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eMnSiM: An Energy Oriented Model and Simulator for Wireless Sensor Networks

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Abstract

One of the key design criteria in Wireless Sensor Network is that of power conservation since all nodes are battery powered.

According to researchers, due to the high importance of energy usage, it is highly desirable to define and measure the amount of energy a Wireless Sensor Network can spend to perform its goal efficiently. In this context a number of related efforts have been carried out. However there is a lack of widely accepted experimental energy models and simulators which are needed to accurately simulate and evaluate the efficiency of a protocol or application design. Thus the need to develop an improved energy efficient model and consequently an energy-oriented simulator for Wireless Sensor Networks crops up to meet researchers' needs.

For this purpose, an energy oriented model and simulator, called eMnSiM has been derived. This model considers the residual energy of a node. Residual energy is an important factor in prolonging the lifetime a Wireless Sensor Network. Moreover, eMnSiM model takes into consideration other parameters that directly or indirectly affect energy consumption. Thus eMnSim serves as a good experimental energy model which can be used by researchers to accurately simulate and evaluate the efficiency of several protocols or application.
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Keywords: Wireless Sensor Network, Energy Modeling, Simulation, Energy Efficiency

**For correspondences and reprints*

Abbreviations

BS- Base Station
CH- Cluster Head
MVC- Model View Controller
UI- User Interface
WSN- Wireless Sensor Network
MREPsum- Sum Maximum Residual Energy Path
MBCR- Minimum Battery Cost Routing
MMBCR- Min–max Battery Capacity Routing

INTRODUCTION

1.1 Overview of WSNs

A WSN consists of dozens, hundreds or even thousands of tiny, battery-powered computers often called motes, scattered throughout a physical environment spatially. Each mote silently and wirelessly, collects the sensed data and relays the collected data to its neighboring motes and then to a specified destination where it is processed. This sensory input, when gathered from all the motes and analyzed by more traditional computers, paints a comprehensive, high-resolution picture of the surroundings in real time. The size of a single sensor node can vary from shoebox-sized nodes down to devices the size of grain of dust. Size and cost constraints on sensor nodes result in corresponding constraints on resources such as memory, computational speed, bandwidth and mainly energy.

1.2 Importance of energy efficiency in WSNs

The WSN nodes are designed to be battery operated, since they may be utilized in any kind of environment including thick forestry, volcanic mountains and ocean beds. Consequently, everything must be designed to be power-aware in these networks since sensor nodes are too small and too numerous to recharge or replace batteries, as reported in Journal of Computers (2007). The simplest interpretation of energy efficiency is the energy required to transmit and receive a single bit.

In many applications, sensors are placed in locations that are not conveniently accessible. For instance, the focus of surveillance missions is to acquire and verify information about enemy capabilities and positions of hostile targets. Such missions often involve a high element of risk for human personnel and require a high degree of stealthiness. Hence, the ability to deploy unmanned surveillance missions, by using wireless sensor networks, is of great practical importance for the military. Because of the energy constraints of sensor devices, such systems necessitate an energy-aware design to ensure the longevity of surveillance missions. Solutions proposed recently for this type of system show promising results through simulations as reported by Sokwoo Rhee *et al*.

Moreover, if the batteries must be replaced often (every week or every month), not only will the primary benefit (freedom from wiring constraints and costs) of wireless networks be lost, but also many remote sensing applications may become impractical. Therefore, long battery life (several years) is essential in wireless sensor networks.

The following graph shows the lifetime of different types of batteries. For instance, a 1 cm^3 of non-rechargeable Lithium-Ion battery lasts less than 6 months as stated by Jan M. Rabaey *et al*.

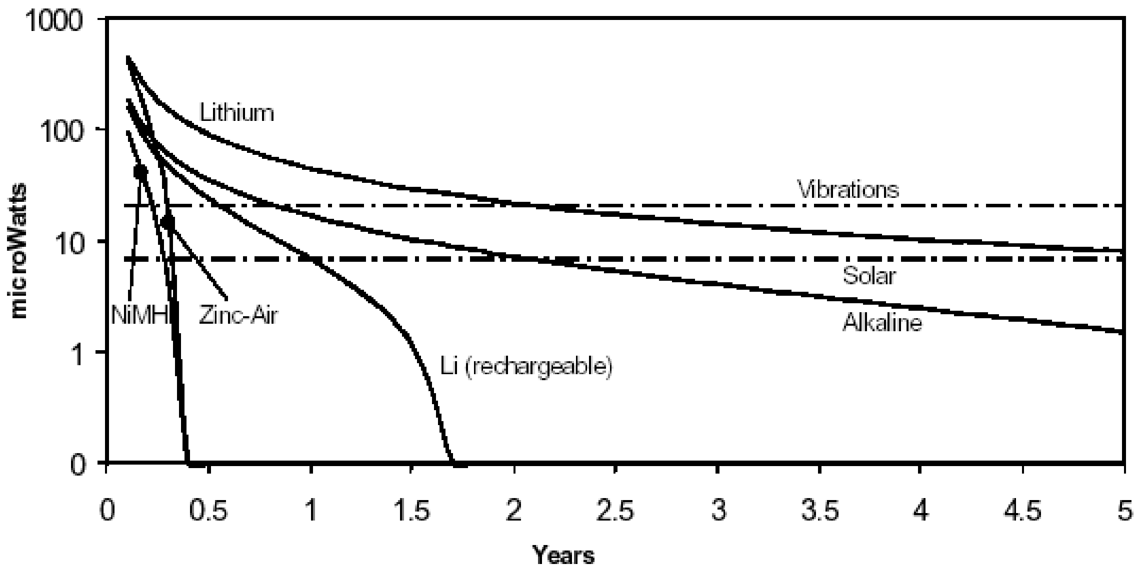


Figure I. *Battery lifetime (0.5 cm3), compared to continuous power sources (1 cm2 solar cell, 1 cm2 vibration converter).*

In addition, lowering the power consumption of a node greatly reduces the maintenance effort of having to replace the batteries of so many nodes, and makes the network operation more robust, free from the impact of dead nodes.

Hence the energy consumption of a sensor node must be tightly controlled. The three main energy consumers are: sensing, communication, and data processing.

1.3 Problem Statement

The lifetime of a WSN is determined by the duration over which the network can perform its assigned tasks. If a sufficient number of nodes run out of energy, it may impair the ability of the sensor network to function. In many applications, sensors are placed in locations including thick forestry, volcanic mountains and ocean beds that are not conveniently accessible. Moreover, if the batteries must be replaced often, not only will the primary benefit (freedom from wiring constraints and costs) of WSNs be lost, but also many remote sensing applications may become impractical. Therefore, long battery life which lasts up to several years is essential in WSNs.

Consequently, everything must be designed to be power-aware in these networks since sensor nodes are too small and too numerous to recharge or replace batteries. In addition, lowering the power consumption of a node greatly reduces the maintenance effort of having to replace the batteries of so many nodes, and makes the network operation more robust, free from the impact of dead nodes.

Hence any solution proposed for WSNs necessitate an efficient analysis of the lifetime of a WSN, which in turn requires a good model of energy consumption. According to researchers, due to the high importance of energy usage, it is highly desirable to define and measure the amount of energy a WSN can spend to perform its goal efficiently. In this context a number of related efforts have been carried out. However, with respect to a comparative study of existing energy models and simulators, it can be derived that most of them do not specifically address the energy consumption measurement and analysis of WSNs. This has resulted in a lack of widely accepted experimental energy models and simulators which are needed to accurately simulate and evaluate the efficiency of a protocol or application design, and which can also be used for automatic energy optimizations and real-time energy profiling. Thus the need to develop an improved energy efficient model and consequently an energy-oriented simulator for WSNs crops up to meet researcher's needs.

1.4 Research Contribution

Intensive work has been done to address the problem described in the previous paragraph. This is summarized below.

Firstly, the field of WSN has been explored to identify the energy challenges and energy importance in such networks. The main sources of power consumption have been investigated so as to be able to identify the root cause and ultimately come up with an energy-efficient solution.

Existing techniques on energy measurement in WSNs have been investigated to spot the parameters that directly or indirectly affect energy consumption. Moreover a detailed analysis of existing energy models has been carried out followed by an in-depth investigation of current WSN simulators to learn about the mechanisms or techniques employed to deal with energy consumption in WSNs. Ultimately a comparative study on existing energy models and simulators has been done to identify the strengths and weaknesses of the latter to finally come up with the new functional and non-functional requirements for an improved energy model and simulator since comparison results have shown that there is a lack of experimental energy models and WSN specifically targeted towards energy consumption measurement and analysis.

