On Using Battery State for Medium Access Control in Ad hoc Wireless Networks

S. Jayashree, B. S. Manoj, and C. Siva Ram Murthy*
Department of Computer Science and Engineering
Indian Institute of Technology Madras, INDIA
sjaya@cs.iitm.ernet.in, bsmanoj@cs.iitm.ernet.in, and murthy@iitm.ernet.in

ABSTRACT

One of the challenging issues in the energy-constrained ad hoc wireless networks is to find ways that increase their lifetime. Squeezing maximum energy from the battery of the nodes of these networks requires the communication protocols to be designed such that they are aware of the state of the batteries. Traditional MAC protocols for ad hoc networks are designed without considering the battery state. Major contributions of this paper are: (a) a novel distributed Battery Aware Medium Access Control (BAMAC(k)) protocol that takes benefit of the chemical properties of the batteries, to provide fair scheduling and increased network and node lifetime through uniform discharge of batteries, (b) a discrete time Markov chain analysis for batteries of the nodes of ad hoc wireless networks, and (c) a thorough comparative study of our protocol with IEEE 802.11 and DWOP (Distributed Wireless Ordering Protocol) MAC protocols. The key idea proposed in this paper is to piggy-back nodes' battery-state information with the packets sent by the nodes by means of which the nodes are scheduled to ensure a uniform battery discharge. We model the operation of the battery using a discrete time Markovian chain. Using the theoretical analysis, we calculate lifetime of the battery in terms of maximum number of packets that a node can transmit before its battery drains fully. Extensive simulations have shown that our protocol extends the battery lifetime consuming 96% and 60% less percentage nominal capacity spent per packet transmission compared to the IEEE 802.11 and the DWOP MAC protocols, respectively. In general, performance results show that BAMAC(k) outperforms IEEE 802.11 and DWOP MAC protocols, in terms of power consumption, fairness, and lifetime of the nodes. We have also analyzed the factors that influence the uniform discharge of batteries and their lifetime.

Categories and Subject Descriptors

C.2.1 [Computer-Communication Networks]: Network Architecture and Design–*Wireless Communication*

General Terms

Performance, Design

Keywords

Ad hoc wireless networks, batteries, energy, MAC scheduling protocol, lifetime, Markov chains

1. INTRODUCTION

The nodes of an ad hoc wireless network, a group of uncoordinated nodes which self organize themselves to form a network, have constrained battery resources. For example, in search-and-rescue operations and battle-fields, and in other places where setting up of a network is difficult, it becomes almost impossible to replace or recharge the batteries of the dead nodes. In such scenarios, there exists a need for battery (energy) aware protocols at all the layers of the protocol stack. On the other hand, ad hoc wireless networks, with characteristics such as the lack of a central coordinator and mobility of the nodes (as in the case of battle-field networks), require nodes with a very high energy reserve. However, advances in the battery technologies are negligible when compared to the recent advances that have taken place in the field of mobile computing and communication. The increasing gap between power consumption requirements and energy density (energy storable per unit weight of a battery) tends to increase the size of the batteries and hence increases the need for energy management in such networks. By energy management, we mean the energy-aware design of ad hoc networks and their protocols, which efficiently utilize the battery charge of the nodes and hence increase the lifetime of the network. The lifetime of ad hoc networks can be defined in many ways. It can be defined as the time between start of the network (when the network becomes operational) to the death of the first node. It can also be defined as the time that elapsed from the start of the network till the point of time at which there can be no more communication amongst the nodes, that is, there exists no two live nodes within the reach of one another. In this paper we will be using the former definition because in ad hoc networks the death of even a single node may lead to partitioning of the network and hence may terminate many of the ongoing transmissions.

---

*Author for correspondence. This work was supported by the Department of Science and Technology, New Delhi, India.

MobiCom'04, Sept. 26-Oct. 1, 2004, Philadelphia, Pennsylvania, USA.

Recent work in [1]-[17] proposes ways to increase the lifetime of the nodes by means of power-aware techniques, such as, using an optimal transmission power or by switching off the nodes when idle. Our approach is entirely different. Though the above mentioned protocols try to increase the lifetime of the network, they do not directly consider the behavior of the batteries. In our protocol, we propose a MAC protocol that exploits the chemical properties of the battery to increase their lifetime. Our protocol shows that a uniform discharge of the nodes of the network can increase their lifetime. This ultimately postpones the death of individual nodes and hence increases the network lifetime.

