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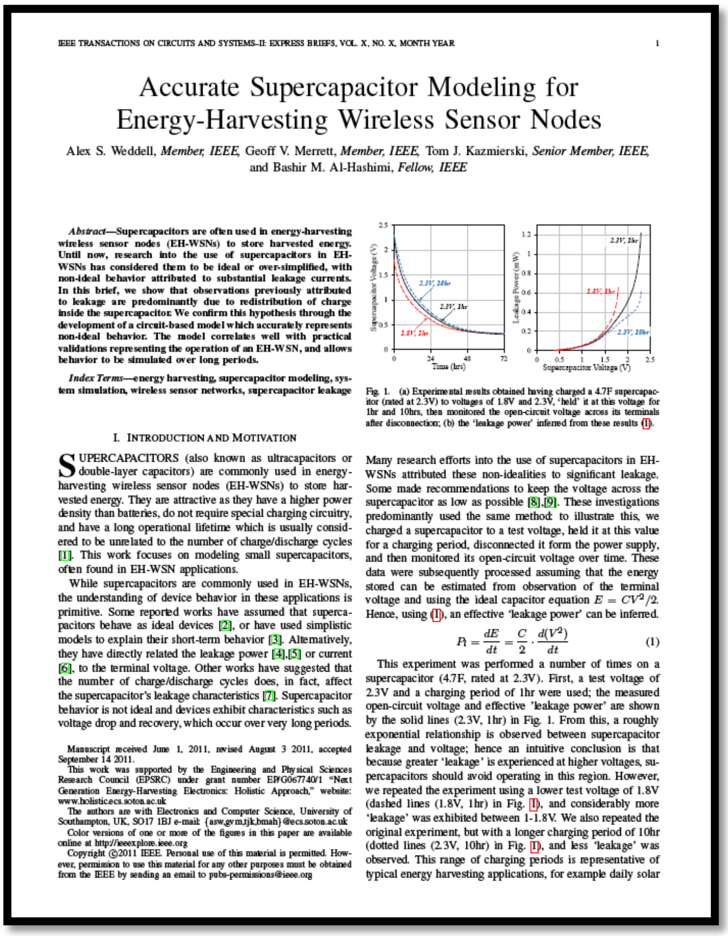

Accurate Supercapacitor Modeling for Energy-Harvesting Wireless Sensor Nodes

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***Abstract*—Supercapacitors are often used in energy-harvesting wireless sensor nodes (EH-WSNs) to store harvested energy. Until now, research into the use of supercapacitors in EH-WSNs has considered them to be ideal or over-simplified, with non-ideal behavior attributed to substantial leakage currents. In this brief, we show that observations previously attributed to leakage are predominantly due to redistribution of charge inside the supercapacitor. We confirm this hypothesis through the development of a circuit-based model which accurately represents non-ideal behavior. The model correlates well with practical validations representing the operation of an EH-WSN, and allows behavior to be simulated over long periods.**

***Index Terms*—energy harvesting, supercapacitor modeling, system simulation, wireless sensor networks, supercapacitor leakage**

Fig. 1. (a) Experimental results obtained having charged a 4.7F supercapacitor (rated at 2.3V) to voltages of 1.8V and 2.3V, 'held' it at this voltage for 1hr and 10hrs, then monitored the open-circuit voltage across its terminals after disconnection; (b) the 'leakage power' inferred from these results (1).

I. Introduction and Motivation

SUPERCAPACITORS (also known as ultracapacitors or double-layer capacitors) are commonly used in energy-harvesting wireless sensor nodes (EH-WSNs) to store harvested energy. They are attractive as they have a higher power density than batteries, do not require special charging circuitry, and have a long operational lifetime which is usually considered to be unrelated to the number of charge/discharge cycles [1]. This work focuses on modeling small supercapacitors, often found in EH-WSN applications.

While supercapacitors are commonly used in EH-WSNs, the understanding of device behavior in these applications is primitive. Some reported works have assumed that supercapacitors behave as ideal devices [2], or have used simplistic models to explain their short-term behavior [3]. Alternatively, they have directly related the leakage power [4],[5] or current [6], to the terminal voltage. Other works have suggested that the number of charge/discharge cycles does, in fact, affect the supercapacitor's leakage characteristics [7]. Supercapacitor behavior is not ideal and devices exhibit characteristics such as voltage drop and recovery, which occur over very long periods.

