

Bond Graph Modeling for Energy Harvested WSNs

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Abstract

We propose Bond Graphs model for Energy Harvesting WSNs (EHWSNs). It is an energy conservation based approach. We model several system blocks such as energy source, storage buffer, microcontroller, radio and wireless channel. The dynamic behavior of both physical and computational elements of a system can be modeled accurately and this allows us to seek answers to some of the key questions in EHWSNs including finding stability regions. The outage probability result of a wireless link shows a close match between the model and the test-bed.

I. INTRODUCTION

Networked embedded systems are becoming battery-less, thanks to the growth of ultra-low power electronics. Energy can be harvested from the environment and efficiently stored in supercapacitors and thin film batteries to drive Wireless Sensor Networks (WSNs). Energy sources for WSNs include solar photovoltaic cells, wind, temperature differential (Seebeck effect), vibration and flutter of piezoelectric fibers, RF energy from mobile phone towers and Wi-Fi Access points, water flow, linear or mechanical motion, etc. Often it might be possible that energy is converted from one form to another before conversion into electricity. For example, solar energy may be converted into heat and then converted into electricity. Similar possibilities exist when wind can be converted into vibration and flutter. Thus multiple energy domains can exist simultaneously. Since available environmental energy varies with time, software and other computational elements need to be constantly adapting to this energy variation for perpetual operation of WSN nodes. Often nodes have to stall packet transmissions during energy accumulation and replenishment. Power management strategies have to be flexible and also exploit several low power modes and other deep sleep mechanisms. Thus energy conservation principles have to be applied for Energy Harvesting Wireless Sensor Nodes (EHWSNs). Since stability of data queues depends on the energy availability, modeling of such dynamic systems is a challenge. The dynamics of energy source and fan-in, fan-out of several blocks in the system including computational and physical elements require a detailed energy audit. Some key questions in EHWSNs are: (i) Given an energy form available for harvesting, what is the critical input energy required to meet the application requirement? (ii) What is the energy buffer required to meet a specific target application performance? (iii) Which system block is most energy consuming? (iv) What strategies extends the system stability region?

These questions could be answered using *Bond Graph* (BG) model of EHWSNs focusing on energy conservation principle. The model is a directed graph with object oriented declarative, hierarchically structured and support encapsulation of subsystems modeling. The graphs are continuous time and, can model energy sources, storage buffers, systems and communication links. Energy constraints can be introduced and studied under realistic application scenarios. The state space equations automatically generated can be used for analyzing the system stability region. It provides insights into energy neutral operational requirements. Hitherto, models used in network simulators such as QualNet, NetSim, ns-3, OPNET, Contiki COOJA, TOSSIM are based on energy consumption model rather than energy conservation model. A detailed survey of existing simulators can be found in [1]. Table I shows the key differences between the modeling and simulation approach of BG compared to existing simulators. Using BGs, energy required for sensing the environment, communication, computation, and actuation can be modeled accurately. BGs model the dynamic physical system with a strict energy domain independence [2], [3], [4]. This method is commonly used in mechatronics [5] and automotive applications [6]. In [7], the authors discuss BG modeling, control and simulation of the photovoltaic system performance. Literature on EHWSN [8], [9] is mostly towards modeling the energy source and designing several power management strategies to efficiently use this harvested energy. Almost no work is found on system stability when other energy forms such as wind speed, flow rate, vibration or flutter is used in EHWSNs. Some works model EHWSN systems using markov chains where battery state, energy harvested and traffic is modeled [10], [11]. They however do not consider the system stability and other leakages in the system. In this article, we describe a novel modeling approach to model EHWSNs.

This article is organized as follows: An overview of BG is in Section II and a model of energy harvesting system is in Section III. In Section IV BG models for EHS is provided. A simple EHWSN application modeled using BG in Section V and we conclude in Section VI.