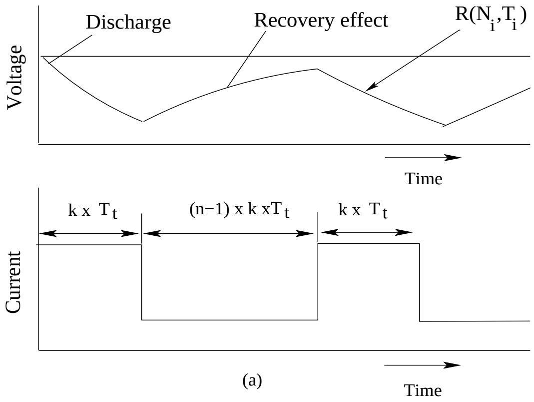
The rest of the paper is organized as follows. First, in Section 2, a detailed description of the proposed BAMAC(k) protocol is provided, followed by Section 3, which provides a theoretical analysis of the protocol using Markov chains. In Section 4, we present the simulation results, the performance analysis, and also a comparative study of theoretical and simulation results. In Section 5, we analyze, through simulations, the factors that influence the performance of the protocol and the lifetime of the network. Finally, in Section 6 of this paper, we provide the existing work in this area and Section 7 summarizes the paper.

2. OUR WORK

Section 6 provides an overview of the existing research work in the fields of battery technology and power aware ad hoc networks. Our observation from these existing works is that though there exist power-aware protocols for ad hoc networks, they have not considered the actual behavior of the batteries and the works which address the chemical properties of the batteries and the study of their behavior have not considered the limitations of the ad hoc networks. Hence, there exists a need for battery awareness at all the layers of the protocol stack. In [18], Chiasserini and Rao studied the behavior of a system in which more than one battery is used for powering up each of the nodes in the network.Though the study is limited to a set of batteries of a particular node, an interesting observation that can be made is that the lifetime of the battery increases the most when an ideal $round-robin$ scheduling of the batteries is made and hence any ideal round-robin node scheduling carried out at the MAC layer also would indirectly provide a better lifetime for the network. In our work, we have used the basic battery model proposed by Chiasserini and Rao in [19]. This model, for the behavior of the batteries of a mobile node, is very close to that of the behavior of the real batteries.

We, in this paper, propose a MAC protocol which tries to utilize the battery in an efficient manner. We have also shown how battery awareness influences throughput, fairness and other factors which describe the performance of the network.

Existing MAC protocols do not consider the state of nodes' batteries in their design. To the best of our knowledge, there has been no reported work till date for integrating the battery awareness with the MAC scheduling protocols for ad hoc wireless networks. In our BAMAC(k) protocol, we propose a novel distributed battery aware MAC scheduling scheme, where we consider nodes of the network, contending for the common channel, as a set of batteries and schedule the nodes using a round-robin scheduler. In this section we discuss the BAMAC(k) protocol which provides a back-off scheduling mechanism to schedule the nodes based on their remaining battery capacity. The key idea in our protocol lies in calculating the back-off period for the contending nodes which can be stated as follows: "The higher the remaining battery capacity, the lower the back-off period". That is, a node with higher remaining battery charge backs-off for a longer duration of time than the one with lower battery charge. This ensures a near round-robin scheduling of nodes and a uniform discharge of their batteries. We have thus provided a value for the back-off, which guarantees alternate periods of discharge and recovery of the batteries and also ensures that the throughput of the network is not degraded significantly. BAMAC(k) protocol forces the nodes to transmit k packets on gaining access to the channel. We found that as the chosen value of k increases, the throughput of the network increases without any degradation in the number of packets transmitted, till an optimum value of k is reached; beyond which, though the throughput still increases, the number of packets transmitted starts decreasing rapidly.



T_i	$\phi(T_i)$
200 to 196	0.0
195 to 101	0.0025
100 to 6	0.008
5 to 0	15.6

(b)

Figure 1: Illustration of battery discharge of nodes using BAMAC.

2.1 BAMAC(k)

Battery Aware MAC (BAMAC(k)) protocol, an energy-efficient contention-based MAC protocol, tries to increase the lifetime of the nodes by exploiting the *recovery capacity effect* (see the appendix) of the battery. As explained earlier, when a battery is subjected to constant current discharge, the battery becomes unusable even while there exists a sizable amount of active materials. This is due to the *rate ca-*

pacity effect (see the appendix) of the battery. If the battery remains idle for a specified time interval, it becomes possible to extend the lifetime of the battery due to the recovery capacity effect. By increasing the idle time of the battery, the whole of its theoretical capacity can be completely utilized. Also, Equation 2 (explained later in this section) clearly shows that this effect will be higher when the battery has higher remaining capacity and decreases with decrease in the remaining battery capacity. Thus, BAMAC(k) protocol tries to provide enough idle time for the nodes of ad hoc wireless networks by scheduling the nodes in an appropriate manner. It tries to provide uniform discharge of the batteries of the nodes that contend for the common channel. This can be effected by using a round-robin scheduling (or fair-share scheduling) of these nodes.