Based on these requirements and the energy parameters identified, an improved energy-oriented model has been derived to address the shortcomings of existing energy models and to provide venues and guidelines for energy reduction and design improvement. To be able to analyse, evaluate and experiment with the proposed energy model and other energy models and protocols/ algorithms such as directed diffusion, LEACH, Directed Routing, K-Means Clustering Algorithm, a WSN simulator has been implemented. Such tool will allow researchers to vary/ experiment with the different energy parameters, while portraying a clear picture of what happens in real WSNs, primarily with respect to energy metric. The developed simulator which integrates both the proposed energy-oriented model and simulator is called eMnSiM.

After implementing eMnSiM, a simulation study was performed where a series of test scenarios was run on the latter to finally assess and evaluate it so as to compare the degree to which eMnSiM stands out from existing energy models and simulators with regards to energy consumption. The simulation results have been evaluated and interpreted to validate the efficiency and correctness of the model.

2 ANALYSIS OF ENERGY MODELS FOR WSNs

An efficient analysis of the lifetime of a WSN requires a model of energy consumption, which is needed to accurately simulate and evaluate the efficiency of a protocol or application design, and can also be used for automatic energy optimizations.

In this context a number of related efforts have been carried out. An overview of some existing work is given below.

2.1 Existing work on energy modeling for WSNs

2.1.1 Model 1-Data communications subsystem most energy consuming: Heinzelman et al proposed a low energy consumption model for sensors based on the analysis that the data communications subsystem is the most energy consuming component in a WSN (Heinzelman et al 2006). Table I reproduces such model.

Table I. Radio Characteristics, Classical model

Radio mode	Energy Consumption
Transmitter Electronics ($E_{Tx-elec}$) Receiver Electronics ($E_{Rx-elec}$) ($E_{Tx-elec}$) = ($E_{Rx-elec}$) = E_{elec}	50 *nJ / bit*
Transmit Amplifier (ε_{amp})	100 *pJ / bit / m*^{2}
Idle (E_{idle})	40 *nJ / bit*
Sleep	0

However, the model has not been tested for the behavior of a physical radio in a WSN. When computing node energy consumption, the CPU and the sensors are consumers that may or may not be ignored, depending on the nature of the application. Hence, the radio model must be used jointly with some figure of the energy consumption of those elements, since power supply must feed all the system and not just the radio as reported by Heinzelman *et al (*2006*)*.

2.1.2 Model 2- µAMPS Specific Model: Heinzelman *et al* (2006) presented the µAMPS Wireless Sensor Node model. The model takes into consideration the energy consumed by the microcontroller, energy lost due to leakage and the average consumption of the radio. However, the µAMPS model does not specify the power consumed in transmitting or receiving one bit. Nonetheless, the platform uses transmission rate of 1 Mbps, hence the energy used in transmitting or receiving one bit and is calculated as follows:

Time to send or receive one bit = 1 / 1 Mbps = 1 sec

*Energy = Power * Time,* (1)
where Power is in Watts and Time is in seconds
Energy $_{Txonebit}$ = 1040 * 1 *10^{-3} W * 1 *10^{-6} sec
Energy $_{Txonebit}$ = 1.04 μJ/bit
Energy $R_{xonebitReadystate}$ = 0.4 μJ/bit
Energy $R_{xonebitMonitorstate}$ = 0.27 μJ/bit

2.1.3 Model 3- Specific Model: Polastre *et al* (2006) proposed a model that presents the total energy consumption for Mica2 as the summation of energy transmitting, receiving, listening, sampling data and sleeping. Table III in Appendix 1 presents a summary of current consumption.

As the authors present current consumption and time, and assuming that Mica2 is powered by a 3V source, energy to transmit and receive one bit can be calculated as follows:

*Energy = Current * Voltage * Time* (1)
Where current is in Amperes, Voltage is in Volts and Time is in seconds.
Energy Tx = 20 * 10^{-3} A * 3 Volts * 416 *10^{-6} sec / 8 bits = 3.12 μJ/bit
Energy Rx = 15 * 10^{-3} A * 3 Volts * 416 *10^{-6} sec / 8 bits = 2.34 μJ/bit

The difference with the Heinzelman model is two orders of magnitude, as stated by Sriporamanont *et al* (2006). With the μAMPS model, energy for transmission is comparable, while energy for reception is one order of magnitude bigger in the Mica2 case.

2.1.4 Model 4: Heinzelman *et al* (2006) proposed a component based modeling methodology for energy modeling of wireless sensor nodes such as MICAz and the Particle Node. Based on the static models of the individual components that make up a sensor node, a static model of the whole device is created which basically is a reduced form of the product machine of all component models. A dynamic model based on flow charts, as shown in Figure II, that show the traversal through the finite state machines is created.

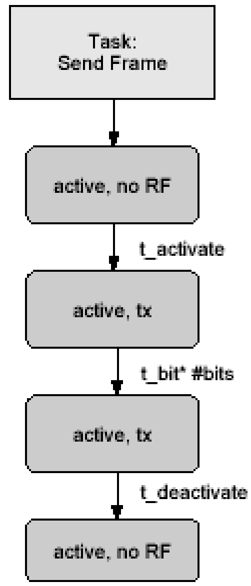


Figure II. *Parametric flowchart for frame transmission.*

From the flowcharts it is very easy to calculate the energy consumed by the specified task, conforming to the equation below:

$E = \sum P_{state} \cdot t_{state} + \sum P_{trans} \cdot t_{trans},$ (1)

Where P_{state} = Power consumed in the state "state";

T_{state} = Time spent in this state and;

P_{trans} and t_{trans} = Power and time for the transitions between the states.

2.1.5 Model 5- An integrated data-link energy model: An integrated data-link energy model for WSNs is proposed by Heinzelman *et al* (2006), where energy models of all components of the data link layer of a WSN are integrated into a single framework. The power control model is portrayed in Figure III. The validity of the models is verified using OMNET++ network simulations.

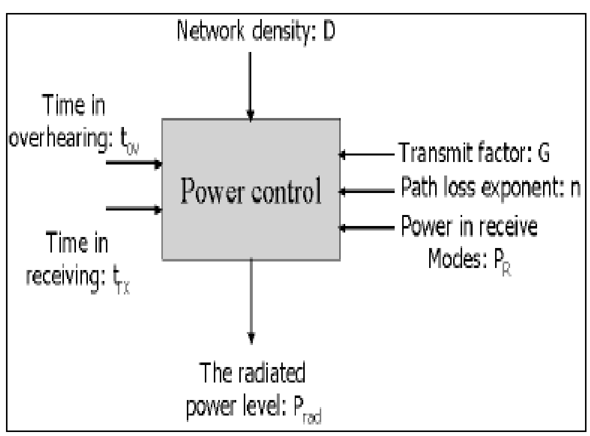


Figure III. Power control model

2.1.6 Model 6: J F Shi *et al* presents a communication topology and assumes a simple energy model for the radio hardware energy dissipation where the transmitter dissipates energy to run the radio electronics and the power amplifier, and the receiver dissipates energy to run the radio electronics. This model takes into account single hop and multi hop communication. Qing Cao *et al* reported that when the sensor nodes use single hop communication, the sensor node located farthest from the base station (at a distance *nr*) has to spend the maximum amount of energy. Since all the sensor nodes are alike, the lifetime of the network is determined by the lifetime of the shortest-living node.

On the other hand, when the sensor nodes use multihop communication, except the sensor node located farthest from the base station, every sensor node needs to send itself the data packet, at the same time, obviously the sensor node closest to the base station has most relay task, and require most battery energy. Hence the battery energy of the sensor node E_m in multihop communication system should be:

$$E_m = I * ((n-1) * (2e + ur^k) + (e + ur^k)) = I((2n-1)e + nur^k) \quad (2)$$

Total energy cost of system

When all sensor nodes use single hop mode, the total energy cost of system E_{ds} is:

$$E_{ds} = l*(e+u*(nr)^k + e+u*((n-1)*r)^k + \ldots + e+u*r^k) = l*(ne+ur^k(n^k+(n-1)^k+\ldots+1))$$

let k=2, then $E_{ds} = l*(ne + \frac{n(n+1)(2n+1)}{6}ur^2)$

let k=3, then $E_{ds} = l*(ne + \frac{n^2(n+1)^2}{4}ur^3)$

When all sensor nodes use multihop mode, the total energy cost of system E_{ms} is given by

$$E_{ms} = l*((1+2+\ldots+n)(e+ur^k) + (1+2+\ldots+n-1)e) = l*(n^2e + \frac{n(n+1)}{2}ur^k)$$

let k=2, then $E_{ms} = l*(n^2e + \frac{n(n+1)}{2}ur^2)$

let k=3, then $E_{ms} = l*(n^2e + \frac{n(n+1)}{2}ur^3)$

Results are shown in Figure IV.

