A Novel Routing Metric for Environmentally-Powered Sensors With Hybrid Energy Storage Systems

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***Abstract*—Sustainable Wireless Sensor Networks (WSNs) are potential candidates for remote patient monitoring, monitoring the health of civil structures (e.g. bridges, office buildings, pipelines), environmental monitoring, industrial monitoring and surveillance. However, limited battery life has been a barrier for widespread deployment of such networks. This paper proposes the novel Communication Using Hybrid Energy Storage System (CHESS) routing metric for networks such that each node has an Hybrid Energy Storage System (HESS). An HESS is composed of a supercapacitor (SC) and a rechargeable battery (RB). SCs and RBs have quite different characteristics, the most important for WSNs being that RBs can be recharged 100s of times, while SCs can be recharged on the order of a million times before failing. While HESS architectures have been used for wireless devices, no routing algorithm has considered how to exploit these two storage mechanisms to maximize network life. CHESS also allows control of the depth of discharge of the RB.**

***Index Terms*—Network longevity, hybrid energy storage systems, wireless communications, sensor networks.**

I. INTRODUCTION

THE main barriers to large-scale deployment of wireless sensor networks are limited battery life and concerns about reliability [1]. Harvesting ambient energy, such as solar and vibration energy, is a way to extend battery life. However, even rechargeable batteries (RBs) have finite lifetimes because they have a limited "cycle life," which is the number of charge-discharge cycles before the capacity falls below 80% of its initial rated capacity [2], [4]. The hybrid energy storage system (HESS), in which a supercapacitor (SC) protects the battery from current spikes, is another strategy for battery-life extension. The SC and RB differ greatly in terms of their leakage and cycle life characteristics. The main contribution of this paper is to propose and investigate a new routing metric for multi-hop wireless networks that use HESSs. Through the new "communications using hybrid energy storage systems (CHESS)" routing metric, we intend to extend the lifetime of an energy-constrained network using the fundamental characteristics of energy harvesting systems and energy storage systems.

The following key characteristics of RBs and SCs form the motivation and basis for our proposed protocol.

- An RB is characterized by its capacity (typically given in mAh), its leakage, and its "cycle life," A RB, depending on is type (e.g. Nickel Metal Hydride (NiMH) or Lithium Ion Polymer) can have cycle life ranging from 100's to 1000's of cycles [14], [15]. The cycle life is what ultimately limits the lifetime of a wireless network that depends on RBs even if all nodes do energy harvesting. However, the existing literature on harvesting-aware routing does not consider this limitation.
- An SC is also characterized by its capacity, leakage, and cycle life, but the values of SC parameters are different from the RB values. For example, SC cycle life is typically in the millions of cycles [7]. On the other hand, SC leakage is much higher than RB leakage and depends highly on the residual energy [8], [17].
- Shallow discharging, that is, limiting the battery discharge to 25% or less of the capacity, preserves capacity and increases the number of cycles; this is true for all battery chemistries. The number of cycles yielded by a battery goes up exponentially by the reduction of the depth of discharge [5], [6].

Related Work: [10] proposed a cost metric that takes into account the nodes' RB residual energy, harvesting rate and energy requirement for routing the packet. [9] analyzed the requirements for "energy neutral" WSN operation. By characterizing the nominal energy harvesting rate and its maximum deviation and by characterizing the nominal energy consumption rate and its maximum deviation, [9] determined bounds on the nominal consumption, the required battery capacity, and the required starting battery stored energy. Neither [9] nor [10] considered cycle life or hybrid energy harvesting systems. Additionally, wireless sensors having only the SC or a HESS have been investigated and designed in [11]–[13]. Researchers have investigated the performance improvement in the RB when the SC was used. The SC delivered a current pulse for the required time, minimized the voltage drop [11],

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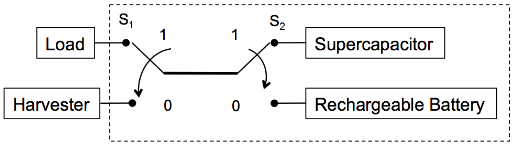