Many research efforts into the use of supercapacitors in EH-WSNs attributed these non-idealities to significant leakage. Some made recommendations to keep the voltage across the supercapacitor as low as possible [8],[9]. These investigations predominantly used the same method: to illustrate this, we charged a supercapacitor to a test voltage, held it at this value for a charging period, disconnected it form the power supply, and then monitored its open-circuit voltage over time. These data were subsequently processed assuming that the energy stored can be estimated from observation of the terminal voltage and using the ideal capacitor equation $E = CV^2/2$. Hence, using (1), an effective 'leakage power' can be inferred.

$$P_l = \frac{dE}{dt} = \frac{C}{2} \cdot \frac{d(V^2)}{dt} \quad (1)$$

This experiment was performed a number of times on a supercapacitor (4.7F, rated at 2.3V). First, a test voltage of 2.3V and a charging period of 1hr were used; the measured open-circuit voltage and effective 'leakage power' are shown by the solid lines (2.3V, 1hr) in Fig. 1. From this, a roughly exponential relationship is observed between supercapacitor leakage and voltage; hence an intuitive conclusion is that because greater 'leakage' is experienced at higher voltages, supercapacitors should avoid operating in this region. However, we repeated the experiment using a lower test voltage of 1.8V (dashed lines (1.8V, 1hr) in Fig. 1), and considerably more 'leakage' was exhibited between 1-1.8V. We also repeated the original experiment, but with a longer charging period of 10hr (dotted lines (2.3V, 10hr) in Fig. 1), and less 'leakage' was observed. This range of charging periods is representative of typical energy harvesting applications, for example daily solar

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Regards,

The Authors.

An Empirical Energy Model for Supercapacitor Powered Wireless Sensor Nodes

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***Abstract*—The modeling of energy components in Wireless Sensor Network (WSN) simulation is important for obtaining realistic lifetime predictions and ensuring the faithful operation of energy-aware algorithms. The use of supercapacitors as energy stores on WSN nodes is increasing, but their behavior differs from that of batteries. This paper proposes a model for a supercapacitor energy store based upon experimental results, and compares obtained simulation results to those using an 'ideal' energy store model. The proposed model also considers the variety and behavior of energy consumers, and finds that contrary to many existing models, the energy consumed depends on the store voltage (which varies considerably during supercapacitor discharge). Furthermore, energy models in a node's embedded firmware are shown to be paramount for providing energy-aware operation.**

***Index Terms*—wireless sensor networks, supercapacitors, network simulation, energy storage devices, energy consumption**

I. Introduction

Wireless sensor networks (WSNs) are receiving considerable research interest in both academia and industry, primarily due to the wide range of potential applications to which they are suited [1]. A WSN consists of multiple spatially distributed nodes, which communicate sensed data over a wireless channel [2], obtaining a spatial and temporal representation of the surrounding environment. Nodes are small, cheap, and inherently energy constrained. In order to overcome the many limitations of batteries, nodes using supercapacitors have recently been reported [3], [4].

Though alternatives exist including practical deployments and analytical methods, the majority of algorithms and protocols for WSNs are evaluated through simulation. To ensure correlation between simulation and practical results, accurate models representing the hardware, node, and surrounding environment are needed. However, implementing accurate models for all aspects of simulation is a non-trivial task, dramatically increasing development time and reducing performance. As algorithm development for WSNs generally targets specific performance criteria, realistic models should be used for the areas that affect these criteria. For example, a large volume of research is concerned with developing energy efficient algorithms; to simulate these, realistic energy models are required to ensure close correlation with practical results.

The contributions of this paper are to present a simple empirical model for supercapacitor energy stores (section III.A) and energy consumers (section III.B), showing that the behavior of energy consumers is of particular importance to modeling of supercapacitor powered nodes. Finally, the need for energy store and consumer models in practically deployed energy-aware nodes is presented (section IV).

II. Background to WSN Simulation Models

There are three techniques for analyzing networks: analytical methods, practical deployments, and computer simulation. The complexity of WSNs often causes analytical methods to be unsuitable [5]. Additionally, the proportion of algorithms that are evaluated through practical deployment is comparatively low, possibly due to the relative infancy, broad diversity and application dependence of WSNs. In contrast, simulation allows for the rapid evaluation, optimization, and adjustment of proposed algorithms and protocols.