TABLE I
COMPARISON BETWEEN BOND GRAPH MODELING AND OTHER SIMULATORS

Sl no	Bond Graph Modeling	Other Simulators
1	Modeling a physical system using basic building blocks. For example, Pathloss could be modeled using resistive load, Queues, Transceivers, etc. could also be modeled with Bond Graphs using equivalent physical representations. (see Fig. 1)	Operation of the system based on energy is abstracted as only a resource. Thus it usually takes discrete values in the system to be simulated.
2	Continuous time modeling (model's behavior is represented by a differential equation)	Discrete event based simulations
3	System characteristics are modeled (e.g., V-I curves) with both modeling and simulation of the dynamic system	Requires either an analytical model as the first step or modification of existing generic components or uses traces.
4	BGs are multi-domain (e.g., electromechanical, hydraulics) and domain neutral (Energy conversion is seamless)	Most of the simulators are domain dependent
5	Adheres to law of conservation of energy	Energy is treated as a time varying function
6	Composed of bonds that represents instantaneous flow of energy	Since energy is not modeled but only abstracted as a resource, flow of energy cannot be traced in simulation.
7	Energy source, energy buffer, and loads (microcontrollers, trans-receivers) can be modeled and simulated accurately	Models have to created with several assumptions and hence simulation may not be accurate to the real system in general.
8	Hardware independent and supports a generic framework for all WSN nodes	Most assumptions on the models are hardware dependent.
9	Bond Graphs are detailed and tries to use differential equations to represent the change in system. Thus very detailed modeling and simulations in some cases might be difficult.	Abstracted and discrete event based, thus it is faster and also easier to simulate.

II. BOND GRAPH - AN OVERVIEW

A Bond Graph consists of several subsystems linked together by energy bonds representing the connections of the dynamic system. Models of complex systems are built as a collection of the basic elements and relationships derived from the representation. The representation describes how power flows through the system. The variables used are 'Effort' $e(t)$ and 'Flow' $f(t)$. Power $P(t)$, flowing in or out of a bond can be expressed as the product of Effort and Flow. In the electrical domain, while the *Effort* variable is represented by voltage, the *Flow* variable is represented by current. Momentum ' p ' and displacement ' q ' from the mechanical domain maps to flux linkage ' ϕ ' and charge ' q ' in electrical domain respectively. The standard elements in BGs are ports and junctions. Ports could be 1-port or multi-port based on the number of bonds. 1-port elements include power dissipating, energy storage and power supply elements such as the resistive, capacitive and inductive elements, and also Effort and Flow sources. Example of multi-port elements are transformer and gyrator. Junctions interconnect components in the subsystem. Junctions are power conserving and the power transports of all bonds sum up to zero always. Junctions could be 1-junction and 0-junction which, in electrical terms are series and parallel connections respectively. The flow direction in BG is determined by the causality stroke. The end of power bond with the causal stroke indicates that Flow is starting from that point. The flow direction of Effort is opposite to the Flow variable. Causality for each element is determined by its linking equation of Effort and Flow variables. If the direction of the Flow variable is found to be flowing into the element, then the causal stroke is drawn away from the element and vice versa. Relation between Effort and Flow variable for each element and its corresponding causality is shown in Fig 1.

III. MODEL OF ENERGY HARVESTING SYSTEM

In Energy Harvesting WSNs (EHWSN), each node can harvest varying amounts of energy. A perpetual lifetime of a node is possible if the energy flow is copious. EHWSN nodes can operate in two ways: (a) powered directly from harvesting source and (b) harvest-store-use model [12]. Here, we employ the harvest-store-use model to drive our example EHWSN. Fig 2(a) shows the block diagram of a EHWSN node. We have considered a photovoltaic panel as the energy source and the harvested energy is stored in a supercapacitor to drive sensor node. A typical sensor node comprises of a microcontroller, radio and a few sensors. The analog front end of the radio transceiver is shown in Fig 2(b). We next provide a method to systematically build BGs from physical models.

IV. BOND GRAPH MODELS FOR EHS

A. Energy Source - Photovoltaic Model

The operation of the Photovoltaic (PV) model is described by the standard model as shown in Fig. 3(a). In this model, I_{ph} is the current generated proportional to the surface temperature and insolation. R_s is a small series resistance and R_p is the shunt resistance of the PV model. When I_{ph} flows through these resistors, an output voltage of V_o is generated across the load.