To attain a round-robin scheduling of the nodes in a distributed manner, each node maintains a battery table which contains information about the remaining battery charge of each of its two-hop neighbor nodes. The entries in the table are arranged in the non-increasing order of the remaining battery charges. The RTS, CTS, Data, and ACK packets carry the following information: remaining theoretical (in terms of remaining battery voltage) and nominal capacities of the battery and the time of last usage of the battery (the time at which the battery underwent its last discharge) of the node that originated the packet. A node, on listening to these packets, makes a corresponding entry in its battery table. The objective of the back-off mechanism used in BAMAC protocol is to provide a near round-robin scheduling of the nodes. The back-off period is given by,

$$\begin{aligned}\mathrm{back-off} &= Uniform[0, (2^x \times CW_{min}) - 1] \times \\ & \quad rank \times (T_{SIFS} + T_{DIFS} + T_t)\end{aligned} \qquad (1)$$

where, CW_{min} is the minimum size of the contention window and *rank* is the position of that entry in the battery table of the node which is arranged based on the following rule: "the battery table is arranged in descending order of its theoretical capacity of the nodes. Any tie, that arises, is broken by choosing the one with higher nominal capacity and then by choosing the one with least value for the time of last usage. Further ties are broken randomly". T_{SIFS} and T_{DIFS} represent the SIFS (Short inter-frame spacing) and DIFS (DCF inter-frame spacing) durations. Their values are the same as those used in IEEE 802.11. T_t is the is the longest possible time required to transmit a packet successfully, including the RTS-CTS-Data-ACK handshake. The node follows the back-off even for the retransmission of the packets. When this back-off scheme is followed, nodes with lesser *rank* values back-off for smaller time durations compared to those with higher *rank* values. $Uniform[0, (2^x \times CW_{min}) - 1]$ returns a random number distributed uniformly in the range 0 and $(2^x \times CW_{min} - 1)$, where x is the number of transmission attempts made so far for a packet. Thus the nodes are scheduled based on their remaining battery capacities. The higher the remaining battery capacity, the lower the back-off period. This ensures a near round-robin scheduling of the nodes. Hence, a uniform rate of battery discharge is guaranteed across all the nodes. This provides a discharge time of $k \times T_t$ and an average recovery time of $(n-1) \times k \times T_t$ for the nodes as shown in Figure 1(a), where n is the number of nodes. In each idle/recovery

