Rogowski coil is interfaced with the integrator, clamper and envelope detector circuit, shown in Fig. 9. Use of Rogowski coils as the current sensor provides advantages over regular current transformers in terms that it has an air core leaving no scope for saturation, it is compact and comparatively cost effective.

(a) (b)

Fig. 7. (a). MTS300CA sensor board [7]. (b). MicaZ sensor node [13].



(a) (b)

Fig. 8.(a). MDA 300CA data acquisition board [7]. (b). Rogowski coil [12].

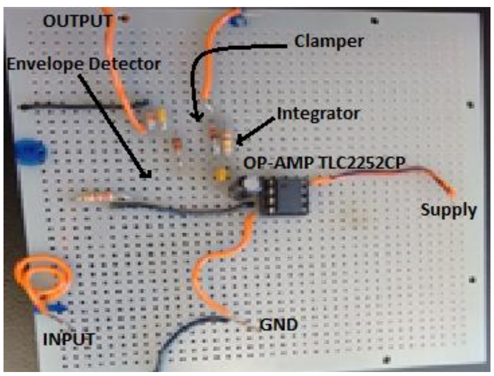


Fig. 9. Integrator, clamper and envelope detector combination interface circuit.

The programming language used in this system is NesC (Network Embedded System C) [8]. An interface board, the MIB510 (Fig. 10), is used to program the MicaZ nodes. The programming scheme comprises three files namely the main program, the component wiring file, and the makefile. The main program implements a set of predefined interfaces along with coding algorithm. The wiring component file triggers the hardware by wiring a certain hardware to its corresponding interface and the makefile provides the path.

The default medium access control protocol (MAC) of the MicaZ sensor node isn't compliant with the ZigBee network. So, in order to create a network which allows successful transfer of data packets from the MicaZ WPAN to the ZigBee module a change of MAC is much needed. Thus, a modified version of the default MAC of MicaZ has been used. This MAC is TKN154 which enables compatibility between MicaZ nodes and the ZigBee devices [9]. This TKN154 MAC is implemented using the MLME set of interfaces [10]. MLME stands for MAC Sublayer Management Entity.

Fig. 10. Programmer MIB 510

For the MicaZ to accept this change in MAC, it has to identify certain parameters as its default. Some of them are the node ID, Beacon Order, Superframe Order etc. All of these are initialized using the header files so that the MicaZ can observe them as its default parameters. These parameters can be controlled over a range of values and can provide desirable changes in the performance of the nodes. A new set of parameters are passed over in the payload using this MAC in order to achieve compliance with the ZigBee module. The main parameters passed are the node ID, channel information, payload length, time stamp information and the sensor information. All this information is transferred from the sensor nodes to the coordinator.

III. Design for Energy Conservation

The MicaZ WPAN can work in two modes: beacon enabled and non-beacon enabled. When the beacon enabled mode is used, the beaconing requires some form of time synchronization. Due to this, the MicaZ coordinator and the sensor nodes have to spend additional energy in exchanging synchronization messages. The sequence of transmission and reception events can be described as follows: first the coordinator sends a beacon to the sensor node indicating it is the right time for the sensor to transmit its data to the coordinator. After that the sensor node transmits its information when the coordinator is ready to receive. Meanwhile, when the nodes neither transmit nor receive, they remain in their idle state, when some of the components of the boards are turned off but aren't completely turned off. Since the beacon enabled mode requires time synchronization, deep sleep cycles can't be entered, which is the key to saving energy. This makes energy conservation challenging.

Figs. 11-13 depict the current drawn from the node batteries by plotting the voltage drops across a 1 Ohm resistor connected in series with the battery of the corresponding node. Thus, these plots depict the current drawn in mA in each of these nodes.

Fig. 11 shows the energy consumption of the current sensor node with the MDA 300CA data acquisition board. It shows two sets of current spikes: the shorter spikes represent the current drawn for energizing the interface circuit for the current sensor using the 5V excitation signal, and the taller spikes represent the periodic beaconing. The current consumption is approximately 7 mA for sensing, and 26 mA while beaconing. Note that, in this application, the mote acquires current sensor data just prior to the beaconing, when the corresponding data is transmitted.