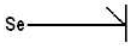

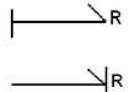
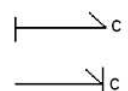
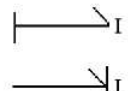
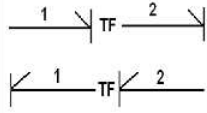
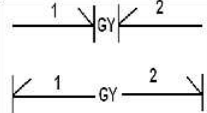
ELEMENT	SYMBOL	CAUSALITY	EQUATION
SOURCE OF EFFORT	S_e		
SOURCE OF FLOW	S_f		
RESISTIVE ELEMENT	R		$e(t) = R \cdot f(t)$ $f(t) = R/e(t)$
COMPLIANCE ELEMENT	C		$e(t) = \frac{1}{C} \int f(t) dt$ $f(t) = C \cdot \frac{d}{dt} e(t)$
INERTIAL ELEMENT	I		$e(t) = I \cdot \frac{d}{dt} f(t)$ $f(t) = \frac{1}{I} \int e(t) dt$
TRANSFORMER	TF		$e_2(t) = \text{const} \cdot e_1(t)$ $f_2(t) = \text{const} \cdot f_1(t)$ $f_1(t) = \text{const} \cdot f_2(t)$ $e_1(t) = \text{const} \cdot e_2(t)$
GYRATOR	GY		$f_2(t) = \text{const} \cdot e_1(t)$ $f_1(t) = \text{const} \cdot e_2(t)$ $e_2(t) = \text{const} \cdot f_1(t)$ $e_1(t) = \text{const} \cdot f_2(t)$

Fig. 1. Elements in Bond Graphs and their causalities.

General procedure to develop BG is as shown in Algorithm 1. The photovoltaic generator is modeled using a Flow source represented using $S_f = I_{ph}$. The diode and the parallel resistance (R_p) are then connected in parallel to the Flow source using 0-junction. Non-linear behaviour of diode is modeled in BG by its reverse resistance (R_r) and forward resistance (R_f). The switching between the two resistors is based on the threshold voltage of the diode. The resistance R_s is connected in series to the graph using 1-junction. Since, S_f is bringing the Flow, the arrow is inwards to the 0-junction and the causality stroke is in the beginning of the bond. Since the Flow gets divided in R_r , R_f & R_p , the arrow is outwards from the junction and one of them becomes the Effort decider of the block which decides the Effort brought into the junction (usually applied in a 0-junction). The Effort gets divided in the 1-junction across the series resistance (R_s) and the load (R_l). The PV model in BG is as shown in Fig. 3(b).

B. Energy Buffer- Supercapacitor

Supercapacitors are energy buffers for EHWSN due to its infinite charge-discharge cycles and sufficiently good energy density. Fig. 3(c) shows the standard supercapacitor circuit with Equivalent Series Resistor (R_{sc}) and Equivalent Parallel Resistor (R_{pc}). R_{sc} provides the initial voltage drop across supercapacitor and R_{pc} corresponds to the self-discharge characteristics of the supercapacitor. Ideally, R_{pc} value should be very large and R_{sc} should be close to 0. Supercapacitor is a storage element and acts as the load to the above described PV model. We follow the same steps as described in Algorithm 1 to develop the equivalent BG for supercapacitor. Therefore, R_l the load connected to the PV model is replaced with the corresponding BG model of supercapacitor. The voltage generated by the PV model charges the supercapacitor and the Flow gets divided in the 0-junction between the R_{pc} and C. Fig. 3(d) shows the BG modeling of PV and supercapacitor.

C. Microcontroller subsystem

The energy stored in the supercapacitor is used to drive the wireless sensor node which consists of microcontroller and radio. The microcontroller block can be split into three major parts namely processor, memory, analog-digital converter and sensing. Each component is a power dissipating element and dissipates 9.6mW, 9.9mW, and 300 μ W respectively. The BG model uses resistors as shown in MCU block of Fig. 4. The energy source for microcontroller is supercapacitor i.e., Effort source (S_e) and hence the causal stroke is at the end of the port. Thus, S_e gets distributed across R_{prc} , R_{adc} and R_{mem} , and one of them becomes the Effort decider in the microcontroller subsystem.