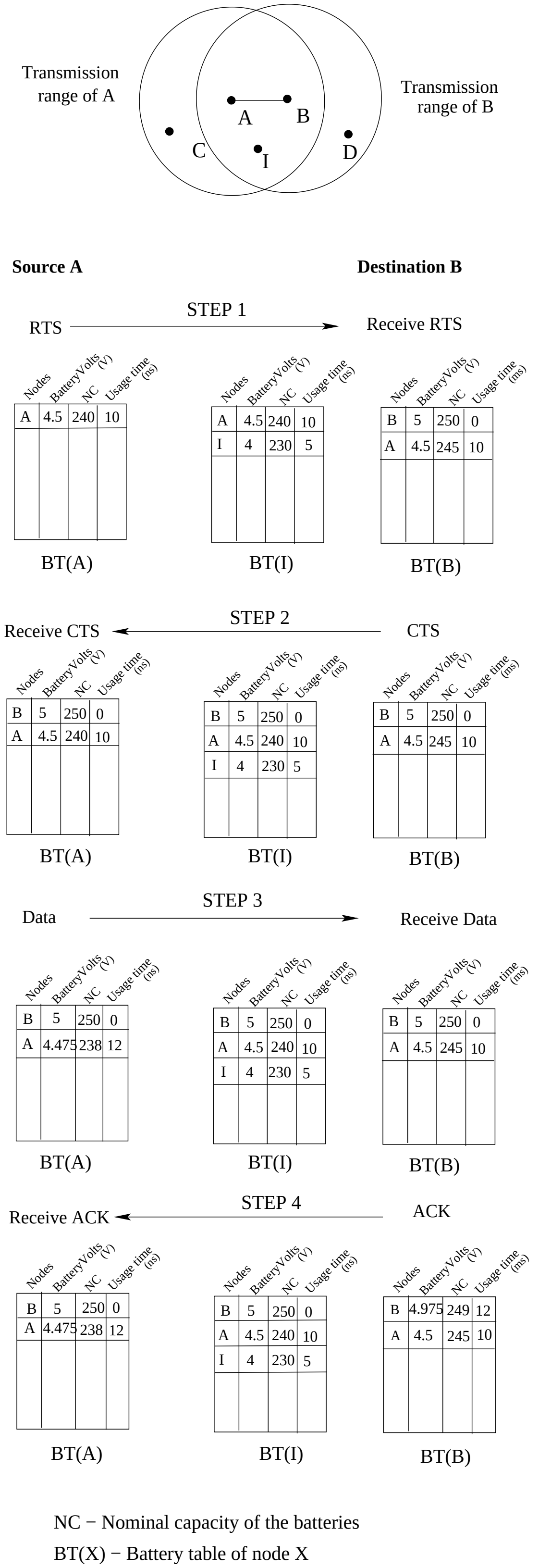


Figure 2: Battery table at various instances.

slot, the battery recovers one charge unit with a probability $R_{i,j}$ (explained in Section 3). This improves the lifetime of the battery as it gains more idle time to recover charge because of the recovery capacity effect. Though a higher value of k results in higher recovery time, it also increases the discharge time of the battery during the transmission of k packets. This increases the rate capacity effect due to fast depletion of the battery charge. As this effect increases, the probability for the battery to recover decreases. A smaller value of k, on the other hand, not only decreases this effect but also the recovery time of the battery. Hence, choosing an appropriate value for k is very important for optimum performance of the protocol.

In the BAMAC(k) protocol, whenever a node attempts to gain access to the channel, it waits for DIFS time duration before transmitting the first packet. If no other neighbor transmits in this duration, the active node (the node that gains access to the channel) initiates its transmission. For transmitting each of the next $k-1$ packets, it waits only for an SIFS duration; since the channel remains idle during this SIFS duration, the active node proceeds with the transmission of the packet. This ensures that none of the neighboring nodes gains access to the channel until the active node completes the transmission of k packets. This is ensured since the neighbors never find the channel idle for DIFS time duration, which is greater than that of SIFS.

2.1.1 *Example*

The following discussion explains our protocol through an example. Figure 2 shows the battery table at various instances of time and the transmission ranges of the nodes. The figure indicates the four main steps involved in a packet transmission. We have shown the battery table at the end of all these four steps. Let A and B be the source and the destination nodes, respectively. Let I be the intermediate node which lies in the transmission ranges of both A and B. In Step 1, the battery state of node A is sent along with the RTS packet transmission. After this step the nodes which fall in to the transmission range of A, namely nodes B, C, and I, make a corresponding entry in their battery tables about node A, based on the piggy-backed details in the RTS frame. Similarly, when node B sends the CTS frame, it piggy-backs both, its own details and about node A. The same procedure is followed for transmission of Data and ACK packets. The sender and the receiver update, about the latest transmission in their battery table, only after the transmission of Data and ACK packets. Hence, the new updated entry will be piggy-backed only in the subsequent packet transmissions. In our example, after Step 2, node D makes an entry about nodes A and B in its battery table. Similarly, node C makes an entry about node B after Step 3. This method of piggy-backing is to ensure efficient information exchange between a node and its two hop neighbors. Also, the above method allows some of the nodes to listen to the piggy-backed details more than once. This ensures minimal probability for having stale entries in the battery table in case of loss of packets. Assuming $k = 1$, after Step 4, if nodes A, B, and I have packets for transmission, node B will have higher probability for gaining access to the channel, followed by nodes A and I, since node B has the least rank value, and it will back-off for a lesser amount of time than nodes A and I.

3. MODELING THE BATTERIES USING DISCRETE TIME MARKOVIAN CHAIN

The behavior of the batteries of the nodes, which use BAMAC(k) protocol for transmission, is represented using a Markov model as shown in Figure 3. The state of the battery in the Markov model represents the remaining nominal capacity of the battery. Hence, the battery can be in any of the states from 0 to N, where N is the nominal capacity of the battery. The battery model assumes that, in any Δt time unit, the battery can remain in any one of the two main states – transmission state (Tx) or the reception state (Rx), where Δt is the sum of the average back-off value and the time taken for one packet transmission.