Simulation allows the entire scenario and scale of a network to be quickly altered. However, it also permits certain areas of network operation to be omitted or simplified; for example assuming that particular components do not consume energy, or that collisions, interference and noise do not occur. While simplifications make development and evaluation faster, they can result in algorithms that are not realizable in practice; a simulation is only as realistic as the models it is based upon.

Many existing simulators fail to implement an energy model with anything more than an 'ideal' (or linear) battery model, which does not provide an accurate representation of practical hardware [6], [7]. The subject of battery modeling has received interest in the WSN research community [8], and has been incorporated into simulators, from simply considering rate discharge effects [9], to modeling additional effects such as relaxation and self-discharge [5]. However, the modeling of supercapacitors (which behave differently to batteries [10]) has not been considered in WSN simulation.

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The extent to which energy consumers (components that require energy to operate) are modeled varies considerably between simulators. Some consider only the radio transceiver as an energy consumer [5], while others also consider the microcontroller [9], sensors, and other peripherals [11]. Energy models considering many consumers on a node have been proposed, but these are generally to be used with low-level executable machine or device-dependent code [12], [13].

III. Modeling Energy Components

The energy components of a sensor node can be considered (and modeled) as having three energy components:

- **Energy Stores**: components that are used to store energy; for example batteries and supercapacitors (subsection A).
- **Energy Consumers**: components that consume energy; for example microcontrollers, sensors, radio transceivers, and other peripherals (subsection B).
- **Energy Sources**: components that provide energy; for example photovoltaics and mains electricity.

The energy hardware on a node lends itself to this categorization, whereby the three models describe physically separated hardware elements (meaning no complex interplays are left unaddressable). Due to space limitations, the accurate modeling of energy *sources* is not considered in this paper.

To substantiate the claims made in this paper, and to provide comparative results, simulation results (from our in-house simulator, WSNsim [14]) are included where appropriate. While explicit details of these simulations are not strictly necessary in order to fulfill the aim of this paper (showing the effect that these models have on results) they are summarized for completeness. The simulated network consists of 9 nodes in a 3x3 grid. All nodes routinely sample the environment, and report data to a sink node. Packets are flooded throughout the network, hence every node transmits each packet that is generated (with the exception of the sink that does not need to transmit as it is the sink of all its data). The media access control (MAC) layer used is similar to B-MAC [15], and each node wakes from a sleep state every 250ms to see if a neighbor wishes to communicate. To simulate a practical case study, the parameters (for example energy consumptions and timings) are tailored towards the CC2430 platform [16]. However, all hardware specific parameters can be changed to accommodate other platforms.

A. Energy Stores

This section discusses how the use of different energy store models can affect simulation results. The energy stores considered are an ideal energy store and a supercapacitor. In the results presented, nodes report packets every 2 minutes.

1) *Ideal Energy Store:* The ideal energy store (a purely theoretical device) provides a constant voltage until the stored energy is depleted, when it provides 0V. Two intuitive rules define the operation of an ideal energy store, a) it cannot store more energy than it has capacity to store, and b) once the store is depleted, no more energy is available until some is added.

The energy removed from the store (E_{used}) is equal to the amount of energy consumed by the circuit ($E_{consumed}$), and the energy added to the store (E_{added}) is equal to the amount of energy provided by energy harvesting ($E_{harvested}$). These are shown in (1) and (2).

$$E_{used} = E_{consumed} \tag{1}$$

$$E_{added} = E_{harvested} \tag{2}$$

The example ideal energy store used in the WSN simulations has a maximum (and initial) capacity of 15.3J (chosen to equal the capacity of the supercapacitor store shown in the next section) at 3.6V (the maximum operating voltage of the CC2430). Fig. 1 shows the results of the network simulation with this energy store. In this graph, the energy depletions fit into two categories: 1) the nodes that have to both transmit and receive (including routing received packets) deplete their energy reserves after around 2hrs30, and 2) the sink node (that is not required to transmit any packets) depletes its energy reserve in just under 11hrs.