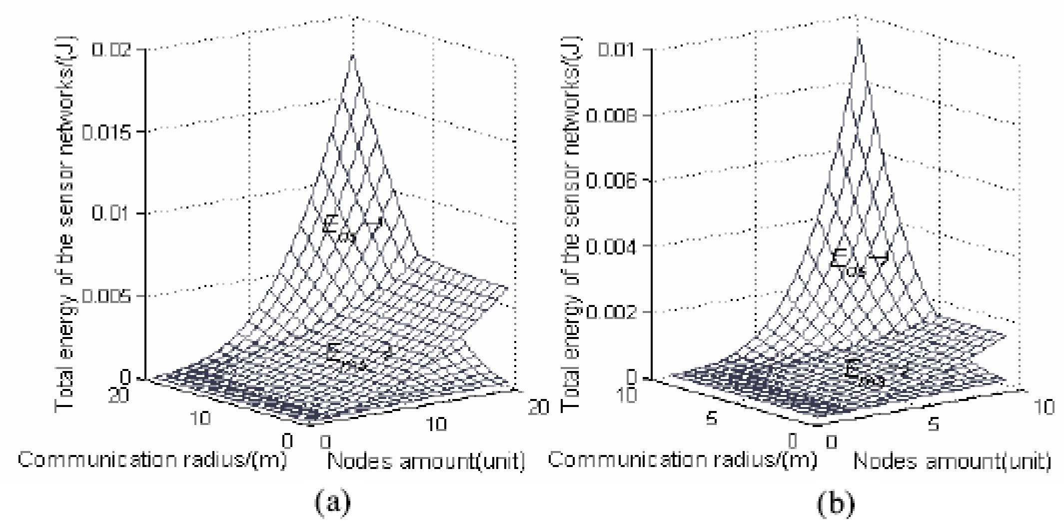


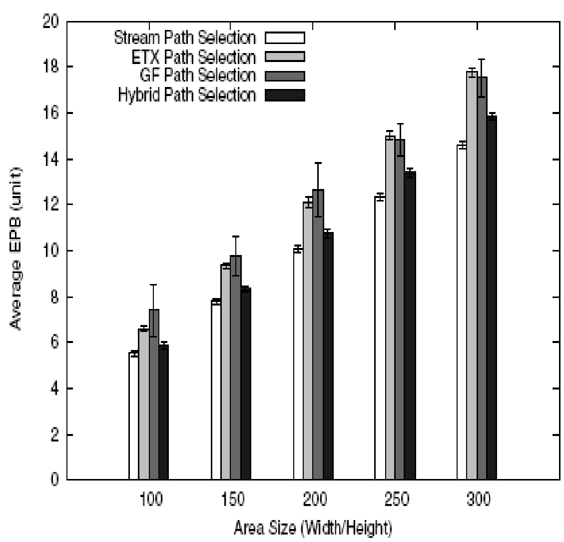
Figure IV. *Total energy dissipation of system in different communication mode.*

2.1.7 Model 7: David Stein (2006) models an unreliable link between nodes A and B as (p, q), where p represents the packet delivery ratio from A to B, and q represents the packet delivery ratio from B to A. To model this traffic, Energy per Bit, or EPB, has been used to characterize represent the average energy consumption for each delivered bit from the source to the destination.

The expected EPB value over this link is calculated as follows:

$$EPB = p \times 1 + (1-p) \times (1 + 1/p + \lambda/pq) = (1/p) + ((1 - p)/pq)\ \lambda \qquad (1)$$

Once the above metric is incorporated into the routing layer design, it can significantly improve the path energy efficiency of data streams, called the stream model. The correctness of the implementation results is demonstrated in the Figures V-VII below:



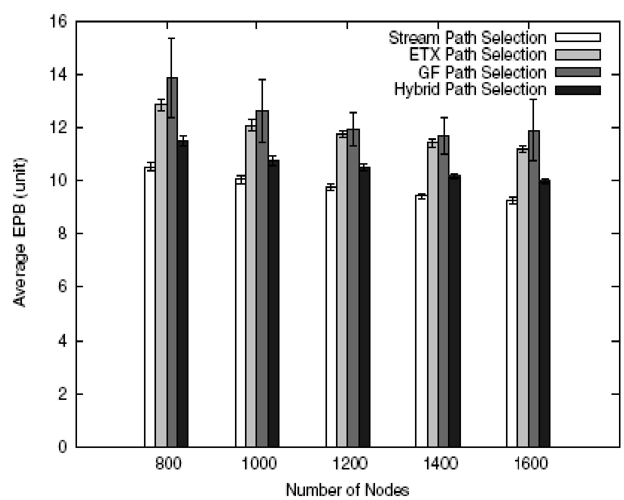


Figure V. Impact of area size ***Figure VI. Impact of density***

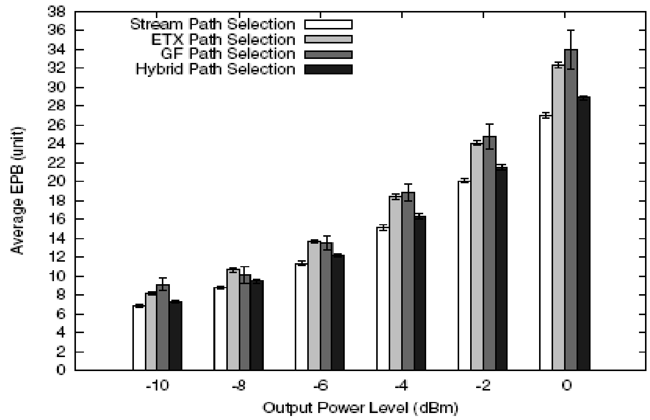


Figure VII. Impact of Output Power Level

2.1.8 Sleep mode TDMA Scheduling: Nikolaos A. Pantazis *et al* (2007) have proposed a TDMA based scheduling scheme that maximizes energy savings by using an appropriate scheduling of the wakeup intervals, to allow data packets to be delayed by only one sleep interval for the end-to-end transmission from the sensors to the gateway. An evaluation of the TDMA scheme has been performed by calculating the probabilities of each state for different power conservation schemes, using the model below:

$$P = \text{Prob}\{\text{SEND}\}P_{send} + \text{Prob}\{\text{RECV}\}P_{recv} + \text{Prob}\{\text{IDLE}\}P_{idle} + \text{Prob}\{\text{SLEEP}\}P_{sleep} \quad (1)$$

where Prob{SEND}, Prob{RECV}, Prob{IDLE}, and Prob{SLEEP} are the probabilities of the transmitter of the node being in states SEND, RECV, IDLE and SLEEP, respectively, and P_{send}, P_{recv}, P_{idle}, P_{sleep} are the amounts of power consumed when the node is the corresponding state. In this paper, the P_{sleep} has been omitted. Evaluation results showed that the proposed scheme achieves higher power conservation than other relevant schemes when the traffic generation rate is low; it can hence be used in WSNs which monitor rare events and are expected to operate for a long period of time.

2.1.9 xMBCR and xMREPsum: Two new route-selection schemes have been derived by Dimitrios J. Vergados *et al* (2008). These are summarized below:

2.1.10

xMBCR: This scheme is based on the MBCR strategy, but improves the battery cost function by introducing the p-value in the initial formula:

$$f(n_i) = \left(\frac{1}{c(n_i)}\right)^p \quad (1)$$

Where $c(n_i)$ denotes the residual energy of node n_i and p is a constant parameter. The performance of this scheme depends on the value of the constant p. For p=1, the xMBCR becomes equivalent to the MBCR scheme. For p=0, it becomes equivalent to the shortest path scheme, and for $p \to +\infty$, it becomes equivalent to the

MMBCR scheme. However, if the value of p is in the range of 3 to 30 approximately, the performance of the scheme seems to be optimal.

xMREPsum: The xMREPsum algorithm is based on the MREPsum algorithm, but also uses an exponential parameter to calculate the cost. Thus,

$$f(c_{ij}) = \left(\frac{1}{Er_i - e_{ij}}\right)^p \quad (2)$$

Where E_{ri} is the residual energy at node i and e_{ij} is the energy expenditure per bit transmission across link (i,j). The xMREPsum scheme aims at combining the advantages of the xMBCR and MREPsum schemes.