Fig. 1. Simplified block diagram of the switched hybrid energy storage system.

and reduced the internal losses in the battery [12], all of which increased the lifetime of the RB. In [13], the authors proposed and implemented a multi-stage energy buffering system consisting of a SC and a RB, which limited the use of the RB to emergencies to increase the lifetime of the network. The contribution of this paper is absorb this "intelligent energy transfer mechanism" in a HESS into a routing metric and investigate the network lifetime performance for such systems. We are studying the HESS, rather than the SC-alone because while an SC with solar energy may be sufficient for routine monitoring, if there is an alert, the RB will be necessary to support the heavier reporting requirements.

II. HESS MODEL

A simplified block diagram of the HESS is shown in Figure 1. The switches, S_1 and S_2, respectively represent our assumptions that a node cannot harvest energy and transmit a packet at the same time, and that the SC is never connected to the RB. This latter assumption distinguishes our model from other "hybrid" system models that always have a connection between the SC and the RB [16]. Also, we assume that the RB is not connected to the harvesting source until the RB has discharged down to the specified depth of discharge. This collection of assumptions enable us to use a simplified cycle life model [5], [6]. As in [10], we assume that the node is dead if the battery exceeds its cycle life.

A node that is selected to relay sets Switch S_1 to the "1" or "Load" state. Unselected nodes set Switch S_1 to the "0" or "harvesting" state. The RB is recharged when its residual energy falls below a pre-set threshold $(1-D)u_{\mathrm{RB}}$, where D is "depth of discharge" (DoD), and u_{RB} is the maximum capacity of the RB. For example, if we never want to use more than 30% of the energy of the RB within a single discharge cycle, then $D = 0.3$; to determine the cycle life from the graph of [14], express DoD as a percentage, e.g. $D \times 100\% = 30\%$. If the RB energy is above the threshold, then the SC is charged using the harvested energy, which corresponds to Switch S_2, being set to "1." If the RB has discharged below $(1-D)u_{\mathrm{RB}}$, then the node will not accept any more route requests until the RB has been fully recharged.

Next, we describe our update equations that model HESS leaking, charging, and loading. The CHESS cost function will be described in the next section. We assume that each node knows its energy level (battery reserve) and has an accurate short-term energy replenishment schedule. We also assume that the reduction in energy after fulfilling a packet route request is instantaneous, as the rate of energy replenishment is much slower than the energy used for transmitting a packet [10].

We assume that the source transmits equal-length packets periodically. Let t_k denote the arrival time of the k-th packet request at a node. t_k defines the beginning of the k-th time slot, which is illustrated in Fig. 2. If the the routing algorithm selects the node, the node relays the packet. The period of activity comprising route selection and relaying of the packet, and during which the node does not harvest energy, is assumed to be t_p seconds long. We define $t_k^+ = t_k + t_p$. The node harvests energy during the remainder of the time slot, which is t_h seconds long. It follows that $t_{k+1} = t_k^+ + t_h$.

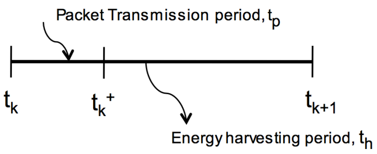

Fig. 2. Representation of a time slot.

Now, we describe our models of residual energy on the RB and SC. We define the following events:

$$\begin{aligned}
\texttt{SC-ABLE} &= \{\widehat{E}_{\mathrm{SC}}(n,t_k) - l(j)E(n,R(j)) > 0\},\\
\texttt{RB-ABLE} &= \{\widehat{E}_{\mathrm{RB}}(n,t_k) - (1-D)u_{\mathrm{RB}}\\
&\quad -l(j)E(n,R(j)) > 0\},\\
\texttt{RB-RECHARGE} &= \{\widehat{E}_{\mathrm{RB}}(n,t_k) \le (1-D)u_{\mathrm{RB}}\},
\end{aligned}$$