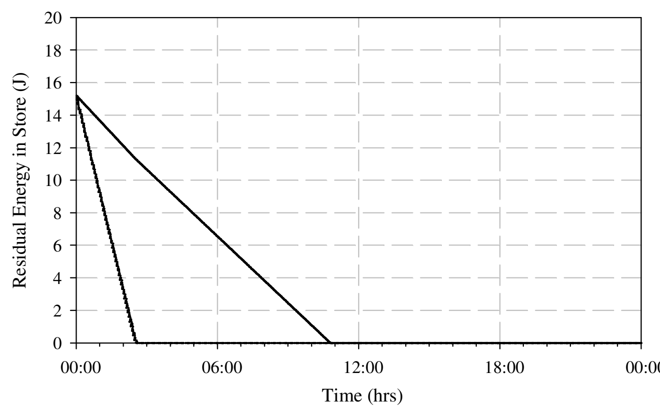

Fig. 1. The simulated discharge of the nodes powered by the ideal store. The solid line shows the discharge of the receive-only node, while the dotted lines represent the discharge patterns of the eight transmitting nodes.

2) *Supercapacitors* (also known as ultracapacitors) such as the Panasonic Gold HW series [17] have capacitance values of several Farads, can dissipate and absorb energy very quickly, and behave in a similar way to conventional electrolytic capacitors. They are suited for use as WSN energy stores due to their ease of charging (requiring no additional circuitry), and their insensitivity to charge/discharge cycling.

$$E_{cap} = {}^{1}\!/_{2}\, CV_{cap}^{2} \tag{3}$$

$$E_{store} = {}^{1}\!/_{4}\, CV_{store}^{2} \tag{4}$$

The energy stored in a capacitor is given by (3), where E_{cap} is the energy stored in the capacitor (J), C is the rated capacitance of each capacitor (F), and V_{cap} is the voltage across the capacitor (V). The supercapacitors used in this work

[17] are rated at 2.3V and hence two supercapacitors are required in series to achieve the required store voltage of 3.6V. The energy in the store is given by (4), where E_{store} is the stored energy, and V_{store} is the voltage across the store.

The energy stored in two 4.7F supercapacitors in series is 15.3J at 3.6V, and is directly proportional to the capacitance. Therefore, tolerances on the rated capacitance (quoted in the datasheet as -20/+40%) have a considerable effect on the stored energy; in this example the capacity is in the range 12.2-21.3J. Neglecting this by assuming that all nodes' stores are identical provides misleading simulation results. In the proposed model, each capacitor has a tolerance applied as a normally distributed offset from the nominal capacitance.

Fig. 2 shows how the voltage across the store drops as the energy decreases (shown by the solid line). As the CC2430 has a minimum operating voltage of 2.0V, the store cannot power the node once the voltage drops below this (shown by the shaded region). Therefore, the 'usable' stored energy is lower than the actual stored energy (shown by the dotted line).

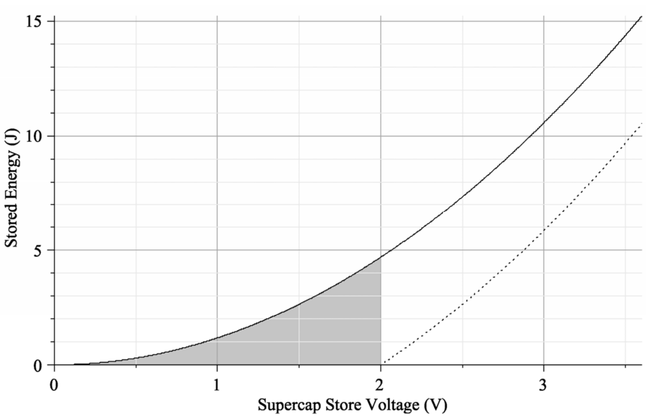

Fig. 2. The voltage across a capacitor as its stored energy decreases. The solid line represents the E-V relationship, while the shaded area under shows the energy that is unusable by devices requiring a 2V minimum operating voltage. The dashed line shows the stored 'usable' energy that is therefore available.