Results of a simulation study showed that compared to a number of other algorithms such as the Shortest Path, MBCR, MMBCR and MREPsum scheme, the proposed battery cost strategies have the best connectivity at all times. The performance of the proposed schemes is related to the value of the p-parameter. Starting at p=1, the performance of all schemes is similar. As the p value increases, the xMBCR and xMREPsum strategies achieve initially longer lifetimes, and then the lifetimes decrease.

2.2 Comparative study

An efficient analysis of the models is required in order to better evaluate the latter and acquire a better understanding of the impact of the performance of the models on energy consumption. The comparison was based on the evaluation metrics such as mechanism, parameters, components used in energy measurement, complexity of the model, application domain, energy measurement, efficiency and energy optimisation. A comparison of the above mentioned models is shown in Table II.

As shown in the table, each model uses a new mechanism to model energy consumption in WSNs. While most of the parameters used to calculate energy focus on distance, time, power, number of bits transmitted or received and energy spent per bit per distance, the units are mainly energy per bit or energy per bit per distance in almost all the cases. On the other hand the complexity of the models range from low in most cases to medium and high level in models 6 and 7 respectively. Microcontroller and radio devices such as transmitter, receiver and amplifier are the common components which have been considered in all the models. However, model 1 has also considered the data communication subsystem as the main consumer of energy in WSNs. Furthermore most models measure energy in terms of per node or per bit or per bit per second or per bit over a certain distance. In comparison to the other models, the first two ones are less efficient and have a poor energy optimization technique. Finally, all the models are quite popular. However models 1 and 2 are the most widely used ones

Model	Mechanism	Parameters	Units	Components used in energy measurement	Complexity of the model	Application Domain	Energy Measurement	Efficiency	Energy Optimization
1		Distance, number of bits transmitted/ received, power of transmitter/ receiver/ transmit amplifier.	nJ / bit, pJ /bit/ m^2	Data communication subsystem, Radio devices: receiver, transmitter, transmit amplifier. Optional: CPU, sensors.	Low	Used mostly to model energy consumption with respect to data communication. Classical Model- Popular.	Per node energy consumption.	Low since may/ may not consider CPU and sensors as consumers of energy.	None
2	Based on states: Deep sleep, Active, Ready, Monitor, Observe.	Power, time to send or receive one bit, transmission rate.	µJ/bit	Microcontroller, radio, energy lost due to leakage.	Low	Quite popular.	Per bit per second energy consumption.	Low	Low
3	Summation of energy transmitting, receiving, listening, sampling data and sleeping.	Current, Voltage, Time.	µJ/bit	Radio, sensors, CPU.	Low	Used to model Mica2 sensor node.	Per bit energy consumption.	Energy for transmission is comparable to model 2; energy for reception is one order of magnitude bigger.	None.
4	Component-Based. FSM. Parametric	Power consumed in a state, time spent in this state, Power and time for the		Considers microcontroller, transceiver chip and flash		Mostly used to model energy of MICAz sensor node.	Per node energy consumption.	High 80% energy savings.	Optimizes the consumed energy on each level.

	Flowchart representing power saving. Use of flowcharts to easily trade-off communication against computation in early design stages.	transitions between the states.		memory.		Used in communication protocols such as SDL. Applicable for a wide range of wireless sensor nodes and applications.		Energy consumption is reduced from 16.2 J to 3.09 J for time of 10 min.	Uses SDL scheduler extension.
5	Assumptions: Sensor nodes have power control, are homogenous, uniform energy constrained. Focus on short energy transmissions to save energy. Uses data fusion. Chain-based binary scheme.	Uses first order radio model. Distance, energy to run transmitter/receiver, energy (per bit per d) or trans amplifier.		Radio: amplifier, electronics, transmitter, receiver.	Medium	Popular	k- bit energy consumption over a distance d.	High. Delay of 8 for 100 nodes and performs better than LEACH by a factor of 8. Improves on LEACH by saving energy and delay in several stages. At the lower levels, nodes are transmitting at shorter distances compared to nodes transmitting to a cluster head in the LEACH protocol, and	Nodes take turns transmitting to the BS so that the average energy spent by each node per round is reduced.

								only one node transmits to the BS in each round of communication.	
6	Assumptions: e=50nJ/bit, u=50pJ/bit/m^2 (k=2), u=10pJ/bit/m^3 (k=3), l=300bit and initial energy of all nodes is equal. Focus on data communication.	Distance, energy spent in the radio electronics circuitry, energy spent in the radio amplifiers to counter the propagation loss, energy spent on receiving a packet, antenna gains of transmitter/ receiver.	nJ/bit, pJ/bit/m^2	Radio electronics circuitry, amplifiers, transmitter, receiver.	High		Per node and k-bit over a distance d energy consumption.	High. Uses multihop communication.	Sensor networks use less total energy in multihop mode than single hop mode.
7	Focus on data communication.	Energy per bit, Length ratio between packets, probability that a packet transmission is successful, path efficiency.			High	Used to model link layer and routing layer.	Per bit energy consumption.	High Considerably reduces EPB compared to other approaches.	Medium. Joint optimization of EPB in the link layer and routing layer respectively, for a given transport task.

3 ANALYSIS OF EXISTING ENERGY SIMULATORS

Few sensor networks have come into existence, for there are still many unresolved research, design and implementation problems. Hence measurements are virtually impossible. Moreover WSNs require large scale deployment (smart dusts) in remote and physically inaccessible places and applications are deployed only once with little or no scope to re-deploy during the life time of the network devices. Hence it appears that simulation of energy usage before deployment is currently the primary feasible approach to the quantitative analysis of sensor networks, as reported by Simon Kellner *et al*. Simulation helps in design improvements, provides basis for real test-bed deployment and provides a cost effective alternative since if anything goes wrong we can always go back to the drawing board. A number of existing simulators exist:

3.1 Existing energy simulators

3.1.1 ‘ns’ or the network simulator: ‘ns’ or the network simulator (also popularly called ns-2) is a discrete event network simulator, which is mostly used in the simulation of routing and multicast protocols and is heavily used in ad-hoc research. ns supports an array of popular network protocols, offering simulation results for wired and wireless networks alike, as stated by Victor Shnayder *et al*.

3.1.2 Wireless Sensor Network Simulator: This simulator deals with the simulation of a WSN that is used to detect and report certain events across an expanse of a remote area - e.g., a battlefield sensor network that detects and reports troop movements. The network may be deployed based on a wide range of parameters such as network size (number of nodes), communications distance, and energy costs for transmitting and receiving packets. Each node also simulates an energy store, which is depleted by sending receiving packets, and by detecting vectors. Since the nodes have finite energy, they will eventually power down and drop out of the communications network, causing network failure, as reported by Sagnik Bhattacharya (2001).

3.1.3 A Sensor, Environment and Network Simulator (SENS): SENS is a customizable and platform-independent sensor network simulator for WSN applications. In SENS the Physical component simulates a node’s power usage. The power model operates on any of 5 modes: TRANSMIT, RECEIVE, IDLE, SLEEP, and OFF. Victor Shnayder *et al* reported that when the Application or Network enters a different power mode, they notify the Physical by actuate messages to turn on or off associated virtual hardware.

3.1.4 PowerTOSSIM: PowerTOSSIM estimates per-node power consumption in a WSN. It is an extension of TOSSIM, which is an event-driven simulation for TinyOS applications. It is designed to scale to very large networks. The key features of PowerTOSSIM are: easy to use, scalable, accurate, integrated with TinyOS, efficient CPU profiling, trace based modeling and offline processing.

PowerTOSSIM includes a detailed model of hardware energy consumption based on the Mica2 sensor node platform, as reported by Sriporamanont *et al* (2006).

The components of PowerTOSSIM are illustrated in the Figure VIII.