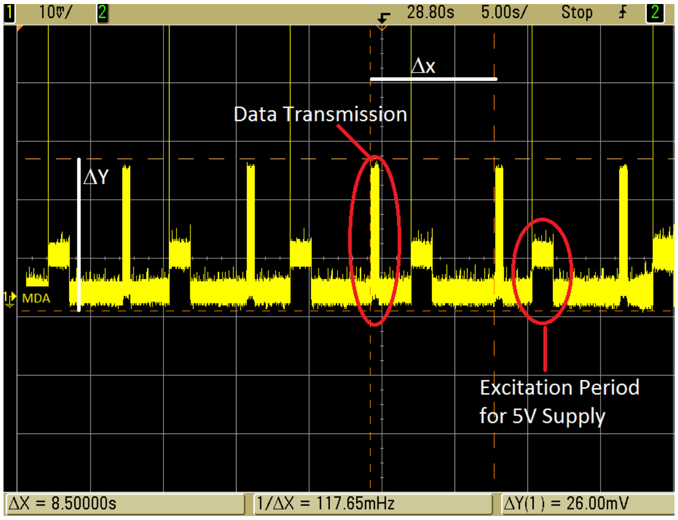


Fig. 11. Current consumption in the current sensor node with MDA 300CA.

Fig. 12 depicts the current consumption of the tilt sensor node using the sensor board MTS 300CA. Here, sensing and beaconing/transmission takes place at the same time. The total current consumption during these events while beaconing is 27.5 mA. One way of reducing it is by changing the transmission power parameter which was set high to -10 dbm (defined in the header files). Even the beaconing rate can be reduced with the help of the beacon order parameter. Beacon order in the aforementioned cases was 9, for which the beacon interval is 8.5 sec. In the Idle state, when the receiver is on but it is not receiving or transmitting data, the power consumption is 1 mA, approximately.

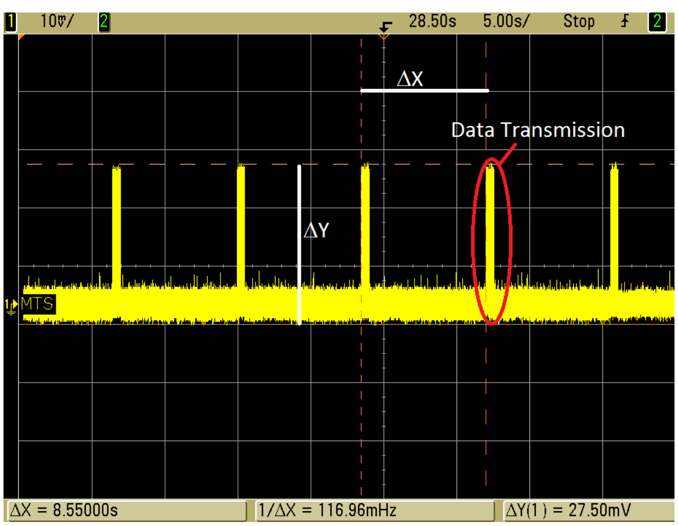


Fig. 12. Current consumption in the tilt sensor node with MTS300.

The current consumption in the coordinator node is depicted in Fig. 13, which illustrates the current spikes during periodic beaconing. Here, the two sensor nodes were turned on after the first two beacons, hence the first two spikes only indicate current consumption for beacon transmissions from the coordinator. However, the successive spikes indicate a slightly higher current, which is due to beacon transmissions as well as data reception from the sensor nodes.