In each time unit Δt, if the node remains in Tx state, it transmits a packet and the battery discharges two units of its charge or, if the node remains in the Rx state, the neighbor nodes transmit and if the node does not receive any packets, the battery recovers one unit of the charge with probability R_{N_i,T_i}, where R_{N_i,T_i} is given by,

$$R_{N_i,T_i} = \begin{cases} e^{-g\times(N-N_i)-\phi(T_i)} & \text{if } 1 \le N_i \le N, \\ & \quad 1 \le T_i \le T \\ 0 & : \text{otherwise} \end{cases} \qquad (2)$$

where g is a constant value and $\phi(T_i)$ is a piecewise constant function of number of charge units delivered which are specific to the battery's chemical properties. An example of the values of the piecewise constant function $\phi(T_i)$ is shown in Figure 1(b). This value affects the battery recovery drastically. If the battery receives a packet in the Rx-state, it discharges one unit of its charge. In the model shown above, Rx_{ij} (Tx_{ij}) represents the battery in the Rx (Tx) state at time unit i and j represents the remaining nominal capacity of the battery. Rx_{I0} and Tx_{I0} represent the battery in its dead (absorbing) state with nominal capacity 0 at any time unit I.

In the BAMAC(k) protocol, assuming a perfect round-robin scheduling, each node transmits for k basic time units and remains in the receiving state for $n \times k$ basic time units where n is the number of neighbors. Here, we assume Δt as the basic time unit and $(nk + k)\Delta t$ as one cycle time for BAMAC protocol and one cycle time refers to the time between two successive entries in to Tx state or Rx state. State of the battery is denoted by the tuple $< Ni, Ti >$ and the initial state is given by the tuple $< N, T >$. In one time unit Δt, a battery which is in state $< N_i, T_i >$, goes to state $< N_{i-1}, T_{i-1} >$ if it is in Rx state. If the battery remains idle in Rx state, it reaches $< N_{i+1}, T_i >$ or $< N_i, T_i >$ with probabilities R_{N_i,T_i} and I_{N_i,T_i} respectively, where the probability to remain in the state on being idle is given by $I_{N_i,T_i} = 1 - R_{N_i,T_i}$. Hence, the battery can be modeled differently in each of these two states and the battery flip-flops between these two states. The stochastic model representing the battery behavior in the network which operates using BAMAC protocol is shown in Figure 3.

Hence, in the battery model, whenever the node enters Tx state, it remains there for k units of time and in each basic time unit discharges two units of its charge with probability 1. The battery, then, enters Rx state and remains there for $n \times k$ units of time. While the battery resides in this state in each time unit Δt, it recovers one charge unit with probability $r_{\Delta t} = R_{N_{\Delta t},T_{\Delta t}}(1 - q_{\Delta t})$ and enters into higher state, or remains in the same state with probability