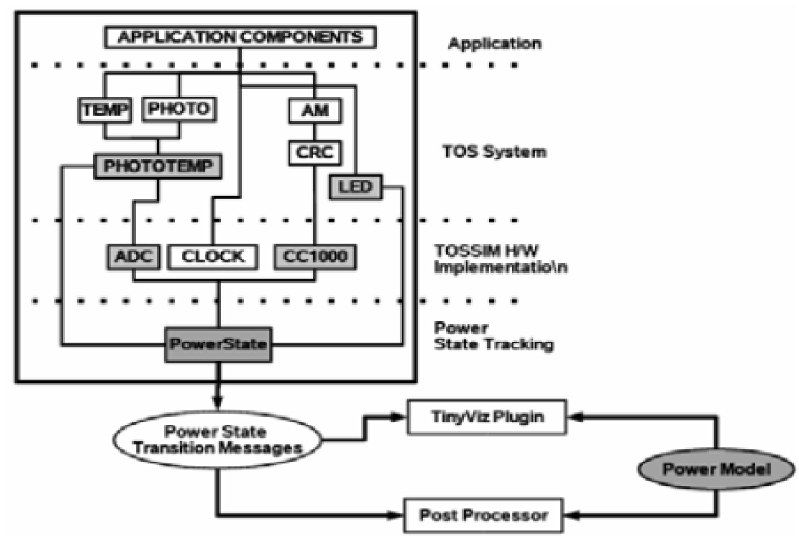


Figure VIII. PowerTOSSIM architecture

3.1.5 Objective Modular Network Test-bed in C++ (OMNeT++): OMNeT++ is primarily targeted at the simulation of communication networks and other parallel/distributed systems. It includes many features such as the graphical network editor, multiple execution environments (both GUI and command line), a result plotting tool and many sample simulations. Sriporamanont *et al* (2006) also reported that OMNeT++ has been successfully used in other areas like the simulation of IT systems, queuing networks, hardware architectures, business processes and for scientific and industrial settings as well.

3.1.6 OPNET: Sriporamanont *et al* (2006) also mentioned that OPNET Modeler is a commercial platform for simulating communication networks. Conceptually, OPNET model comprises processes that are based on finite state machines. Users can specify frequency, bandwidth, and power among other characteristics including antenna gain patterns and terrain models.

3.1.7 J-Sim: J-Sim is another object-oriented, component-based, discrete event, network simulation framework written in Java. Modules can be added and deleted in a plug-and-play manner and J-Sim is useful both for network simulation and emulation, as reported by Sriporamanont *et al* (2006).

3.1.8 GlomoSim: GlomoSim is a collection of library modules, each of which simulates a specific wireless communication protocol in the protocol stack. It is used to simulate Ad-hoc and Mobile wireless networks. GlomoSim provides a layered architecture with easy plug-in capability and modular and extensible library for network models. Moreover it provides built-in statistics collection at each layer. However Thomas Trathnigg and Reinhold Weiss reported that the main disadvantage is that it uses fixed protocol layers.

3.2 Evaluation of the existing popular simulators and simulator tools

NS-2 provides scalability + extensibility and a modular approach including fine-grained object composition and reusability. However, NS-2 is comparatively difficult to learn and use. It is supposedly more useful for getting statistics for lower level protocols. It was originally built for wired networks and later extended for wireless. NS-2 has been widely used in network simulations but does not perform well for wireless sensor networks including large topologies, as reported by Thomas Trathnigg and Reinhold Weiss. In addition, Victor Shnayder *et al* stated that it provides extensive support for simulating TCP/IP, routing and multicast protocols over wired and wireless network. One of the problems of NS-2 is its object-oriented design that introduces much unnecessary interdependency between modules. D. Schmidt (2007) argues that such interdependency sometimes makes the addition of new protocol models extremely difficult.

OPNeT++ is also one option for the high level sensor network simulation. The simple modules of OPNeT++ are programmed in C++ while its compound modules are programmed in a high-level language (NED). Although J-Sim provides supporting target, sensor and sink nodes, sensor channels and wireless communication channels, its use of Java as the simulating language is inevitably sacrificing the efficiency of the simulation. As the packet formats, energy models and MAC protocols are not representative of those used in wireless sensor networks; Dare Obasanjo (2007) reported that GlomoSim may not be a good option for the sensor network simulator. Hence NS-2 and GlomoSim provide very abstract simulation of network, do not address the complex interactions among motes, networks stack & environment and are therefore not very suitable for sensor networks

According to John Heidemann *et al*, there are systematic errors in the power model of PowerTOSSIM. The power model of PowerTOSSIM abstracts the motes as a combination of several components. Each of these has several power-states and each power-state has a known current consumption. This approach is quite common for power simulators, but suffers from several inaccuracies. For example, the time needed and the energy consumption caused by power-state transitions is not taken into account. Furthermore the values of the power model may be inaccurate.

On the other hand, Jae-Hwan Chang (2004) states that SENS incorporates simple power usage and battery models, but they do not appear to have been validated against actual hardware and real applications.

Several power simulation tools such as EMSIM, and JouleTrack have also been developed for energy profiling but they are designed for simulating a single host's energy use only. From a sensor network perspective, a tool for efficient large scale profiling is desired as reported by Ritabrata Roy.

With respect to the above comparative study on existing simulators and power simulation tools, it can be derived that most of the simulators and tools do not specifically address the energy consumption measurement of WSNs. As mentioned earlier, a fundamental issue and key challenge in the design of the latter is to devise mechanisms to make efficient use of its energy, and thus, extend its lifetime, which is determined by the duration over which the network can perform its assigned tasks. If a sufficient number of nodes run out of energy, it may impair the ability of the sensor network to function. According to researchers, due to the high importance of energy conservation, it is highly desirable to define and measure the amount of energy a WSN can spend to perform its goal efficiently. Thus an efficient analysis of the lifetime of a wireless network requires a mode l of energy consumption. Models of the energy consumption are needed to accurately simulate and evaluate the efficiency of a protocol or application design, and can also be used for automatic energy optimizations in a model driven design process. This discussion leads us to the key goal of this project, which is described in more details in the next chapter.

4 THE PROPOSED ENERGY MODEL: eMnSiM MODEL

This energy model considers the residual energy R_e of a node N, which is determined by the remaining amount of energy of a node at a particular point in time. R_e is an important factor in prolonging the lifetime of a node and hence that of the whole WSN. The eMnSiM model takes into consideration the parameters that affect energy consumption and the former will be applied to some scenarios. The results gained will be used to accurately simulate and assess the proposed model's effectiveness. While eMnSiM will help researchers to calculate the amount of energy spent by a node to perform a task, it will ultimately be used to calculate the residual energy of the node at each round. Moreover, the number of nodes that the model will consume as input ranges from one to any number of nodes over a specific distance. This means that the eMnSiM caters for both homogenous and heterogeneous nodes. This will help to determine the required action to be taken to optimize the lifetime and hence energy of the whole WSN. For instance, each node in the WSN may send a scan update after performing each task. The scan update corresponds to the current available energy of a node at a specific time. Hence, if R_e reaches a specific bound for a node N1, action may me taken to relay the packet to another node N2 with higher R_e or choosing a Base Station (BS) at another feasible site in the case where multiple BSs are used. N1 can then be used to perform another job which requires lower energy consumption.

Moreover, the proposed approach is applicable for a wide range of wireless sensor nodes and applications. While eMnSiM can allow researchers to estimate or simulate the energy consumption of an application at design time, the former can also be used to estimate the energy consumption at runtime. Moreover, eMnSiM takes into account additional factors such as retransmission due to collision , packet loss or a corrupted packet, delay due to traffic or aggregation, transition between states and energy spent in the different states/ transitions, energy spent in electronics and amplifiers, propagation loss exponent and energy loss due to leakage, which all contribute to energy consumption in WSN.

4.1 The Proposed Energy Model

As mentioned in the previous paragraph, the residual energy R_e of a node N, is determined by the remaining amount of energy of a node at a particular point in time. Hence, $\mathbf{R_e}$ **per node, n** is given by the equation:

$R_e = T_i - E_T$ (1)

Where T_i is the initial energy available in the node and E_T is the total amount of energy spent by the node during a particular task. E_T will be discussed in more details in the following paragraphs.

To calculate E_T which is the total amount of energy spent by the node, n, to carry out a particular task, say to transmit a packet to another node, the different energy consumers involved in that task, need to be identified first. The sources of energy consumption have been covered in details in Chapter 2. However to have a better understanding of how the model works, some of the points covered in Chapter 2 will be mentioned briefly again in the following paragraphs.

A typical sensor node consists of several components such as a microcontroller, a transceiver, sensor electronics and amplifiers. Each of these components operate in different states such as idle, listening, sleep, receive, transmit, and power down. For instance, when a node sends a frame of a particular amount of data to another node, the microcontroller is the only active component of the sensor node. The transceiver is then triggered to transmit the frame, that is, the microcontroller causes the transceiver to change its state from possible idle state to transmit state. After the transmission, the transceiver can go back to the idle or inactive state.