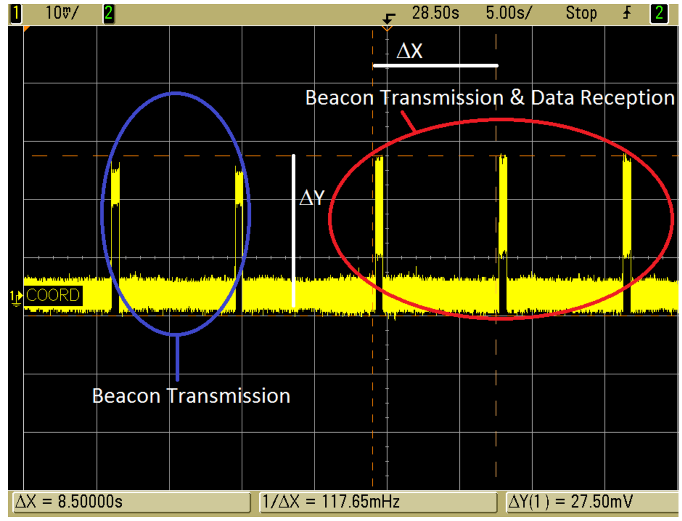


Fig. 13. Current consumption in the coordinator node.

The average current consumption depends on the beacon interval as well as the transmission period, which is approximately 600 milliseconds for both sensor nodes is. A change in the parameters for transmission power and beacon order was made to reduce the power consumption.The average current consumption can be calculated with the help of an equation that considers the current consumed under different states and the corresponding fraction of time in those states, shown in the following steps.

For the tilt sensor using MTS300 the average current drawn can be expressed as:

$$I_{avg} = A_{Tx} I_{Tx} + A_{Idle} I_{Idle}$$

where A_{Tx} is the percentage of time spent on transmission, A_{Idle} is the percentage of time spent in idle state, and I_{Tx} and I_{Idle} are the current drawn in those states. Note that;

- A_{Tx} = 27%, when beaconing period is 2.2 sec, 7% when the beaconing period is 8.5 sec, and 3.6% when beaconing period is 17.5 sec.
- A_{Tx} is negligible when beaconing period is very large => Thus, minimum average current consumption of 1 mA.

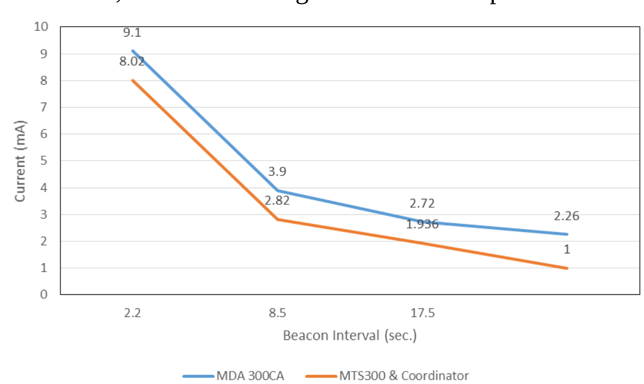


Fig. 14. Average current consumption in different sensor nodes under the beacon-enabled mode.

For the current sensor using MDA 300CA, the average current can be expressed as

$$I_{avg} = A_{Tx}I_{Tx} + A_{Idle}I_{Idle} + A_{Excitation}I_{Excitation}$$

Here, $A_{Excitation}$ is time spent for providing excitation voltage (sensing period) and $I_{Excitation}$ is the corresponding current drawn. The other parameters are the same as defined previously. The average current consumption by the sensors under different beaconing periods is shown in Fig. 14.

A. Design Considerations for Stand-Alone Deployment

For deploying the proposed system on the power grid, a few design considerations should be kept in mind. Factors like physical tolerance of the sensor devices to the weather and performance of the sensors away from a lab setup are very important. However, the main concern is the power consumption of the sensor nodes. If a test bed is to be considered, then the sensors need to be there over a long period of time and with a power source such as two AA batteries the consumption of power even with a current of 1 mA is too much. So, it is necessary to keep the system in sleep state. Sleep state can't be achieved with beacon enabled mode of operation as interfaces that provide explicit control over the radio, like SplitControl, RadioOff, Rx_Enable etc. are not useful here [11]. Hence, non-beacon enabled mode needs to be used to successfully utilize these interfaces. With non-beacon enabled the transmissions become un-synchronized and random. There is certainly a fear of missing data packets but considering the fact that transmissions in this system are only required during a fault which itself is a rare event, such missed packets wouldn't cause significant trouble. The sleep state allows the radio to be completely switched off and as transmission consumes more power than computation or processing of data, the level of current drawn can be reduced to micro Amperes by employing this. Table II shows power consumption in the sensor nodes in different states.