As with the ideal energy store, the energy added to the store (E_{added}) is equal to the amount of energy provided by energy harvesting ($E_{harvested}$) (2). In our, supercapacitors did not exhibit significant signs of discharge-dependent effects, such as those observed in batteries. However, considerable leakage was exhibited, and hence the energy subtracted (E_{used}) is the sum of the energy consumed by circuitry ($E_{consumed}$) and the energy leaked by the store since the last operation (5).

$$E_{used} = E_{consumed} + E_{leaked} \quad (5)$$

An empirical model of a supercapacitor's leakage power was obtained by monitoring its voltage (after being held fully charged for a period of 24hrs) over a period of many days using a high impedance data logger. From this, and using (3), the energy leaked over a period (and hence the leakage power) can be calculated. The observed leakage power (and the leakage approximation used in the energy model) for a 4.7F supercapacitor is shown in Fig. 3. These results were found to be consistent for different samples of the same supercapacitor.

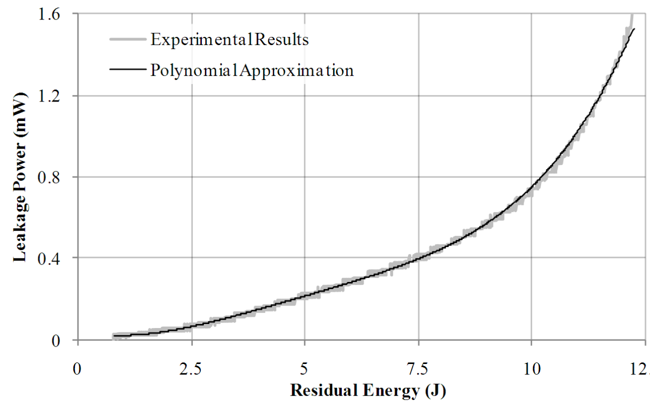

Fig. 3. The leakage power measured in a 4.7F supercapacitor, and the polynomial leakage approximation used in the energy model.

Fig. 4 shows the results of the network simulation with this energy store. In this graph, the energy depletions fit into two categories: 1) the nodes that have to both transmit and receive (including routing received packets) deplete their energy reserves after around 1hr30-2hrs, and 2) the sink node (that is not required to transmit any packets) depletes its energy reserve in just over 4hrs. This creates a network lifetime that is over 2.5 times shorter than the ideal case (seen in Fig. 1), which can obviously have a significant effect on simulation results. This reduction in lifetime is caused by leakage and the inability of the store to power the node below 2V. The effects of tolerances on the rated capacitance are also clearly visible.

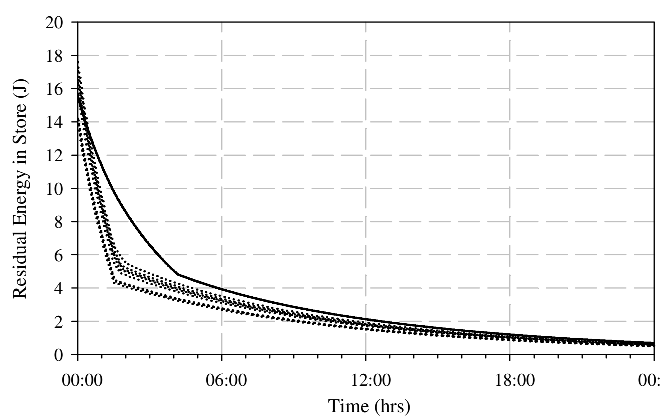

Fig. 4. The simulated discharge of the nodes powered by the supercapacitor. The solid line shows the discharge of the receive-only node, while the dotted lines represent the discharge patterns of the eight transmitting nodes.

While intuitive, it is of interest to note how leakage continues after the node has stopped operating, therefore requiring an energy overhead to return to a operational state (for example, if energy harvesting started at 18:00hrs, around 4J would be required to return the store voltage to 2V).

B. Energy Consumers

Energy consumers are components of a sensor node that require energy in order to operate. This section highlights the need to sufficiently model energy consumers, by considering all the consumers on the node (discussed in subsection 1), and the behavior of these consumers (discussed in subsection 2).