where `SC-ABLE` is the event that the SC has enough energy to route the packet, `RB-ABLE` is the event that the RB has enough energy to route the packet without going below its specified depth of discharge, and `RB-RECHARGE` is the event that the RB has exceeded its depth of discharge and cannot accept further route requests until it has recharged. We note that `RB-RECHARGE` is not the complement to `RB-ABLE`; our model assumes that the act of relaying a packet never takes the RB below its discharge depth- an RB can only cross the threshold by leaking. `RELAY=true` represents that the node has been chosen by the CHESS routing protocol to relay. Otherwise, `RELAY=false`. $\widehat{E}_{\mathrm{SC}}(n,t_k)$ denotes the residual energy (in Joules) on the n-th node SC at time t_k, $l(j)$ is the length of the j-th packet in units of bits, $R(j)$ is the route for the j-th packet, $E(\cdot)$ is the energy per bit required to fulfill the route, $R(j)$, $\widehat{E}_{\mathrm{RB}}(n,t_k)$ denotes the residual energy on the n-th node RB at time t_k, and u_{RB} denotes the maximum capacity in Joules of the RB.

We shall next define the switch states, S_1 and S_2, for the n-th node at time t_k in terms of the above events. We shall use the indicator function, $I(A)$, which is 1 if the condition A is true, and 0 when A is false. We observe that $\mathrm{S}_1 = 1$ only if the node is selected to relay the packet. Therefore,

$$\mathrm{S}_1(n,t_k) = I\{\texttt{RELAY} \cap (\texttt{SC-ABLE} \cup \texttt{RB-ABLE})\}. \tag{1}$$

$\mathrm{S}_2 = 0$ under different conditions depending on if the node is harvesting or transmitting.

$$\mathrm{S}_2(n,t_k) = 1 - I(\overline{\texttt{SC-ABLE}} \cap \texttt{RB-ABLE} \cap \\ \texttt{RELAY}) - I(\texttt{RB-ABLE} \cap \overline{\texttt{RELAY}}), \tag{2}$$

The first indicator function can be 1 only if the node is chosen to relay, in which case, the second indicator function must be zero.

Next we present the update equations for the residual energies stored on the SC and RB. The change in SC energy from time t_{k-1} to time t_k, because of leaking, harvesting, and loading is modeled as follows:

$$\begin{aligned}\widehat{E}_{\text{SC}}(n,t_k) = \min\Big[&(1-\alpha(t_{k-1},t_k))E_{\text{SC}}(n,t_{k-1}^{+}) \\ &+ \mathrm{S}_2(n,t_{k-1}^{+})\gamma_n(t_{k-1}^{+},t_k), u_{\text{SC}}\Big],\end{aligned} \tag{3}$$

$$\widehat{E}_{\text{load, SC}}(n,t_k,R(j)) = l(j)E(n,R(j))\mathrm{S}_1(n,t_k)\mathrm{S}_2(n,t_k), \tag{4}$$

$$E_{\text{SC}}(n,t_k^{+}) = \beta(n,D,t_k)\Big[\widehat{E}_{\text{SC}}(n,t_k) - \widehat{E}_{\text{load, SC}}(n,t_k,R(j))\Big], \tag{5}$$

where $\alpha(t_{k-1},t_k)$ denotes the time-invariant fraction of energy leaked in the SC over a time slot, $\widehat{E}_{\text{load, SC}}(n,t_k,R(j))$ is the energy consumed by a packet if the SC is used,u_{SC} denotes the maximum capacity in Joules of the SC, and $\gamma_n(t_{k-1}^{+},t_k)$ denotes the energy (in Joules) harvested at the n-th node during time slot $k-1$. We assume all the nodes in the network harvest the same amount of energy in a time slot, so we drop the subscript n. Further, for this first treatment of CHESS, we assume that the harvesting rate is time-invariant over the daily harvesting period. $E_{\text{SC}}(n,t_k^{+})$ denotes the residual energy (in Joules) on the n-th node SC at t_k^{+} and $\beta(n,D,t_k)$ is an indicator function for the event that the RB on node n has not exceeded its finite cycle life at the beginning of time slot k. We note that $\beta(n,D,t_k)$ is a non-increasing function of t_k, and for a fixed t_k, is a strictly decreasing function of D, the depth of discharge on the RB. We note that the "min" function in Equation (3) ensures that the SC is not charged beyond its maximum capacity.