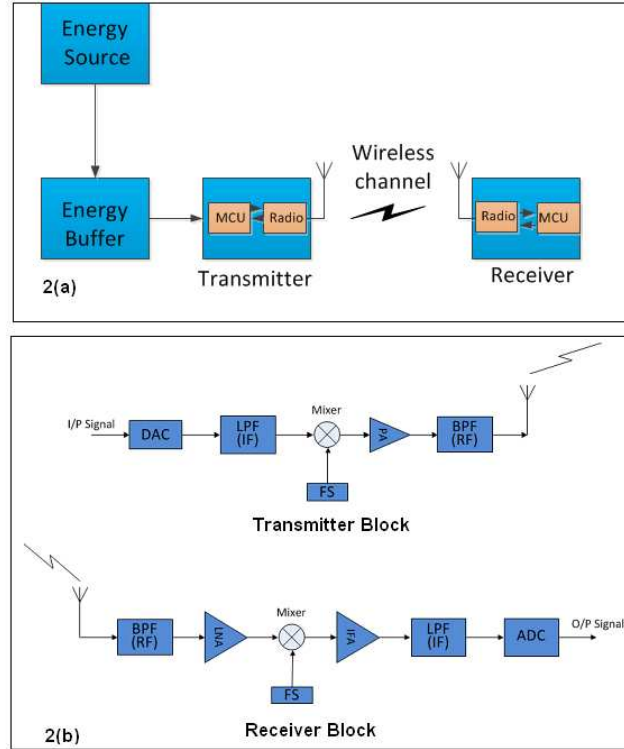


Fig. 2. (a) Block Diagram of Energy Harvesting Wireless Sensor. (b) Analog front end of the radio transceiver

Algorithm 1 Steps to derive BG models

- 1: Determine the physical domain of the system and identify the basic elements like R, C, L, S_e , S_f , TF, GY etc.
 - 2: Provide a unique name to each of the identified element in the above step.
 - 3: Indicate a reference Effort for the given system model.
 - 4: Identify all other Efforts in the system and provide them with unique names.
 - 5: Identify all Effort differences/Flow differences needed to connect the ports of the elements obtained in Step 1.
 - 6: Construct the Effort differences using a 1-junction and Flow differences with 0-junction.
 - 7: Connect the port of all elements obtained in Step 1 with the 0-junction and 1-junction for corresponding Effort differences and Flow differences respectively.
 - 8: Simplify the above obtained graph. (a) a bond between two same junctions can be left out and the junctions can be combined. (b) two separately constructed identical Effort or Flow differences can be merged to a single Effort or Flow differences.
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D. Radio subsystem

Radio block with transceiver is shown in Fig. 2(b). The transmitter and receiver circuits consists of digital-to-analog converter (DAC), low-pass filter (LPF), mixer, frequency synthesizer (FS), power amplifier (PA), and bandpass filter (BPF). Most of these components are power dissipating elements and some elements such as the PA are non-linear components. Thus, this non-linearity should be considered in BGs. It is modeled using a transformer with parameter ' k ' as the transformer ratio. Transformers are used to model the drain efficiency of the power amplifier. Although it is well known that drain efficiency increases with transmission power, almost all WSN related modeling do not consider the efficiency of the PA block. The radio circuit power P_T can be computed by adding individual component power.

$$P_T = P_{PA} + P_{DAC} + 2(P_{LPF} + P_{FS} + P_{BPF}) + P_{LNA} + P_{IFA} + P_{ADC}. \quad (1)$$

We calculate the maximum power delivered P_{max} by the PA using Eq. 2 where V_{DC} is the supply voltage and R is the load resistance for impedance matching.