TABLE I
CURRENT DRAINS USED IN THE ENERGY CONSUMER MODEL

Consumer	Current Drain
microcontroller power mode 3 [16] [full sleep]	0.3μA
microcontroller power mode 2 [16] [slow wakeup sleep]	0.7μA
microcontroller power mode 1 [16] [fast wakeup sleep]	190μA
microcontroller power mode 0 [16] [medium activity, 32MHz XOSC]	10.5mA
radio receive [16]	16.2mA
radio transmit[1] [16, 18] [with a radiated power P_{tx} (mW)]	$7.6\text{mA} + P_{tx}/(V_{store} * \eta)$
monitor energy store voltage [16]	1.2mA
sense temperature [19]	1.2mA
sense light [20]	1.36mA
RTC standby [21]	0.2μA
RTC signal [21]	0.4mA

[1] where the drain efficiency, $\eta = (-0.44P_{tx}^2 + 0.066P_{tx} + 0.005)$

1) Modeling Multiple Energy Consumers: As discussed in section II, it is often assumed that the radio transceiver is the only energy consumer in a wireless sensor node. Energy consumption models have been proposed for radio transceivers that are based upon the energy to transmit and receive a single bit (which is then multiplied by the number of bits transmitted) [22]. While this system permits simplistic modeling, it is largely optimistic in terms of the energy consumption, because it does not factor costs associated with having the transceiver enabled but not receiving or transmitting data. Additionally, this model can make the developer assume that the energy cost per packet is equal to the energy per bit multiplied by the packet length, ignoring overheads (such as acknowledgments, headers, and control packets), collisions (requiring retransmission), and overhearing. Therefore, it is proposed that consumers are modeled having associated current or power drains, which are integrated through time to calculate the energy consumption.

In practice a node has many energy consumers which can have a significant effect on results with only a minor change in the simulation conditions. Therefore, we propose that the energy consumption of all major consumers (for example, the microcontroller, transceiver, sensors and peripherals) is considered, even if it is only to find that under the specific simulation conditions they have negligible effect. This is because, due to the ease of changing the simulation configuration and parameters, a previously negligible consumer can easily become predominant. While this 'multiple-consumer' approach has been suggested elsewhere [12], [13], we suggest it can be used with a higher level simulator (not requiring device-dependent or machine code), and consider the behavior of the energy consumers (of particular relevance to supercapacitors).

In the proposed energy consumer model, the simulator notifies the model when a peripheral is enabled/disabled, or when the microcontroller changes power state; this information is used to calculate the power consumption by using the modeled current drain and instantaneous store voltage. While the consumer models proposed in some papers use experimental results to obtain the current drawn by different consumers [12], [13], we argue that these data have already been measured by device manufacturers in datasheets (which we have found to be in line with experimental data we have obtained, for example Fig. 7). Naturally, these data could be directly replaced with experimental results if available. Table I shows the current drains used in the energy model.

To illustrate the need for 'multiple-consumer' modeling, the same simulation setup used in subsection A is used, but with the nodes adopting a less frequent reporting rate (transmitting packets to the sink every 30 minutes). The energy used by various consumers during an entire simulation is shown in Fig. 5. It can be seen that the radio transceiver dominates consumption. However, it is also interesting to note that the receive power constitutes the predominant sector, and so considering only transmit powers would produce significantly longer (and unrealistic) lifetime predictions. It is also notable that (as mentioned in section III) the communication uses a low power listen MAC, which shifts the overheads of idle-listening to the transmitter. Therefore, if a non low power listen MAC was used, the receive power would constitute a considerably larger portion of the energy consumption.

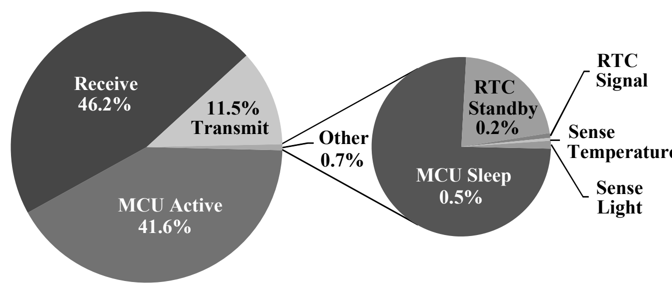

Fig. 5. A breakdown of energy consumption for a node's various consumers.

It can be seen from Fig. 5 that the real time clock (RTC) – a low power device consuming only 0.2μA in standby mode [21] – forms only 0.2% of the energy consumption for the duration of the simulation. Therefore, it would be understandable to ignore this in the simulation. However, as the RTC standby consumption is constant, if the simulation conditions were changed (for example if the MAC sleep cycle was increased to a period of one minute) the RTC would form a considerable portion of the overall energy consumption.