Similarly, the change in RB energy from time t_{k-1} to time t_k, because of leaking, harvesting, and loading is modeled as follows:

$$\begin{aligned}\widehat{E}_{\text{RB}}(n,t_k) = \min\Big\{&\big[(1-\psi)E_{\text{RB}}(n,t_{k-1}^{+})\big] \\ &+ \big[1-\mathrm{S}_2(n,t_{k-1}^{+})\big]\gamma_n(t_{k-1}^{+},t_k), u_{\text{RB}}\Big\},\end{aligned} \tag{6}$$

$$\begin{aligned}\widehat{E}_{\text{load, RB}}(n,t_k,R(j)) = l(j)&E(n,R(j))\mathrm{S}_1(n,t_k) \\ &\cdot \big[1-\mathrm{S}_2(n,t_k)\big],\end{aligned} \tag{7}$$

$$E_{\text{RB}}(n,t_k^{+}) = \beta(n,D,t_k)\Big[\widehat{E}_{\text{RB}}(n,t_k) - \widehat{E}_{\text{load, RB}}(n,t_k,R(j))\Big], \tag{8}$$

where ψ denotes the time-invariant fraction of energy leaked in the RB in one time slot (zero, in case of an ideal RB), $\widehat{E}_{\text{load, RB}}(n,t_k,R(j))$ is the energy consumed by a packet if the RB is used, and $E_{\text{RB}}(n,t_k^{+})$ denotes the residual energy on the n-th node RB at t_k^{+}.

III. CHESS ROUTING

The CHESS routing protocol chooses the route that has the smallest sum of CHESS metrics for each node along the route. The CHESS metric is zero for a node that has sufficient energy on its SC to route a packet. If the SC has insufficient energy, then a non-zero value will be calculated, based on the energy state of the RB. The CHESS metric is based on the cost function of [10], which treats RBs with infinite cycle life and 100% depth of discharge. The metric of [10] , which is claimed in [10] to be asymptotically optimal in terms of the competitive ratio, increases exponentially with energy depletion and thus, discourages use of a node if its harvesting rate is low. We can use this approach to assign cost of discharge within one cycle as in [10]. However, we need to also have a component of cost associated with using up the RB cycle life; for this, we can view the cycle life of a RB similarly to the life of a non-rechargeable battery. Therefore, we define two energy depletion functions for the RB – one to discourage selection of a node (within a single discharge cycle) that is near its specified depth of discharge, and another to discourage use of a node that is near the end of it's battery cycle life. The overall cost function should increase if either one of these cost components increases. This can be achieved by multiplying the components.

Let us first consider the cost component for discharge within one cycle. Following [10], let the within-cycle energy depletion exponent be defined as $\lambda_{\text{RB}}(n,t_k) = \frac{u_{\text{RB}} - \widehat{E}_{\text{RB}}(n,t_k)}{Du_{\text{RB}}}$. In words, this will be zero when the battery is fully charged, and one when it is discharged down to it's specified level of discharge. Next, the "cost component" for the within-cycle discharge is defined as

$$\begin{aligned}&C_{\text{CHESS}}(n,t_k,R(j)) \\ &= \frac{Du_{\text{RB}}}{(\gamma_n+\epsilon)\log\mu}\cdot\Big(\mu^{\lambda_{\text{RB}}(n,t_k^{+})}-1\Big)l(j)E(n,R(j)).\end{aligned} \tag{9}$$

We note that the use of the SC is reflected in the S_2 term in (6).

We denote L_c as the cycle life in units of time slots, which can be known under our assumption that the batteries are charged only when they have been discharged to depth D. Following similarly to the non-rechargeable battery cost function in [10], a cycle-life cost component that penalizes the use of a RB with a shorter cycle life, can be multiplied to the within-cycle cost (in (9) to get an overall cost function. In the results section, however, we only consider the within-cycle cost because of the topology we assume in this paper. The CHESS metric could be modified to include a revenue function as in [10]. We note that in the absence of modification, the CHESS protocol will attempt to find a route, however circuitous, that uses SC energy only.