Here, the average current drawn by the boards will be of the much lower due to sleep modes. For all current equations, the idle will be replaced by sleep mode. For instance, the approx. average current equation for the MDA 300CA,is:

$$I_{avg} = A_{Tx}I_{Tx} + A_{Excitation}I_{Excitation} + A_{Sleep}I_{Sleep}$$

Here as Sleep States are considered, I_{Idle} changes to I_{Sleep}. All the values remain the same except I_{Sleep}, which is 10μA. For the tilt sensor using MTS 300, the same changes apply. The average current values obtained from these equations for different beacon intervals are depicted in Fig. 15. Here the last data point is for theoretically infinite beacon interval.

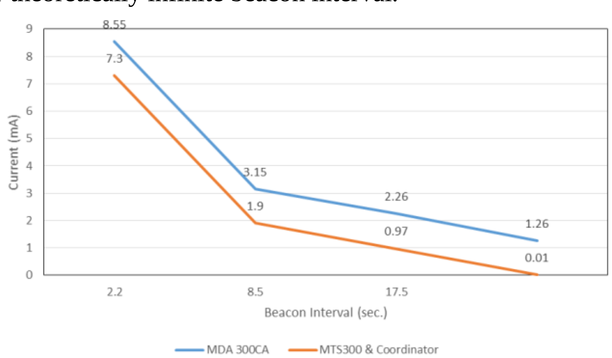


Fig. 15. Calculated average current consumptions in sensor nodes that can be achieved in low-power mode.

TABLE III: POWER SPECIFICATIONS

SYSTEM SPECIFICATIONS		
Currents		**Example Duty Cycle**
Processor		
Current (full operation)	8 mA	1
Current sleep	8 µA	99
Radio		
Current in receive	8 mA	0.75
Current transmit	12 mA	0.25
Current sleep	2 µA	99
Logger Memory		
Write	15 mA	0
Read	4 mA	0
Sleep	2 µA	100
Sensor Board		
Current (full operation)	5 mA	1
Current sleep	5 µA	99
Computed mA-hr used each hour		
Processor		0.0879
Radio		0.0920
Logger Memory		0.0020
Sensor Board		0.0550
Total current (mA-hr) used		**0.2369**
Computed battery life vs. battery size		
Battery Capacity (mA-hr)		Battery Life (months)
250		1.45
1000		5.78
3000		17.35

From Fig. 15, it can be observed that upon using non-beacon enabled mode and initializing sleep state, power can be conserved to a very significant level. Apart from this, another concern is that the Arduino boards still require an external power supply to function. For that, an energy harvester can be placed on the power poles or some other power excitation scheme needs to be constructed such that the available sensor supply can manage to supply the Arduino boards as well. This phase of the project is still under progress. A view of the stand-alone model is illustrated in Fig. 16.

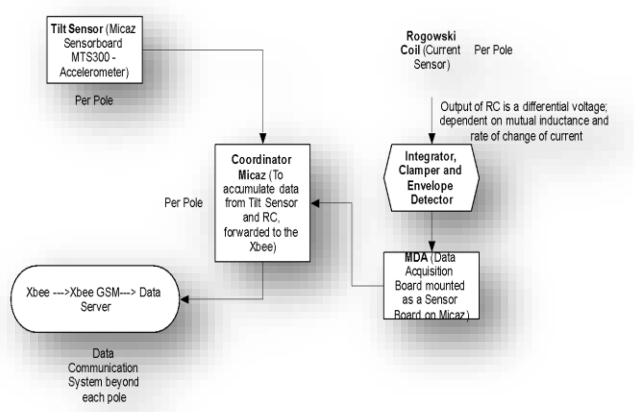


Fig. 16. Block schematic of the Stand Alone Model for the Tier-I network.