The CC2430 is a System-on-Chip solution integrating a microcontroller and radio transceiver. In the conducted simulations, the energy consumption for the microcontroller was separated from that of the transceiver (often quoted and simulated as combined figures), as it can be enabled without the transceiver. Fig. 6 shows the total duration that the microcontroller and transceiver were active for during the simulation. It can be seen that by considering both as individual consumers, the microcontroller was active for an additional 27s, equating to an increase of over 10% in the active time (and hence a reasonable difference in the energy consumption). By considering a microcontroller's different power modes (such as Active/Sleep), consideration has to be given to when the node can enter sleep states, affecting all areas of algorithm development.

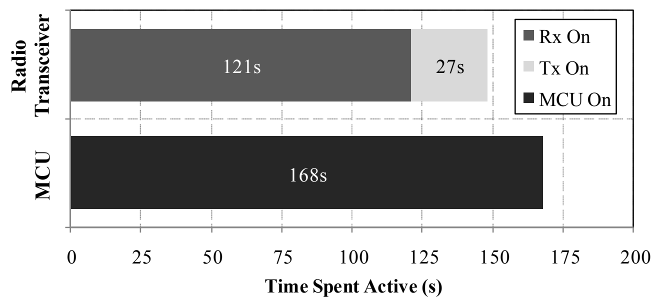

Fig. 6. The total active time of the radio transceiver and the microcontroller/transceiver as a whole.

This section has highlighted the importance of modeling all energy consumers. Small changes in the simulation setup can cause significant changes to the consumption distribution, and cause previously negligible consumers to become influential.

2) *Energy Consumer Behavior:* The behavior of a node's consumers has an effect on simulation results; in simple terms, whether its discharge behavior is dominated by current, power, or resistance. As shown in section II, the majority of simulators consider consumers as constant power drains, and hence are unaffected by the instantaneous store voltage.

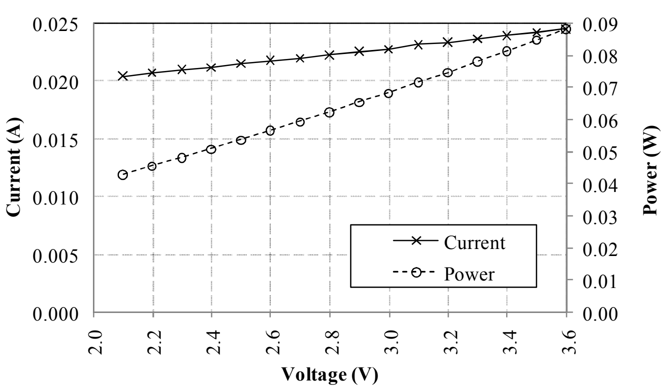

Fig. 7. Current and power consumption of CC2430 at various voltages

Investigations were performed on a CC2430 (operating with a continuous sense/transmit cycle) at a range of voltages, and the current consumption measured. The results are shown in Fig. 7, and it can be seen that the discharge characteristics are not constant-power. In fact, the results show that as the operating voltage drops from 3.6V to 2.1V, the power requirement of the node drops by >50%. This would result in a consumer modeled as being constant-power using more than twice the energy used by a constant-current consumer at 2V. However, the current through this range decreases by under 20%. Hence, it would be more realistic to model a consumer as a constant-current drain as opposed to constant-power.

IV. Energy Models in Embedded Software

The previous sections have highlighted the effect that energy component models can have on WSN simulation and the correlation between simulation and practical results. This section outlines the reasons why practical nodes must have an awareness of the behavior of their energy components in order to deliver energy-awareness, by estimating the remaining lifetime that can be obtained from their energy store(s). The embedded software deployed on sensor nodes must be given access to models of their energy components (such as those presented in the previous sections) in order to obtain a relationship between the store voltage and residual energy.

From the knowledge of the voltage-energy relationships, it is possible to calculate their discharge state, but expressed as a fraction of time (between being fully charged, and discharged to the minimum operating voltage). The 'fractional remaining lifetime', or t_{frac}, is a way of expressing the energy status of the node in terms of how much longer it can operate for against its maximum operating time when the store is full.