$$P_{max} = \frac{V_{DC}^2}{2R} \quad (2)$$

The drain efficiency of the power amplifier is calculated by

$$\eta = \frac{P_O}{P_{DC}}, \quad (3)$$

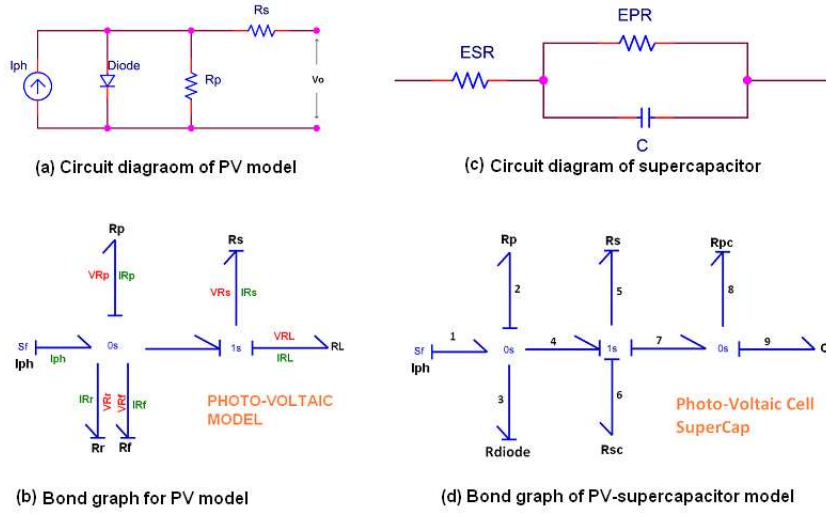


Fig. 3. Circuit diagram and BG model for Photo-Voltaic and supercapacitor

where P_O is the power output and P_{DC} is the supply power to the power amplifier. The Fig. 4 shows BG model of radio block. The R_1 , R_2 and R_{ana} elements are tuned such that the output of power amplifier is matched with the load impedance.

Having constructed the system model, let us take up data arrival and its queuing in BG. The notion of processed data or information communication and its consumption is handled by an intelligent switching logic and power dissipation elements. The R_{data} element in Fig. 4 handles the information block and constitutes packet framing, packet transmission, ACK reception and the sleep (i.e. radio turn-off) blocks. Through extensive measurements on WSN nodes, we found power dissipation values of these blocks including the time required to complete a specified functionality. These blocks are modeled as power dissipation elements, and at each instant at most one block has to be enabled. Therefore the blocks follow a sequential order of packet framing, packet transmission, ACK reception and finally sleep. The time interval in “on” state for each of these blocks is 2ms, 4.4ms, 2ms and 1900ms respectively. The complete BG model equivalent to Fig. 2 is shown in Fig. 4. The graph shows the division of S_e from the capacitor as the source to both microcontroller and radio subsystems. The microcontroller and radio subsystems check the capacitor voltage every 2s and turn “on” only when the supercapacitor’s voltage is above 1.8V.

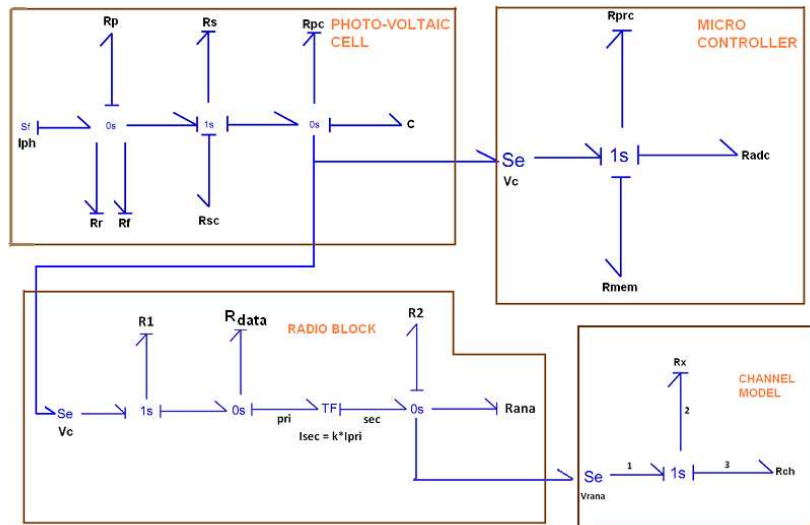


Fig. 4. Bond graph model for EHWSN node.

E. Wireless channel model

We modeled the wireless channel as a simple link with a good coherence time and thus it is a static channel with path loss contributing to the attenuation of the RF signal. Using several datasheets from the vendor/manufacturer, we fixed the maximum

range between any two nodes based on transmission power P_{tx} , receiver sensitivity P_r , and fading margin F_m as,

$$R = 10^{\left[\frac{P_{tx} + F_m + P_r - 10 * n * \log_{10}(f) + 30 * n - 32.44}{10 * n} \right]} \quad (4)$$

The BG model for wireless channel is shown in Fig. 4. The energy source ($S_e = V_{R_{ant}}$) driving the channel is obtained from the antenna out of the EHWSN mote. Thus, the Effort splits across R_{ch} element constituting the channel loss and the power across R_x is the received power.