IV. RESULTS FOR THE TWO-RELAY NETWORK

For this preliminary analysis of the CHESS metric, we consider the small network model, shown in Fig. 3, which consists of a source, and destination, and two relays. The objective of the CHESS routing algorithm in this particular network is to choose (for each packet) the relay to maximize the time until the first relay comes to the end of its cycle life. We will show simulation results for a very simple daily periodic solar energy model of 12 hours of uninterrupted sun, with constant intensity, and 12 hours of total darkness. We assume a traffic model of periodic packets for as long as there is energy to route them. When the sunlight stops, the protocol will use up the SCs first, and then it will use the RBs until they both reach their specified depth of discharge. After that point, we assume no more packets are routed.

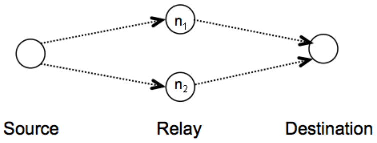

Fig. 3. Network topology for evaluating routing performance using CHESS metric.

In this simulation, we ignore the cycle-life part of the CHESS metric, and use only the within-cycle part. We do this for two reasons, (1) to facilitate debugging and understanding of the results, and (2) because for this small "cluster" of just two nodes, the within-cycle cost alone is sufficient to balance the load. However, for a larger network with many more options for routing, and if the CHESS metric is combined with a penalty for number of hops, we expect the cycle-life part of the CHESS metric to play a role.

The HESS parameters used for the simulation are listed in Table I. The leakage parameters $\tilde{\alpha}$ and $\tilde{\psi}$ and the leakage parameters α and ψ in Equations (3) and (6), are related in the following way: $\tilde{\alpha} = 1-\alpha$ and $\tilde{\psi} = 1-\psi$. For our simulation, the duration of each time slot is $t_h + t_p = 1$ second. The values of α and ψ per time slot are $1-0.8 = 0.2$ Joules and $1 - \frac{5\cdot 130}{100\cdot 30\cdot 24\cdot 3600} = 0.0000002$ Joules, respectively.

Fig. 4 is a plot of the residual energies in Joules on the SCs and RBs for both nodes versus time for the HESS and non-HESS node architectures. Every packet is routed using the CHESS algorithm. For the node equipped with a HESS, when there is sunlight, the packet is routed using the SCs, and the RBs on both the nodes simply leak. Once the sunlight stops, the nodes use the SCs to route the packets until their residual energies are no longer enough to route a packet. Subsequent routing of packets involves computation of the CHESS metrics for the relay nodes, and the node with lowest cost function is selected as the relay node. Since there are only two relay nodes, the CHESS routing metric, in this case, merely alternates between the nodes. Route requests are accepted until the residual energies on the nodes go below the specified depth of discharge. Since there is no sunlight, the nodes cannot recharge the RB, and further packets are simply buffered at the source. The batteries on both the nodes leak during the rest of the non-harvesting period. When there is sunlight, for the non-CHESS scenario, the RBs on both nodes route packets and have several charge-discharge cycles. It was found that one charge-discharge cycle for the CHESS case corresponded to 40 charge-discharge cycles for the non-CHESS case, which implies a network life extension of approximately 40 times by CHESS relative to non-CHESS.

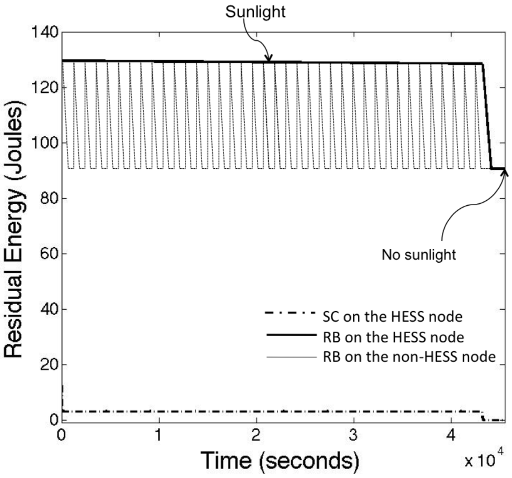

Fig. 4. Comparison of the residual energies for the CHESS and non-CHESS cases over a single harvesting period.