In the simplified case of a node powered by an ideal energy store (section III.A.1), the node's operation is constrained only by the amount of energy remaining in the store (its voltage does not vary until complete depletion). Assuming that the node has a perfect knowledge of the energy stored (reasonable for such an 'ideal' store), it is straightforward to calculate the node's remaining lifetime given a constant workload, owing to the fact that the node will operate at a constant power (as the store voltage is constant). Therefore, for this trivial case, the fractional remaining lifetime can be calculated using (6).

$$t_{frac} = E_{present} / E_{capacity} \tag{6}$$

In the case of a real, non-ideal energy store, the situation is more complex. One must consider the behavior of the energy consumer (section III.B.2). While a fine-grained knowledge of the energy consumer behavior is not needed, it is essential to know which form of discharge is dominant in order to calculate the remaining lifetime. Taking the above example of a node powered by a pair of 4.7F supercapacitors connected in series (section IIIA), t_{frac} can be calculated for power-, current- or resistance-dominated loads.

Through (4) and (6), the t_{frac} can be derived for a supercapacitor store with a power-dominant load (7). Thus, for a store voltage of 2.8V (half way through the voltage range) supplying consumers that are modeled as being power-dominant, the fractional remaining lifetime is 0.43.

$$t_{frac} = \left(V_{present}^2 - V_{min}^2\right) / \left(V_{max}^2 - V_{min}^2\right) \tag{7}$$

A capacitor discharged by a constant current obeys the relationship $I = C\ dV/dT$. Hence, the discharge voltage plot is a straight line, and t_{frac} for a supercapacitor store with a current-dominant load can be derived as (8). Therefore, if the consumers are modeled as being current-dominated, the fractional remaining lifetime at 2.8V is found to be 0.5 (17% higher than if the load was considered to be power-dominated). For the CC2430, this value will still be slightly pessimistic (due to its consumers not being completely constant-current, as shown in Fig. 7), but due to the dynamics of the load will be significantly more accurate than the constant-power value given previously.

$$t_{frac} = (V_{present} - V_{min})/(V_{max} - V_{min}) \quad (8)$$

For completeness, we also consider resistive loads. The discharge dynamics of the system for resistive loads are more complex as they follow a logarithmic discharge relationship (9). While it is possible to calculate t_{frac} for such a load, it involves the use of natural logarithms and is not straightforward to implement on embedded microcontrollers. For a store at 2.8V, its t_{frac} is 0.57 when the consumers are modeled as being resistance-dominated (34% higher than if the load was considered to be power-dominated).

$$V = V_0 e^{-\frac{t}{CR}} \quad (9)$$

The methods presented here apply only to capacitive energy stores. For more complex stores such as secondary batteries, it is necessary to consult battery models, but it is again important to consider whether the node's discharge behavior is dominated by power, current or resistance. The representation and calculation of battery parameters on a resource-constrained microcontroller is non-trivial, and simplification has to be made (such as representing battery discharge curves in memory via the piecewise-linear method).

This section has shown the importance of energy models in nodes' embedded software, highlighting their benefit to actual deployments as well as simulation. It has also demonstrated that incorrectly categorizing the behavior of energy consumers can introduce significant error into remaining lifetime calculations (for example, a t_{frac} of 0.43 compared to 0.57), and adversely affect the operation of energy-aware algorithms.

V. Conclusions

Simulation is heavily used in the evaluation of algorithms and protocols for WSNs, and the reliability of the results obtained depends fundamentally on the accuracy of implemented simulation models. Energy models often do not accurately portray the behavior of deployment hardware in the real world. This paper has shown the significant effect that energy store models (developed from experimental data of a supercapacitor store) and energy consumer models can have on the correlation between simulation and deployment. The necessity for energy models in an energy-aware node's embedded firmware has also been highlighted; a store model allows a node to estimate its residual energy level, while consumer models allow a prediction of the remaining lifetime.

While this paper has focused only on energy models, it is important to have accurate models for other aspects of the node; for example sensing, communication, timing, and location awareness. Careful consideration should be given to which factors can affect the performance of the evaluated algorithm (and hence affect the obtained results), and ensure that these are adequately and realistically modeled.

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