According to Kardi Teknomo (2007), every possible change from one operational state of a node to another one is modeled as a state transition, where each state is associated with some energy consumed per time and every transition, in turn, involves a period of time to switch between two operational states.
As a result, when a node does a specific task, latter encompasses a number of states changes and states transitions. Hence the energy, E_T, consumed by a task by N is calculated as follows:

Based on the common formula, Energy = Power * Time, E_T can be written as:
$E_T = \sum P_{state} \cdot t_{state} + \sum P_{trans} \cdot t_{trans}$ (2)

where $\sum P_{state} \cdot t_{state}$ = sum of the product of the power consumed in the states "state", and time, t_{state}, spent in each different states.

State can be receive, idle, sleep, stand by, inactive, dead, transmit and listen. This parameter also accounts for retransmissions, where a node may need to undergo further similar states transitions in the case of collision, packet loss or corrupted packet.

$\sum P_{trans} \cdot t_{trans}$ = sum of the product of the power, P_{trans}, consumed in changing states and the time, t_{trans}, for the transitions between the states.

The resulting equation (2) only represents the total amount of energy spent in the different operational states and transitions in the perfect case. However, very often, the node can delay in forwarding the packet to a next node due to traffic or aggregation. To account for this issue, the energy spent in delaying the transmission of the particular packet is added to (2):

$E_T = \sum P_{state} \cdot t_{state} + \sum P_{trans} \cdot t_{trans} + \sum P_{delay} \cdot t_{delay}$ (3)

Where P_{delay} = Power consumed in retaining a specific amount of bits due to traffic or aggregation and

T_{delay} = Time spent in the delay state.

Since the major consumer of energy in WSN is data communication, that is, data transmission and reception, the major parameters which affect the latter, need to be further investigated and identified. Energy spent in the transmit and receive state will hence be decoupled from $\sum P_{state} \cdot t_{state}$ and represented individually by:

$\sum P_t \cdot t_t$. (4)

Where $\sum P_t \cdot t_t$. corresponds to the sum of the product of the power, P_t, spent in the transmit/receive state and the time, t_t, spent in the transmit/receive state.

Hence, equation (4) can be written as:

$E_T = \sum P_{state} \cdot t_{state} + \sum P_t \cdot t_t + \sum P_{trans} \cdot t_{trans} + \sum P_{delay} \cdot t_{delay}$ (5)

Where P_{state} now corresponds to other states except the transmission and reception states and $\sum P_t \cdot t_t$ corresponds to possible retransmissions that may occur due to collisions, packet loss or corrupted frames.

As mentioned, a WSN spends most of its energy in data communication. Hence researchers must choose a communication mode: single hop or multihop. In single hop mode, each node sends its data directly to the base station. On the other hand, each node sends its data destined ultimately for the base station through intermediate nodes. However, the preferred mode of communication with respect to energy depends on the specified scenario. P_t will therefore be calculated with respect to single or multihop communication mode. J F Shi reported that the lifetime a node is determined by the shortest living node, that is, the shortest distance from base station, assuming that the transmitter dissipates energy to run the radio electronics and the power amplifier and assuming that the receiver dissipates energy to run the radio electronics, the amount of energy, P_t, required to transmit/receive a l-bit packet over a distance x is calculated as follows:

Let e be the amount of energy spent in the radio electronics circuitry and ux^k be the amount of energy spent in the radio amplifiers. Here u takes into account the constant factor in the propagation loss term, as well as the antenna gains of the transmitter and the receiver. The value of the propagation loss exponent k, depends on the surrounding environment. In free space, k is 2, while for environments such as buildings, factories and regions with dense vegetation, the value of k ranges between 3 and 5.

Hence $P_t = le+lux^k = l\,(e+ux^k)$.

To relay a packet, node must send the packet that has just been received to the next node.

Hence, $P_t = le+ le+lux^k + lux^k = 2l\,(e+ ux^k)$ (6)

Calculating energy spent by a node for single hop communication:

Let WSN consists of n sensor nodes arranged at intervals of r with the base station sitting at the right end as shown below:

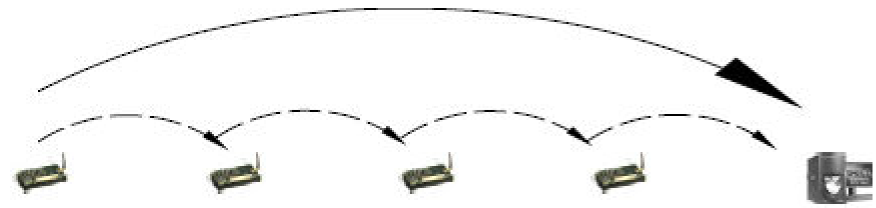


Figure IX. Single/ MultiHop Communication

When the sensor nodes use single hop communication, according to model 10, the sensor node located farthest from the base station, that is, at a distance nr, has to spend the maximum amount of energy. Assuming that all sensor nodes are alike, the lifetime of the network is determined by the lifetime of the shortest-living node. Hence to ensure that at least one *l*-bit packet is sent to the Base Station, with reference to (6), energy required for data communication can be written as:

$P_t = 2\, l * (e + u * nr^k) = 2l\,(e + n^k\, ur^k)$ (7)

Calculating energy spent by a node for multi hop communication:

When the sensor nodes use multihop communication, except the sensor node located farthest from the base station, every sensor node need to send itself data packet while also acting as a router for relaying the data packet of other sensor nodes that locate farther from the base station. The sensor node located closest to the base station has most relay task and require most energy for data communication.

Hence to ensure that at least one *l*-bit packet is sent to the Base Station, with reference to (6), energy required for data communication can be written as:

$P_t = l * ((n - 1) * (2e + ur^k) + (e + ur^k)) = l * ((2n - 1)\, e + (nur^k)$ (8)

Taking the energy loss due to leakage, g into account,

In single hop communication,

From (7), $P_t = 2l\,(e + n^k\, ur^k + g)$ (9)

In multihop communication,

From (8), $P_t = l * ((2n - 1)\, e + (nur^k) + g)$ (10)

Replacing (9) in (5),

In single hop communication,

$E_T = \sum P_{state} \cdot t_{state} + \sum 2\, l\,(e + n^k\, ur^k + g) \cdot t_t + \sum P_{trans} \cdot t_{trans} + \sum P_{delay} \cdot t_{delay}$ (11)

Replacing (10) in (5),

In multiple hop communication,

$E_T = \sum P_{state} \cdot t_{state} + \sum l * ((2n - 1)\, e + (nur^k) + g) \cdot t_t + \sum P_{trans} \cdot t_{trans} + \sum P_{delay} \cdot t_{delay}$ (12)

Replacing equation (11) into (1),

The residual energy of a node in single hop communication mode is given by:

$R_e = T_i - (\sum P_{state} \cdot t_{state} + \sum 2l\,(e + n^k\, ur^k + g) \cdot t_t + \sum P_{trans} \cdot t_{trans} + \sum P_{delay} \cdot t_{delay})$ (13)

Replacing equation (12) into (1)

The residual energy of a node in multi hop communication mode is given by:

$$R_e = T_i - (\sum P_{state} \cdot t_{state} + \sum l * ((2n - 1) e + (nur^k) + g) \cdot t_t + \sum P_{trans} \cdot t_{trans} + \sum P_{delay} \cdot t_{delay} \quad (14)$$

Where R_e and T_i is in nJ, P_{state} and P_{delay} is in nJ, t_{state} and t_{delay} is in seconds and r is in m.

Additional Assumptions and rules:

1. P_{state} = Current * Voltage (voltage=3V), can be obtained from data sheets.
2. t_{trans} depends on the number of packets transmitted over distance r.

5 eMnSiM: THE PROPOSED ENERGY SIMULATOR

Models of energy consumption are needed to accurately simulate and evaluate the efficiency of a protocol or application design. Based on this statement, the need for a tool that will allow simulation and evaluation of models crops up. For this purpose, a WSN simulator has been implemented to allow researchers to experiment with energy models and parameters that affect lifetime of WSNs. eMnSiM performs simulations based on the proposed model in Chapter 4.

5.1 Design Issues

eMnSiM has been implemented on .Net framework in C#, which is an object-oriented and cross-platform language that is aimed at shortening development time by freeing the developer from worrying about several low level plumbing issues such as memory management, type safety issues, building low level libraries, deterministic object cleanup and array bounds checking. As a result, C# provides more reliability, flexibility and robustness than Java or C++ as discussed by David J. Stein, Esq. (2005).