Each of the sensor nodes i.e., the coordinator MicaZ, MDA on MicaZ and Tilt Sensor on MicaZ work on two AA batteries (1.5V each). The Rogowski Coil is a passive component which senses and passes information to the Integrator, Clamper and Envelope Detector combination interface circuit. This takes a

5V supply to function, which is provided by the MDA using excitation levels over MicaZ. The output from this interface circuit is forwarded through the MDA to the coordinator. Meanwhile, the tilt sensor information is also forwarded to the coordinator. From the coordinator, the information is passed on to the ZigBee Communication module which obtains its supply from 5V adapters. In all, a compact collective box can be deployed with the MDA, interface circuit and the coordinator. The tilt sensor needs to be placed near the top of the pole and the current sensors should be wrapped around the three phases. The longevity of the battery life for the nodes in different modes of operation is provided in Table III.

TABLE IVII: CALCULATED BATTERY LIFE OF THE NODES IN DIFFERENT MODES OF OPERATION

MODE OF OPERATION	**MIN. AVG. CURRENT CONSUMPTION**	**BATTERY LIFE (IN DAYS)**
Beacon Enabled	1 mA	42 days
Non Beacon Enabled	10 microamperes	4200 days

IV. VISUALIZATION

In this project, interactive visualization tools are used to (1) understand the overall health of the power grid, (2) display output of live sensors and send appropriate alarms or warnings to the central operator, (3) visually display and identify faults to provide relevant fault information. In the long-term, these tools will assist and enable interactive routing/steering of power under emergencies (human in the loop for override, for instance). In the current implementation, we have incorporated several of these capabilities to illustrate the potential of visualization tools, that includes intercepting data from wireless sensors in real-time and visualize them on the feeder.

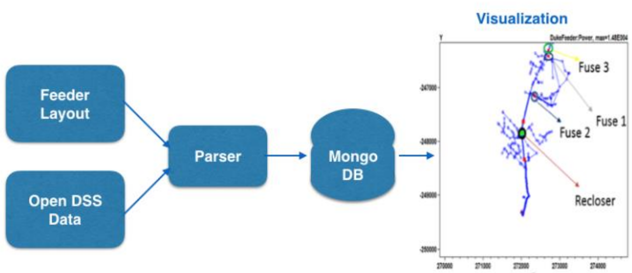


Fig. 17. Visualization Design

The visualization system architecture is illustrated in Fig. 17. The system reads feeder (Courtesy of Duke Energy, Inc.) layout information to position the various components of the feeder in the display and all other data is obtained through the OpenDSS simulation/analysis [15], and stored in a Mongo database [16]. The sensor data (tilt and current sensors) in our current implementation is directly transmitted by the GSM module to the database via a proxy server. The visualization system monitors changes to the database and updates the display as and when new sensor data is received.

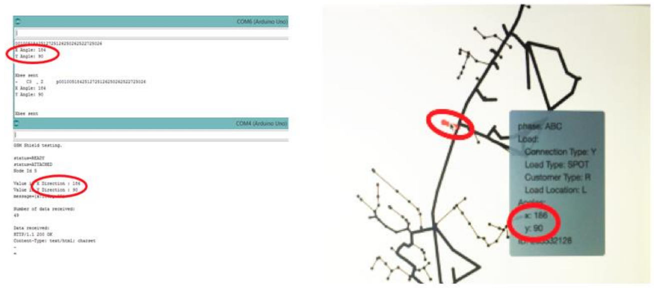


Fig.18. Visualization of Tilt Sensor Output on the Feeder

Fig. 18 illustrates tilt sensor output being transmitted to the visualization system for display on the feeder. The left panel indicates textual output of the tilt sensor values on the ZigBee end device (upper left panel), which is received by the ZigBee coordinator (lower left panel) and then transmitted via GSM to the visualization server (Mongo DB). The visualization display shows the feeder circuit and the specific sensor location (red circle); a display panel illustrates the actual tilt sensor output (angles) for verification.

