In this paper we propose a routing protocol for wireless ad hoc networks whose nodes are largely battery powered. The battery capacity of the nodes is viewed as a common resource of the system and its use is to be optimized. Results from a previous study on battery management have shown that: (1) pulsed current discharge outperforms constant current discharge, (2) battery capacity can be improved by using a bursty discharge pattern due to charge recovery effects that take place during idle periods, (3) given a certain value of current drawn off the battery, higher current impulses degrade battery performance, even if the percentage of higher current impulses is relatively small. We develop a network protocol based on these findings. This protocol favors routes whose links have a low energy cost. We also distribute multihop traffic in a manner that allows all nodes a good chance to recover their battery energy reserve.

INTRODUCTION

In this paper we consider an ad hoc network with battery powered nodes. Several schemes for efficient routing algorithms in wireless ad hoc networks have been proposed in the literature [1, 2, 3]. In particular, the problem of energy efficient routing has been addressed in [4, 5, 6]. While in [4, 5] the goal is to minimize the energy consumed to transport a packet from the source to the destination, in [6] the objective is to maximize the lifetime of a network with static or slowly varying topology by finding optimal traffic splits.

The routing protocol proposed here aims at maximizing the network lifetime of a network with dynamic topology. We consider the battery capacity of the nodes as a common resource of the system and we improve the network lifetime by efficiently exploiting the available battery capacity.

In [7, 8] it was shown that the lifetime of a battery depends on the discharge demand profile and on the level of power (current) that is drawn off. If a battery is discharged for short time intervals followed by idle periods, significant improvements in delivered energy seem possible. During the idle periods the battery can partially recover the capacity lost while delivering current impulses. This mechanism is called recovery effect. Moreover, if the requested current exceeds a rated current specification of the battery, the battery delivers a smaller amount of energy. This phenomenon is called rate capacity effect.

We exploit these findings to develop a routing protocol, called BEE (Battery Energy Efficient) protocol, that aims to balance the battery consumption among all network nodes. The scheme selects routes whose links have a low energy cost; e.g., a route with 3 hops may be preferred to a route with 2 hops if the maximum level of power per link is lower. Also, the proposed scheme favors the nodes with low battery status by routing the multihop traffic through nodes with high battery capacity and allowing the others to benefit of the recovery effect.

Results show that the BEE scheme greatly extends the network lifetime; in comparison with the MTE scheme, which minimizes the total transmission power, a factor of improvement up to 1.8 can be obtained. When a simpler version of the BEE algorithm is used in order to reduce its complexity, an improvement with respect to the MTE protocol is still possible.

BATTERY BEHAVIOR

The maximum energy that can be obtained from real bat-
teries greatly depends on the power level drained from the cell and whether the discharge is constant or pulsed.

Under constant discharge a cell can provide a certain value of current, called the *limiting* current [9]. Above this threshold the cell potential drops very quickly below the cut-off value, and, even if the capacity reserve of the cell has not been exhausted, the cell is considered discharged.

Under a pulsed discharge profile, the battery is able to recover charge during the interruptions of the drained current thanks to the *diffusion process* [9, 7]. As shown by several experimental tests [10, 11], the *recovery effect* can lead to a significant improvement in battery performance when a pulsed discharge is implemented. It is observed that [7] by using a pulsed discharge, a greater delivered specific energy can be obtained for a fixed power level.

The efficiency of a battery decreases as the supplied current overcomes a specified value of *rated current*, that depends on the battery chemistry. The *rate capacity effect* implies that for values of current higher than the rated current, the capacity loss is greater than the amount of capacity actually delivered.

To show the real behavior of batteries and evaluate their performance we considered the electrochemical model of a dual lithium ion insertion cell [12], which is often used to supply portable devices. The electrochemical model was numerically solved by using a program developed by Newman et al. [13]. The program was modified to let the discharge of the cell be driven by a stochastic process. Under a stochastic discharge profile, the model is solved by considering the current that is drained from the cell as a stochastic variable. At each current impulse we can derive the cell potential and, hence, the energy delivered by the impulse; the discharge process ends as soon as the cell potential drops to the cut-off value [7].

In Fig. 1 it is shown a plot obtained assuming a Bernoulli driven stochastic discharge process with current impulse duration equal to 1 ms and a cut-off voltage equal to 2.8 V. Curves illustrate the delivered specific energy as a function of the pulse discharge rate for different discharge profiles. Each profile corresponds to a different mix of 100 and 110 A/m² impulses drained from the cell. (Labels in the plot refer to the percentages of 110 A/m² impulses.)

Looking at the 0% and 100% curves, corresponding to 100 and 110 A/m² discharge respectively, we can see that as the pulse discharge rate decreases, the obtained gain dramatically increases for both the values of current density since the chance to recover for the cell increases. This proves that a significant improvement in performance of real batteries is possible when batteries can remain idle for sufficiently long periods of time.