5.2 Components of eMnSiM

The WSN may be deployed based on a wide range of parameters as shown on label 6 in Figure X. The network can then be used to simulate the detection of events traveling across the field. In this simulation, when a vector visits the sensor node, the latter generates a data packet and sends it to a downstream network node. The packets are routed appropriately until they reach the BS. Each node also simulates an energy cache, which is depleted by sensing, processing, sending, receiving packets, and by detecting events. Since the nodes have finite energy, they will eventually power down and drop out of the communications network, causing network failure.

Figure X shows eMnSiM's components, which are broken down into tabs, a main menu, quick menu and a toolbar menu. These menus allow easy and quick navigation to different windows or forms.

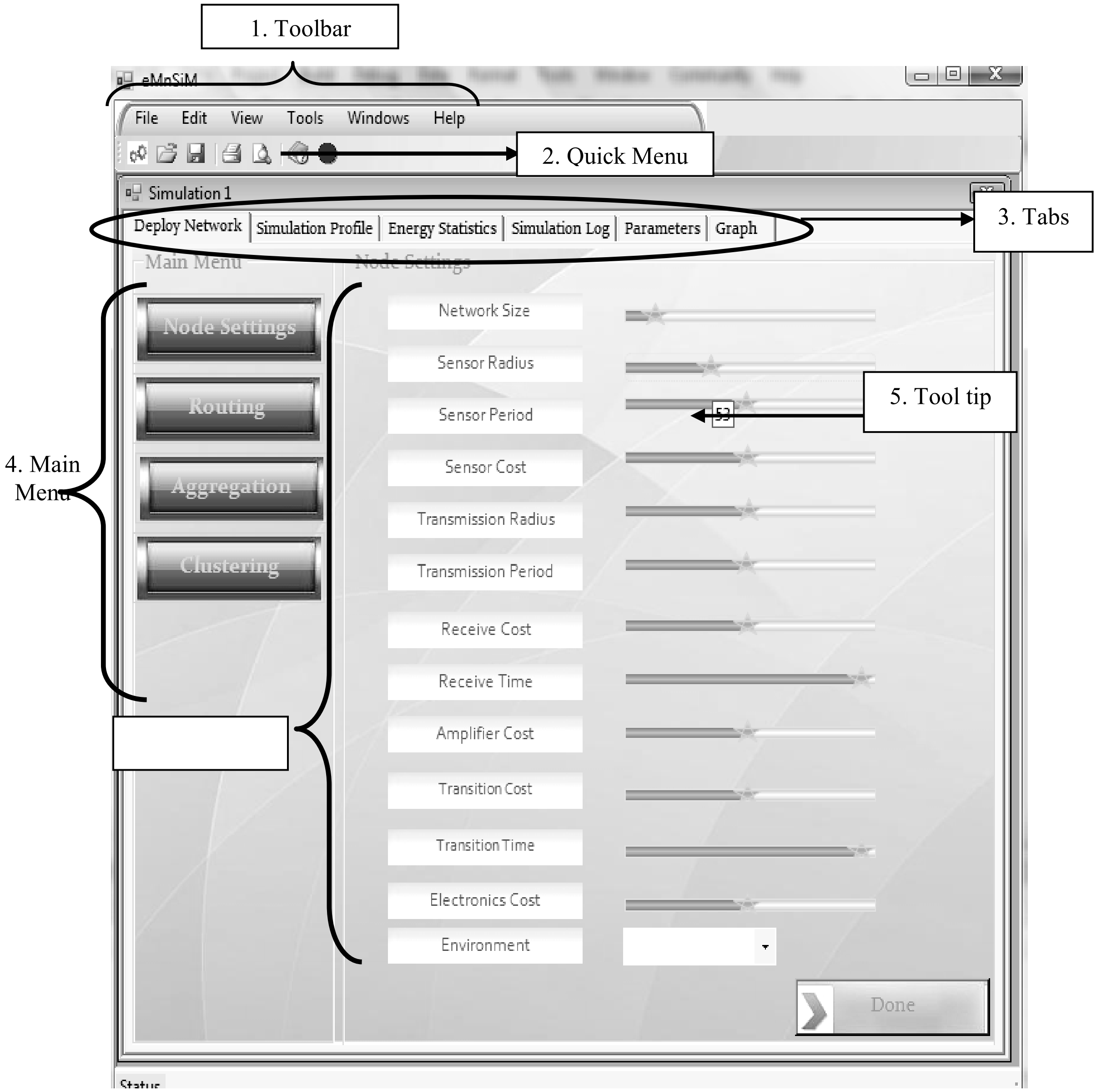


Figure X. Screenshot of eMnSiM

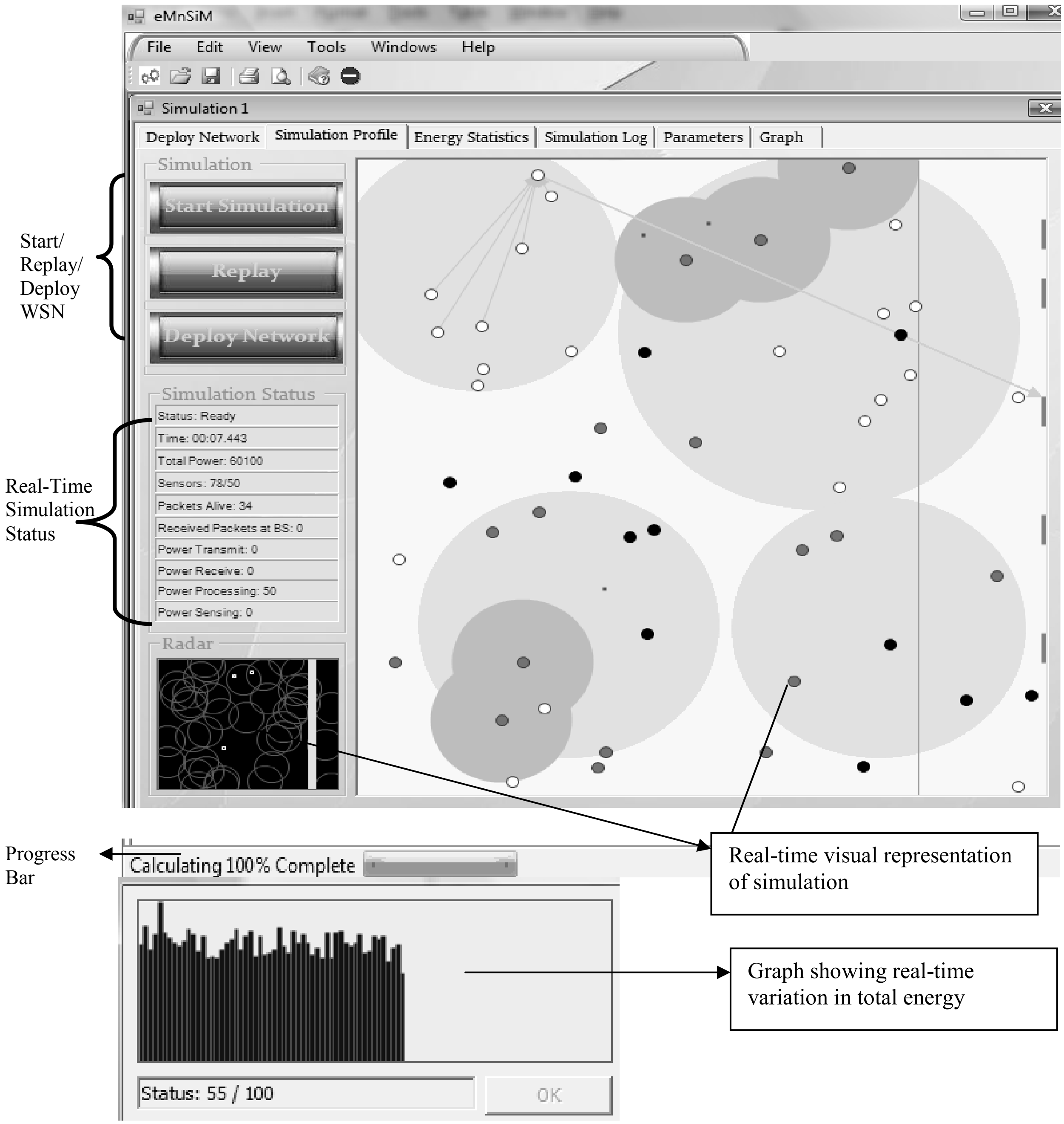


Figure XI. Screenshot – Simulation Profile Tab of eMnSiM

eMnSiM is a simple, yet efficient energy oriented simulator for WSNs. The simulation tool allows nodes to be created, linked and plotted with respect to various routing or communication algorithms. For the development of this project, eMnSiM allows for testing scenarios such as Directed Diffusion, Directed Routing, LEACH, K-Means and aggregation. However it provides support for other protocols and different types of environment as well. This functionality allows researchers to conduct their experiments and energy analysis over a wide number of scenarios, which is similar to real life ones, thus resulting in more accurate and precise results.