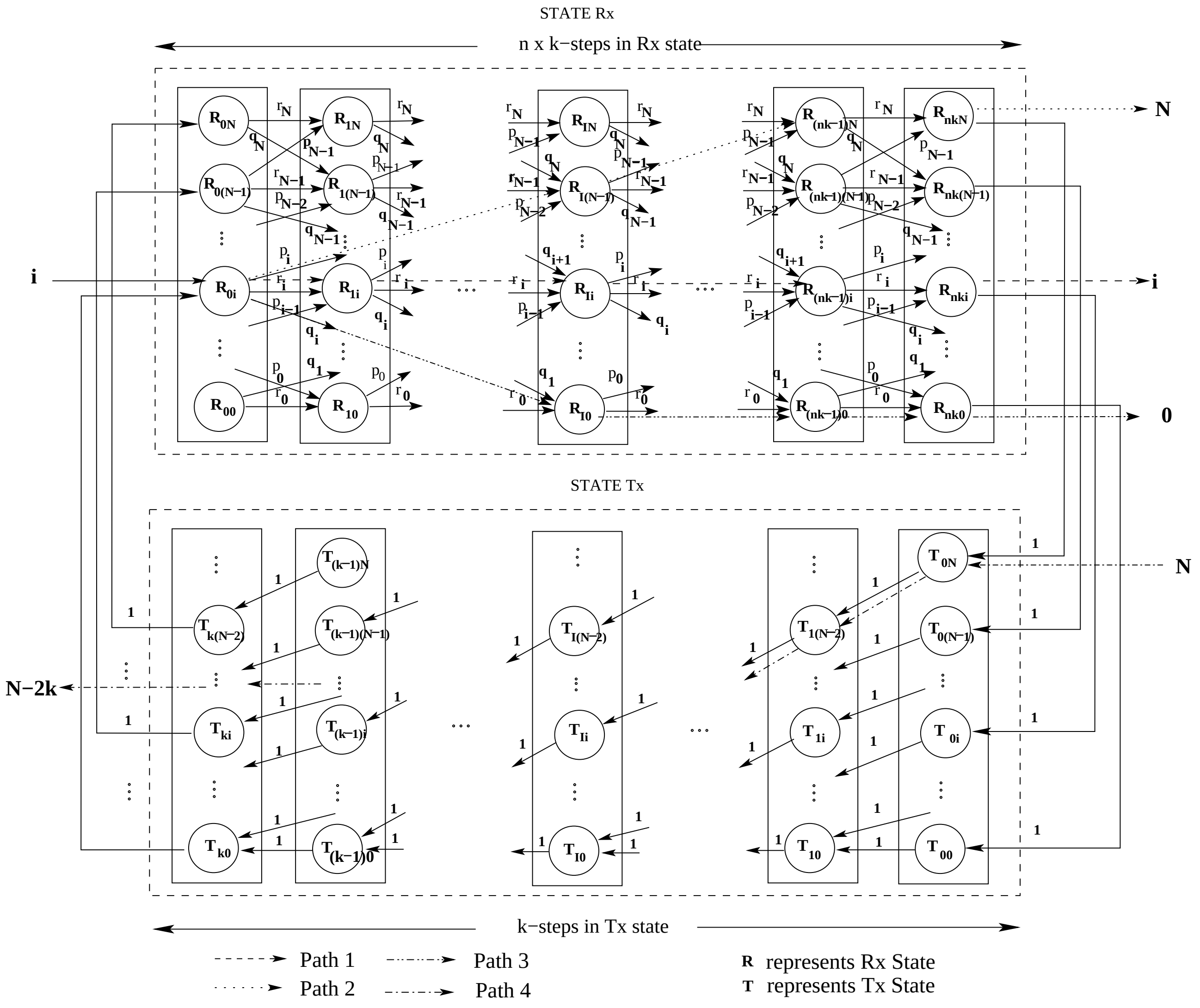


Figure 3: Discrete-time Markov model representing battery states.

$p_{\Delta t} = I_{N_{\Delta t},T_{\Delta t}}(1-q_{\Delta t})$. Here, $q_{\Delta t}$ is the probability that the node receives a packet in Δt time unit. The transition probability matrix for this model can be calculated as follows. The transition probability matrix for Rx state is given by $Rx = Rec^{nk}$. That is,

$$Rx = \begin{bmatrix} 1 & 0 & 0 & 0 & \dots & 0 & 0 \\ q_1 & r_1 & p_1 & 0 & \dots & 0 & 0 \\ 0 & q_2 & r_2 & p_2 & 0 & \dots & 0 \\ \vdots & \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & 0 & \dots & q_{N-2} & r_{N-2} & p_{N-2} & 0 \\ 0 & 0 & \dots & q_{N-1} & r_{N-1} & p_{N-1} & \\ 0 & 0 & 0 & \dots & 0 & q_N & r_N \end{bmatrix}^{\mathbf{nk}}$$

Here, Rec is the probability matrix of the battery for one basic time unit in Rx state. We assume the matrix index to start from 0 for the ease of denoting 0^{th} or the dead state. When the battery enters in to Rx state with a remaining nominal capacity of i, the probability that the battery will leave Rx state, after nk slots, with a nominal capacity of j, where $j = i$ is given by $Rx_{i,i}$. Hence, $Rx_{i,i}$ is the probability that the battery does not recover any charge after spending nk slots in Rx state and $Rx_{i,j}$ represents the probability that the battery, on entering Rx state with a nominal capacity of i leaves Rx state, after spending nk basic time units with a nominal capacity of j. Similarly, the transition probability matrix for Tx state is given by $Tx = Trans^k$.