Figure 1: Specific delivered energy versus pulsed discharge rate obtained through the electrochemical model for different discharge profiles.

Fig. 1 also shows that higher current density impulses may degrade performance, even if the percentage of higher current impulses is really small. It is worth noticing that for a low discharge rate the curves corresponding to 10% and 100% overlap since the idle time between impulses is sufficiently long for the cell to recover. Thus, these results suggest that applications that involve the use of different levels of power should carefully administrate the available battery capacity depending on the values of drained current density and cut-off potential of the cell.

Summarizing, results on battery management have shown that: (1) pulsed current discharge outperforms constant current discharge, (2) battery capacity can be improved by using a bursty discharge pattern due to charge recovery effects that take place during idle periods, (3) given a certain value of current drawn off the battery, higher current impulses degrade battery performance, even if the percentage of higher current impulses is relatively small. Based on these findings, in the next section we define a novel routing scheme for ad hoc networks that takes advantage of efficient battery management.

THE BEE ROUTING ALGORITHM

We assume an ad hoc network environment where nodes, either mobile or fixed, are battery-powered. We define *N* as the set of all nodes in the network, *S* as the set of nodes generating data traffic and *G* as the set of destination nodes. Nodes belonging to *S* can direct the traffic to any of the destination nodes using the other nodes as relays.

We consider that time is discretized into intervals corresponding to the packet transmission time, which is assumed to be equal to 1. Nodes are assigned an initial amount of en-
energy, i.e., initial battery status, denoted by $B_i$, whereas the instantaneous battery status is denoted by $b_i$ with $i \in N$. The transmission range of each node is limited to a certain value, indicated by $\rho$, so that a radio link can be established between any pair of nodes $(i, j)$ only if the distance $d_{ij}$ is less than or equal to $\rho$. We indicate as $R_i$ the set of nodes whose distance from $i$ is less than $\rho$. The energy spent for each data transmission is a function only of the distance between transmitter and receiver; for a transmission from node $i$ to node $j$ we have [6]

$$e_{ij} = \begin{cases} (d_{ij}/\rho)^4 & \text{if } j \in R_i \\ \infty & \text{else} \end{cases}$$

(1)

The energy consumed by node $j$ $(j \in R_i)$ to receive a data unit is considered to be ten times lower than the transmission energy $e_{ij}$.

We discretize the transmission energy to any node in $R_i$ $(i \in N)$ into few levels ranging from $e_{\min}$ to $e_{\max}$. To represent the benefit of the recovery phenomenon, the battery status of a node is increased whenever the node’s transmission rate is sufficiently low. We model the energy accrue at node $i$ as a function of the transmission rate $\lambda_i$ and of the mean energy necessary to node $i$ to transmit a packet ($\bar{e}_i$). We indicate the energy increase function as $\Gamma(\lambda_i, \bar{e}_i)$ with $\bar{e}_i = \frac{1}{R_i} \sum_{j \in R_i} e_{ij}$. $\Gamma(\cdot, \cdot)$ is obtained through the stochastic battery model presented in [14], where the recovery effect is represented as a decreasing exponential function of the state of charge of the battery. The stochastic model was matched to the electrochemical model [8] for the case of impulses energy equal to $\bar{e}_i$ drained from the battery at rate $\lambda_i$.

Similarly, whenever a node needs to use a transmission energy level $e_{ij} > e_{\min}$, the node’s battery status is decreased by $e_{ij} + \Phi(e_{ij} - e_{\min})$, where $\Phi(\cdot)$ takes into account the rate capacity effect and is derived from the electrochemical model results. For instance, a current supply equal to 60 A/m$^2$ causes 30% of efficiency degradation with respect to the case of a current supply equal to 50 A/m$^2$.

Thus, at each time unit the evolution of the battery status is,

$$b_i = \begin{cases} b_i + \Gamma(\lambda_i, \bar{e}_i) & \text{if node } i \text{ is idle} \\ b_i - [e_{ij} + \Phi(e_{ij} - e_{\min})] & \text{else} \end{cases}$$

(2)

The routing algorithm assigns to each route a cost function that takes into account both energy transmission and battery behavior. Given the generic source $s$ and the generic destination $g$, the cost function associated to the $k$-th route, $r_{sg}^k$, is

$$F_k = \sum_{i \in r_{sg}^k} [\Psi(\lambda_i)e_{ij} + p_{ij}] - \min_{i \in r_{sg}^k} b_i$$

(3)

where:

i) $l_{ij}$ is the link between nodes $i$ and $j$ belonging to route $r_{sg}^k$.

ii) $\Psi(\lambda_i)$ is a weighting function that emphasizes the energy loss of the source node and depends on the source transmission rate. We have: $\Psi(\lambda_i) = A \cdot \lambda_i$ for $i = s$, with $A$ being a proper constant value greater than 1, and $\Psi(\lambda_i) = 1$ otherwise.

iii) $p_{ij}$ is the energy penalty due to the rate capacity effect experienced at node $i$ when a power level higher than the mean power value is required to transmit a packet over link $l_{ij}$. We have $p_{ij} = \max(0, e_{ij} - \bar{e}_i)$;

iv) $\min_{i \in r_{sg}^k} b_i$ is the minimum value of battery status among the nodes belonging to route $r_{sg}^k$.