While the simulator delivers a precise visual image of how WSNs are setup in real life, it also helps researchers in experimenting with the different parameters that affect energy consumption in WSNs. The parameters are shown in the following screenshot:

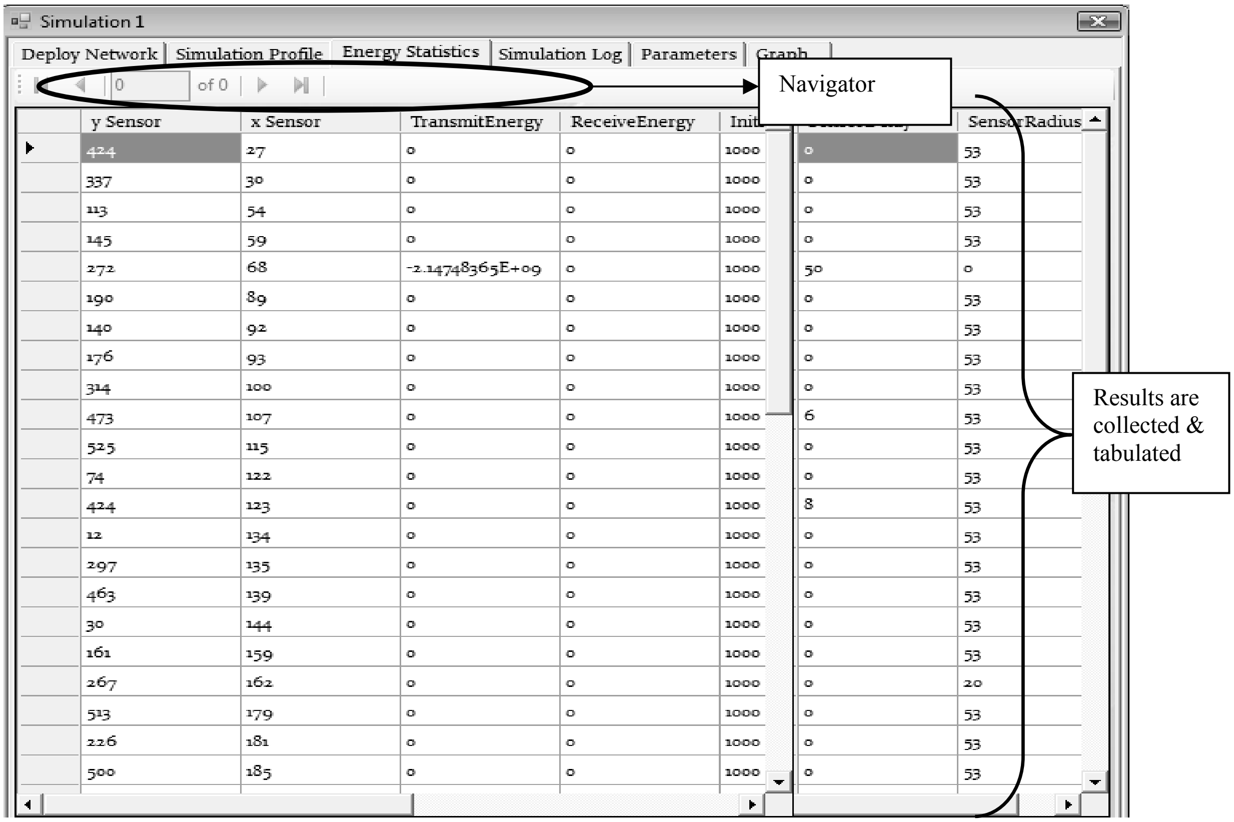


Figure XII. Screenshot - Tabular Results

Additional functional requirements include: Efficient energy profiling whereby the results obtained from the simulation experiment is collected, tabulated (Refer to XXXVI) and represented on graphs to be able to accurately analyse the effect of energy consumption in WSNs; Easy modifications of the main parameters via sliders; Graphical interface which is useful for debugging or illustration purposes, variables inspection; and finally simulations are easy to configure and execution of the same simulation for different parameters are also included.

Another interesting feature of eMnSiM is that it offers the possibility to vary the different energy parameters and ultimately different graphs can then be plotted to allow researchers to better analyse and compare the different parameters against the main parameters such as total energy or residual spent by the node or WSN against number of nodes.

Moreover, eMnSiM is user friendly. This allows researchers to carry out their related experiment in a fast, simple and modular approach. This will enable them to focus more on the results and spend less time in manipulating the simulator. Additional useful features are portrayed in Figure X.

6 EVALUATION OF eMnSiM

A simulation study based on several parameters has been performed to assess the performance and efficiency of eMnSiM in comparison to existing energy models and simulators. For this purpose, two existing simulators namely OMNET++'s Sensor Simulator and WirelessSensorNetwork have been chosen for a comparison study with eMnSim.

6.1 Evaluation Conclusion

Following the simulation study, eMnSiM has been validated to be a stable tool for simulation purposes for various routing, aggregation and clustering algorithms since the simulation results are comparable to existing energy simulators' energy statistics. Moreover it has proven to be more efficient in terms of execution time and packet delivery ratio as compared to OMNET++ SensorSimulator and NS-2.

eMnSim provides venues and guidelines for energy reduction and design improvement while delivering a precise image of what happens in real WSNs, primarily with respect to energy metric and providing and energy map/profile for each simulation in a well represented tabular form.

7 CONCLUSION

This project aimed at addressing energy, the key constraint and challenge in WSNs and hence addressing the needs of researchers to accurately simulate the energy efficiency of any proposed solution or protocols designed for optimizing the lifetime of a WSN. After intensive research work in the related field and an in-depth analysis on energy consumption, challenges, measurement, parameters and existing energy models and simulators for WSNs, the objective was met with the derivation of eMnSiM, an improved energy model and ultimately the implementation of an energy-oriented simulator specifically targeted towards energy consumption measurement and analysis in WSNs.

eMnSiM model takes into consideration several important parameters that directly or indirectly affect energy consumption in WSNs. Moreover the latter model considers the residual energy R_e of a node N, which is determined by the remaining amount of energy of a node at a particular point in time. R_e is an important factor in prolonging the lifetime of a node and hence that of the whole WSN.

While eMnSim has been proved to be a good experimental energy model which can be used by researchers to accurately simulate and evaluate the efficiency of several protocols or application design by varying/ experimenting with the different energy parameters provided by eMnSiM, it is also an all-in-one simulator specifically targeted towards the lifetime of WSNs. Moreover eMnSim provides venues and guidelines for energy reduction and design improvement while delivering a precise image of what happens in real WSNs, primarily with respect to energy metric and providing and energy map/profile for each simulation in a well represented tabular form. In addition the simulator provides support for several protocols such as routing, clustering and aggregation. As a result, eMnSiM will greatly help researchers in their search to design new protocols to meet the energy challenges in WSN.

However the proposed energy model can be revised to include more parameters that affect energy consumption in WSNs. This will enable researchers to extend their simulation to an even greater range of scenarios.

While the simulator only portrays simulation of heterogeneous nodes, the former can be enhanced by extending eMnSiM's capability to simulate homogeneous nodes as well.

Moreover, the simulator can be modified to accommodate for automatic export of the simulation logs and results to Excel or Word.

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Appendix 1

Table II. Current consumption for Mica2 Model

Operation	Time (s)		I (mA)	
Initialize radio (b)	350E-6	t_{rinit}	6	C_{rinit}
Turn on radio (c)	1.5E-6	t_{ron}	1	Cron
Switch to RX/TX (d)	250E-6	$T_{rx/tx}$	15	Crx/tx
Time to sample radio (e)	350E-6	T_{sr}	15	Csr
Evaluate radio sample (f)	100E-6	T_{ev}	6	Cev
Receive 1 byte	416E-6	t_{rxb}	15	Crxb
Transmit 1 byte	416E -6	T_{txb}	20	Ctxb
Sample sensors	1.1	T_{data}	20	Cdata