Tx=

$$\begin{bmatrix} 1 & 0 & 0 & \dots & 0 & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 \\ 0 & 1 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & \dots & 1 & 0 & 0 & 0 \\ 0 & \dots & 0 & 1 & 0 & 0 \end{bmatrix}^{\mathbf{k}} = \begin{bmatrix} 1 & 0 & 0 & \dots & 0 & 0 \\ 1 & 0 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 1 & 0 & 0 & \dots & 0 & 0 \\ 0 & 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & \dots & 0 & 1 & \dots & 0 \\ 0 & \dots & 0 & 0 & 1 & \dots \end{bmatrix}$$

where, $Trans$ is the probability matrix for one basic time

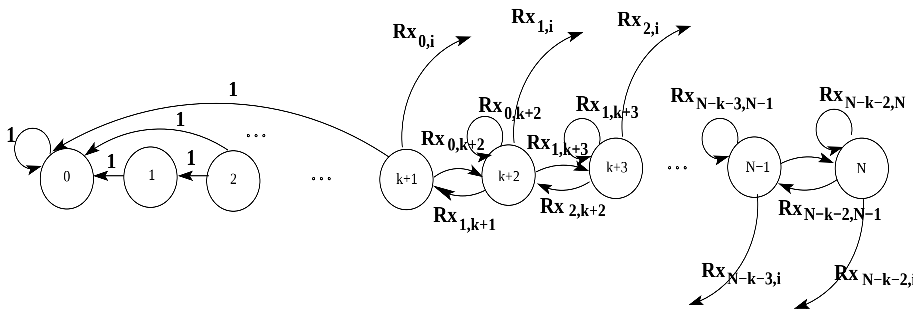


Figure 4: Markov model representing battery behavior.

unit in Tx state. This states that whenever the battery enters in to Tx state with a nominal capacity of i, it leaves Tx state with a nominal capacity of $i - 2k$, with a probability of 1. Here we assume that the data buffer for all the nodes remains always full. That is the nodes always have packets for transmission. Hence, the one-step transition probability matrix for the Markov model for one cycle time of BAMAC(k) is given by

$$P = Tx \times Rx = Trans^{k} \times Rec^{nk} \tag{3}$$

$P =$

$$\begin{bmatrix} 1 & 0 & \dots & 0 & 0 \\ 1 & 0 & \dots & 0 & 0 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ 1 & 0 & \dots & 0 & 0 \\ Rx_{0,0} & Rx_{0,1} & \dots & Rx_{0,N-1} & Rx_{0,N} \\ Rx_{1,0} & Rx_{1,1} & \dots & Rx_{1,N-1} & Rx_{1,N} \\ \vdots & \vdots & \dots & \vdots & \vdots \\ Rx_{N-k-3,0} & Rx_{N-k-3,1} & \dots & Rx_{N-k-3,N-1} & Rx_{N-k-3,N} \\ Rx_{N-k-2,0} & Rx_{N-k-2,1} & \dots & Rx_{N-k-2,N-1} & Rx_{N-k-2,N} \end{bmatrix}$$

Hence, the final Markov model, for one cycle time unit $((nk + k)\Delta t)$ is shown in Figure 4. Figure 4 shows that a battery in state i, at the end of 1 cycle, can be in any of the states from $i - 2k - nk$ (after discharging $2k$ charge units in the transmission of k packets and discharging nk units in the reception nk packets from all the n neighbors) to $i - 2k + nk$ (after discharging $2k$ charge units and recovering for the whole nk time units). The probability value $Rx_{i-k-2,j}$ $(P_{i,j})$ refers to the probability that the battery goes to state j from state i.

In Figure 3, let the battery enter Rx state with a remaining nominal capacity of i units. Hence, at 0^{th} time unit, it remains in state R_{0i}. After nk time units, the battery can be in any of the states from $i - nk$ to $i + nk$ based on the number of packets received and the probability of recovery; that is, if the node receives data in all the nk time units, it goes to $i - nk$ state and if the node does not receive any packet in Rx state, then it remains idle for nk time units and recovers nk charges with a probability $Rx_{i-k-2,i+nk}$. Figure 3 shows two such instances. Path 1 shows that the battery remains in the same state i even after idling for nk time units, which is represented by the probability $Rx_{i-k-2,i}$ and Path 2 shows the state transitions of the battery while traversing from state i to state N in $n \times k$ idle slots. Thus the probability for this transition to happen is $Rx_{i-k-2,N}$ if $N - i \leq nk$ and zero otherwise. This is because in $n \times k$ idle slots, the maximum recovery of a battery, starting from state i, is $i + nk$. Path 3 shows that the node with a remaining battery charge of i receives more than i packets and hence goes to the 0^{th} state or the dead state. Similarly, as shown in Path 4, if the node enters Tx state with a nominal capacity of N, it leaves Tx state with a nominal capacity of $N - 2k$, with probability 1. The states of the battery at different time units in Tx state, for this case, is shown using Path 3.