V. CONCLUSION AND FUTURE WORK

A wireless sensing system that accurately and efficiently reports the health of the power poles and lines has been designed and tested. The objective was to make use of low-cost components to implement the system. It consists of three tiers: one consisting of the sensors, the second consisting of ZigBee network, and the third comprising of the GSM communication and visualization system.

For future research, the plan is incorporate methods to reduce the power consumption even further, and develop a method to inductive power the components from the power lines. For field demonstration in a real-life distribution feeder, the wireless communication network will be made compatible with the DNP3 interface for smart grid compatibility.

ACKNOWLEDGMENT

The authors thank Mr. Andrew Kling of Duke Energy for many hours of fruitful discussion on developing viable sensors for the power grid. The authors also thank the CAPER Industry Advisory Board, particularly Joe Cordaro and Klaehn Burkes of SRNL for their constant support and guidance during the duration of the project.

REFERENCES

[1] Tollgrade., "Smart Grid", Internet: http://www.tollgrade.com/smartgrid/smart-grid-products/smart-grid-mv-sensor . Accessed Dec.13,2016.

[2] F. Zavoda and C.Yakymyshyn. "Sensors for Smart Grids," in Proc. Third International Conference on Smart Grids, Green Communications and IT Energy-aware Technologies, 2013, pp.83-88.

[3] Cooper Power Systems by Eaton, "Grid Advisor Series II smart sensor", June 2014. Accessed: Dec.13,2016.

[4] Paul Doig, "Smart Sensors Enable a Smarter Grid Improving High Voltage Grid Reliability through the use of readily deployable, distributed, wireless intelligent sensors", Schneider Electric, 2006.

[5] William Koon, "*Current Sensing for Energy Metering*", Analog Devices, Inc.

[6] Y. Ouyang, J. He, J. Hu, and S. X. Wang, "A current sensor based on the giant magnetoresistance effect: Design and potential smart grid applications," Sensors, vol. 12, no. 11, pp. 15 520–15 541, Nov. 2012.

[7] Crossbow Technology Inc., "MTS/MDA Sensor Board User's Manual", Internet:http://www.yumpu.com/en/document/view/18712244/mts-mda-sensor-board-users-manual/1

[8] Crossbow Technology, Inc., 2004., "MPR/MIB User's Manual", Internet:http://www.learningace.com/doc/2068521/649215b7ecc2f79d56eec36a94eb0730/mpr-mib-series-user-manual-7430-0021-06_a

[9] Jan-Hinrich Hauer, "TKN15.4: An IEEE 802.15.4 MAC Implementation for TinyOS 2", March 2009. Accessed: Dec.13,2016.

[10] Atmel, " Atmel Software Framework.",Internet: http://www.atmel.com Accessed: Dec.13,2016.

[11] TinyOS Wiki., "TinyOS Documentation Wiki.", Internet: http://tinyos.stanford.edu/ Accessed: Dec.13,2016.

[12] Rogowski Coil Specifications, https://ctlsys.com/ctrc_series_rogowski_coil_current_transformers.

[13] MicaZ features and product specifications, http://www.openautomation.net/page/productos/id/22/title/MICAz-2.4-GHz.

[14] MicaZ Datasheet by Memsic, http://www.memsic.com/userfiles/files/Datasheets/WSN/micaz_datasheet-t.pdf.

[15] OpenDSS:EPRI Distribution System simulator, https://sourceforge.net/projects/electricdss.

[16] Y. S. Kang, I. H. Park, J. Rhee and Y. H. Lee, "MongoDB-Based Repository Design for IoT-Generated RFID/Sensor Big Data," inÂ IEEE Sensors Journal, vol. 16, no. 2, pp. 485-497, Jan.15, 2016.