Whenever source $s$ has a block of data to transmit toward destination $g$, $s$ evaluates the cost function for all the possible loop-free routes and selects the route $r_{sg}^m$ such that

$$F_m = \min_{r_{sg}^k} F_k$$

(4)

We notice that every time the cost function has to be computed the information about the nodes battery status have to be updated.

If the set of routes over which we have to minimize the cost function is very large, the complexity of this scheme may become unacceptable for networks whose topology varies often. A simpler and faster algorithm is obtained as follows. We consider that the node in charge of selecting a route (i.e., either the source or the destination) chooses routes independently and uniformly at random from all the available routes. The cost function is then evaluated over the $c$ routes, and the selected path is the one among the $c$ routes which minimizes $F$.

In the next section we present performance of the BEE scheme as $c$ varies.

RESULTS

Performance of the BEE routing scheme was derived through simulation in terms of mean delay of the transmitted packets, and network lifetime computed as the time elapsed from the time instant when all the nodes have a fully charged battery to the time instant when the first node in the network runs out of battery.
The network scenario consists of 15 nodes randomly scattered all over a circular area with radius equal to 1.5. The maximum transmission range is $r = 2.0$ and the length of the routes connecting any pair source-destination can be equal to 4 hops at most. An example of network scenario is shown in Fig. 2.

![Figure 2: Example of the ad hoc network scenario.](image)

The initial battery status is set equal to 1 for all the nodes in the network. The source nodes are $S = \{0, 1, 2, 3, 4\}$ with traffic rate $\lambda_0 = \lambda_1 = \lambda_2 = 0.4$ and $\lambda_3 = \lambda_4 = 0.3$, whereas the destination nodes are $D = \{13, 14\}$. The traffic flow generated by a source node may be directed to either one of the two destination nodes. A source node updates the cost function and selects a new route to a destination every time it finishes to transmit a block of five packets.

Results are derived by simulating several network topologies randomly generated and then averaging over the obtained values.

Fig. 3 shows the network lifetime obtained through the BEE scheme as $c$ varies, normalized to the value of lifetime derived through the MTE algorithm. Fig. 4 presents the mean packet delay obtained by applying the BEE scheme as $c$ varies. Results are normalized to the mean packet delay obtained with the MTE scheme. The mean packet delay is computed as the average delay from the time instant when a packet is generated at the source node to the time instant when it is delivered to the destination. (The axis of the abscissa is in logarithmic scale.)

Results show that for small values of $c$ (namely, $c = 1, 2, 3$) the BEE protocol gives a network lifetime shorter than the value obtained in the case of the MTE scheme; however, the BEE scheme presents a much lower mean packet delay since the traffic is always distributed among several different routes. For $c > 4$, the BEE algorithm outperforms the MTE technique in terms of both network lifetime and mean packet delay. The BEE scheme gives the maximum value of network lifetime when the cost function is evaluated over all the possible routes. In this case the factor of improvement with respect to the MTE scheme is equal to 1.8, whereas the mean packet delay given by the BEE protocol is slightly higher than in the case of the MTE scheme.

These results suggest that depending on the level of acceptable complexity, an optimal value of $c$ can be selected. In the case of a fast varying network topology, good performance in terms of both network lifetime and packet delay can be obtained by using small values of $c$. When the network topology varies slowly, higher values of $c$ can be chosen in order to achieve a longer network lifetime.

**CONCLUSIONS**

This paper presented a routing scheme for wireless ad hoc networks that efficiently exploits battery capacity. The objective of the scheme is twofold: to select a route with low transmission energy in order to avoid battery inefficiencies due to the rate capacity effect, and to distribute the traffic load in a manner that nodes with low battery can benefit of the recovery effect.

The proposed protocol, so-called BEE protocol, can be easily adapted to either a slow or fast varying network topology. Results show that the BEE scheme gives...
very good performance in terms of both network lifetime and packet delay, and significantly outperforms the MTE scheme. When the complexity of the BEE protocol is reduced, we obtain on the one hand a shorter network lifetime, on the other hand a lower mean packet delay.

REFERENCES