V. A PRACTICAL EHWSN APPLICATION

A. Test-bed and initial data

To study the efficacy of the BG modeling and simulation approach, we built a real EHWSN application that runs on a test-bed of 10 sensor nodes placed in a 200 seating capacity conference hall. Since the goal is to control the air-conditioning in the hall, each node senses the temperature locally and transmits the data over a one hop distance to a base station. The data packet size is of 128 bytes and a sample is obtained every 2s. The transmission power was fixed at +5dBm. Each node is individually powered by a 400mW solar panel under indoor lighting conditions. Our hardware comprised of a temperature sensor interfaced to MSP430 microcontroller and CC2520; a IEEE 802.15.4 compliant radio. To study the outage probability of this application, we selected two irradiance Lux values called W=1 and W=2 with their mapping to 5120 and 10240 Lux respectively. We installed special incandescent lamps with “on-off” control and placed them at about 20cm above the panels. Depending on the light intensity, the measured power output from the panel was used as input power for the simulation. The V-I characterization conducted for our solar panel measured an open circuit voltage (V_{OC}) of 4.08V and the short circuit current (I_{SC}) measured was 13.193 mA for a Lux value of 5120. Similarly for a Lux of 10240, the V_{OC} and I_{SC} measured 4.82V and 26.09 mA respectively. These measurement values were used for the I_{ph} in the PV model. For comparison with ns-2 network simulator, we constructed the multi-node network scenario with energy harvesting applied to the nodes.

B. Energy model

Let time be divided into slots of 2s. Energy E_s is harvested and available at the beginning of each time slot with a probability ρ . It is easy to see that E_s and ρ depend on the energy source. The harvested energy in each slot is identical and independently distributed and thus captures the sporadic and random availability of energy. To power up and inject energy into the node we used the lamps and their associated switches for controlling the energy injection probabilities. Packet transmission is deferred whenever the system is low on energy and unable to support the transmission power.

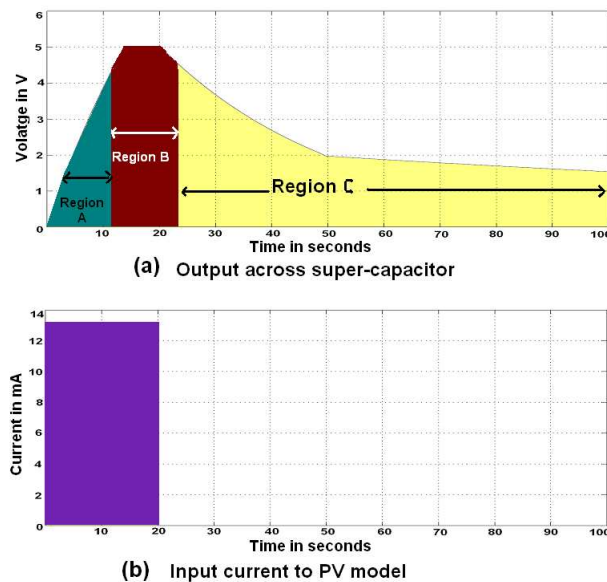


Fig. 5. Input current fed to the PV model and output across supercapacitor.

C. Results - Modeling (BG), ns-2 network simulator, Test-bed experiments

Let us now use the BG model constructed using the BG toolbox created under Matlab-Simulink platform to emulate the temperature sensing application running on the EHWSN node. We compare the results obtained from the model with ns-2 simulator and our test-bed results. Fig. 4 shows the BG model for EHWSN node. We considered several energy injection

TABLE II
OUTAGE PROBABILITY vs ENERGY INJECTION

Energy Injection(%)	Outage (Bond Graphs)		Outage (ns-2)		Outage (Implementation)	
	W=1 (Lux=5120)	W=2 (Lux=10240)	W=1 (Lux=5120)	W=2 (Lux=10240)	W=1 (Lux=5120)	W=2 (Lux=10240)
0	1	1	1	1	1	1
20	0.85	0.46	0.5	0.2	0.8	0.4
40	0.66	0.28	0.05	0.05	0.7	0.2
60	0.44	0.1	0.05	0.02	0.5	0.08
80	0.22	0.05	0	0	0.25	0.03
100	0.04	0	0	0	0	0

probabilities (ρ) with varying irradiance and studied the outage probability. Let us consider a case where $\rho = 0.2$. Firstly, Fig. 5 shows the total charge on the capacitor for an input of 5120 Lux. The supercapacitor charging is indicated by “Region A”. Once it is charged to a threshold, EHWSN node turns “on” and executes the application operating in “Region B”. This region demonstrates energy neutrality of the node. This is the stability region for both the system and data. When energy injection is suspended, the system enters “Region C” where the node defers all transmissions due to insufficient energy. Thus Region C is characterized by both system and data instability. As the available energy is low, the node has to defer packet transmission and the system may soon encounter a buffer overflow condition. It is easy to observe that sum of Region A, Region B and Region C is equal to the energy injected into the system. Table II summarizes the comparison between the BG model, ns-2 network