Once sunlight returns (after 12 hours), the RB starts recharging. Our model assumes that a node does not accept route requests when the RB is charging. The charge-time for the RB for the specified DoD was assumed to be 10 minutes. Further, our model assumes that the SC charging does not start until the RB has been fully charged. This explains the 600 second time gap in Fig. 5 between the rise in RB energy and the rise in SC energy. Immediately after the charging of the RB is complete, the RB energy is used to route a packet before the SC energy is used, since the SC still does not have enough energy to route a packet. Since we have assumed that charging of the SC is not instantaneous, when packet transmission resumes, the CHESS metric selects the node with the least cost function to route the packet. Another observation we can make from Figs. 4 and 5 is that at the data rate and harvesting rate given in Table I, the RB contributes only a small percentage to the total number of routed packets. Yet the cost is high, because the RB uses up one cycle of its life in each dark period. A better strategy is to simply not use the RBs for routine reporting scenarios.

V. CONCLUSIONS

CHESS is a novel routing metric and can be used with any routing protocol for networks that use HESSs. The HESS consists of a combination of a rechargeable battery (RB) and a supercapacitor (SC). The RB has a finite number of charge-discharge cycles, or cycle life, and low leakage. The SC has a relatively unlimited cycle life, but high leakage. SC energy is essentially free, while RB energy always has a cost. CHESS (Communication for Hybrid Energy Storage Systems) assigns different costs to the energy in the SC and the energy in the RB; therefore CHESS favors routes with more SC energy. For

TABLE I
PARAMETERS USED FOR EVALUATING CHESS.

Physical parameter	Symbol	Value	Citation
Energy harvested per unit time	γ_n	$0.015\ \mathrm{mW/cm^2}$	[20]
Fraction of energy leaked in the SC over a second	$\tilde{\alpha}$	0.8	[7]
Fraction of energy leaked in the RB over a month	$\tilde{\psi}$	5%	[17]
Depth of discharge	D	0.3	[19], [27]
Max. energy of RB	u_{RB}	130 J	[18]
Max. energy of SC	u_{SC}	12.5 J	[21]
Energy per bit	E_{rad}	100 nJ	[24]
Circuit Energy per bit	E_{elec}	300 nJ	[25]
Maximum Data rate	$R_{\mathrm{b,\ max}}$	256 kbps	[25]
Packet transmission period	t_p	0.8 seconds	-
Harvesting period	t_h	0.2 seconds	-

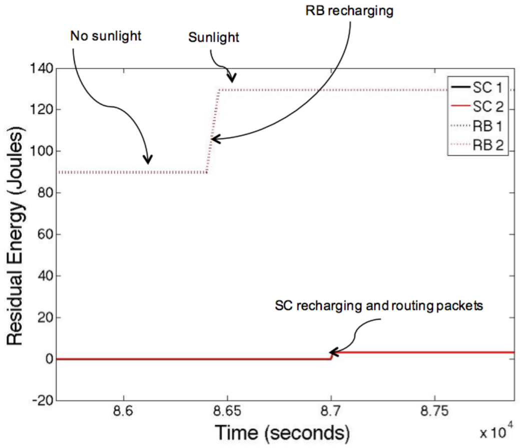

Fig. 5. The residual energies on the nodes versus network lifetime.

the two-relay network with periodic solar-energy harvesting model considered in this paper, CHESS offered a network life extension of about 40 times relative to non-CHESS or until the energy storage device fails from aging during that time frame. Future research directions include extending the development of the CHESS metric to capture the cycle life penalty, building a rigorous theoretical framework for analysis, and analyzing the performance of CHESS for different network topologies and harvesting scenarios.

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