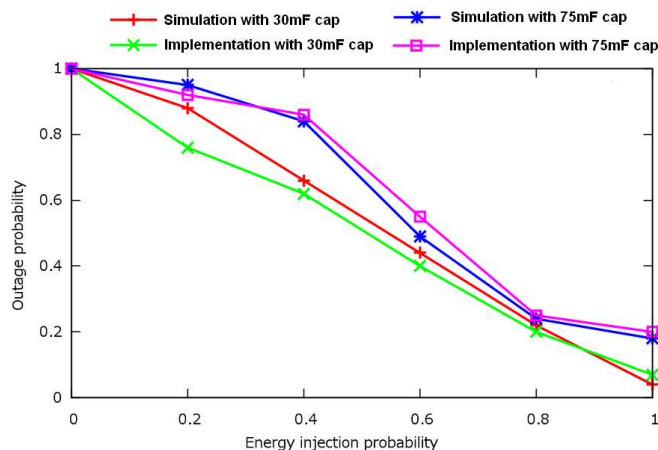


Fig. 6. Outage probability vs energy injection for W=1 (Lux=5120)

simulator and test-bed implementation results. It shows the energy injection probability, the irradiance from the panel and the outage probability obtained from all the three methods. The table illustrates that in general, higher irradiance ($W=2$) can be exploited and a zero outage can be achieved even with a small supercapacitor if $\rho \rightarrow 1$. The table shows that Bond graph modeling is realistic as it considers all aspects of energy flow, storage efficiency, leakage rate, efficiency of power amplifiers etc. This is evident from its close match with the test-bed results. The ns-2 simulations are unable to model all the power losses and dissipations which ultimately results in minimizing the outage probability significantly faster than reality. For instance, for 60% energy injection and $W=1$, ns-2 offers only 5% compared to over 40% outage shown in BG and test-bed. Such results exemplify the strength of BG modeling approach. Fig. 6 shows the impact of energy storage on the outage probability. The BG simulation and test-bed experiment was conducted for two values of supercapacitors. Under low irradiance a large buffer provides very little assistance as it takes a longer time to attain a specified voltage level. Thus this example provides solutions to: (a) how to decrease outage probability? (b) What should be the value of energy buffer? (c) What is the energy injection probability to ensure lower outages? (d) How long does the system remain in energy neutral condition? Seeking answers to such questions is non-trivial in other simulators such as ns-2.

1) *Other BG modeling examples:* Our first example concerns queue stability. Given the energy harvesting rate, how long does the sensor node maintain queue stability for a fixed modulation and coding scheme (MCS). If the MCS is varied how does it affect system stability? A second example concerns RF energy harvesting. Given an input RF power harvesting level, at what rate can the system sense the environment and complete a packet transmission at say +5dBm. Thus RF power harvesting drives a RF packet transmission. A final example is a wireless switch application which requires kinetic energy harvesting due to the mechanical switch action. What is the amount of harvested energy and what type of platform specifications are required to successfully deploy such a switch. This example requires energy flow information.

VI. CONCLUSIONS

In this article we introduced Bond Graph modeling for EHWSNs. We believe that this is the first time Bond Graphs are used to model a EHWSN. We developed a step by step methodology to model EHWSNs using BG. Since BGs model dynamic systems, they are found to be well suited for energy harvesting systems. The state space equations generated by the BG models can be used to analyze the stability region under various energy constraints. Our initial results using BG models show a very close match with the test-bed implementation. However, ns-2 network simulators are unable to model several parameters as experienced by the dynamic system. Our article shows that for the designed application, a *coarse* \rightarrow *fine* range control of temperature is possible by knowing the energy injection probability. Thus the solution to provision any domain independent energy harvester becomes trivial with Bond Graphs as “produce-consume” relationship and can be established with all the power consuming elements modeled accurately.

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