According to the properties of Markovian model, the time for which the model remains in the transient state before it reaches the dead state can be calculated as follows. This gives the time duration for which the battery remains active in transient states (1 to N).

Steps to calculate time duration of the Markov model to remain in transient states

Step 1: Given any probability matrix P, Calculate matrix Q=$[Q_{(i,j)}]$, where i and j represent only the transient states. In our protocol, $Q_{(i,j)} = P_{(i+1,j+1)}$.

Step 2: Calculate matrix $M = (I - Q)^{-1}$, where I is the identity matrix.

Step 3: Now $M_{(i,j)} \times \Delta t$ represents the total number of times the battery enters state j if the starting state is i and Δt is the time duration the Markov model spends in state j once it enters it. Based on the above steps M is calculated as follows,

$M =$

$$\begin{bmatrix} 1 & 0 & \dots & 0 & 0 \\ 0 & 1 & \dots & 0 & 0 \\ \vdots & \vdots & \dots & \vdots & \vdots \\ 0 & 0 & \dots & 0 & 0 \\ Z_{0,0} & Z_{0,1} & \dots & Z_{0,N-1} & Z_{0,N} \\ Z_{1,0} & Z_{1,1} & \dots & Z_{1,N-1} & Z_{1,N} \\ \vdots & \vdots & \dots & \vdots & \vdots \\ Z_{N-k-3,0} & Z_{N-k-3,1} & \dots & Z_{N-k-3,N-1} & Z_{N-k-3,N} \\ Z_{N-k-2,0} & Z_{N-k-2,1} & \dots & Z_{N-k-2,N-1} & Z_{N-k-2,N} \end{bmatrix}^{-1}$$

where,

$$Z_{(i,j)} = \begin{cases} 1 - Rx_{i,j} & if \;\; i = j \\ -Rx_{i,j} & otherwise \end{cases} \tag{4}$$

Here, since state 0 was removed, matrix starts from index 1 (representing state 1). Hence, M is an $N \times N$ matrix starting from state 1 (index 1) whereas, P is an $(N+1) \times (N+1)$ matrix starting from state 0 (index 0). Let, T_{active} of a battery model give the total active time of batteries. Here we assume that the starting state is state N, *i.e.,* we start with a fully charged battery system. Now the time for which it remains active or the lifetime of the battery can be given by,

$$T_{active} = \sum_{i=1}^{i=N} M_{N,i} \tag{5}$$

This is nothing but the total number of transitions (left, right, and stationary) in the model from the starting state N till it reaches state 0. The left, right and stationary transitions of a battery denote battery state as being – discharge, recovery and idle (remains in the same state after recovery) respectively. Equation 5 shows that T_{active} is the sum of the elements present in the N^{th} row of the matrix M, which is equal to the number of times battery enters into states 1 to N if the starting state is N. By substituting the value for the inverse of the matrix $I - Q$, we derive the value for T_{active} as follows.

$T_{active} =$

$$\frac{1}{det(M)} \left[\begin{array}{l} \displaystyle\sum_{j=0}^{2} \left(\sum_{a=0}^{j} (-1)^{a+N} x_{a,j} \;\; det(M_{(3:N-(a),3:N-1)}) \right) \\ \qquad\qquad \displaystyle + \sum_{a=3}^{N} det(M_{(3:N-(a),3:N-1)}) \\ \\ \\ \end{array} \right]$$

where $det(M_{i1:i2-(a),j1:j2})$ denotes the determinant of the matrix, formed by some of the elements of matrix M, which follows the property that the row value ranges from $i1$ to $i2$. The elements corresponding to row a are to be discarded and the column value ranges from $j1$ to $j2$. The generalized formula to calculate the determinant of matrix M ($det(M)$) is given as follows.

$$det(M) = \sum_{a=2}^{N} (-1)^{a+N} x_{a,N} \{ det(M_{2:N-(a),2:N-1}) \}$$

where,

$det(M_{2:N-(a),2:N-1}) =$

$$\sum_{\substack{c_1=2, \\ c_1 \neq a}}^{N} (-1)^{c_1+N} x_{c_1,N} \left[\sum_{\substack{c_2=2, \\ c_2 \neq a, C_1}}^{N} (-1)^{c_2+N} x_{c_2,N} \left[\sum \cdots \sum \right. \right.$$

$$\left. \left[\sum_{\substack{c_N-(2)=2, \\ c_N-(2) \neq a, c_1, \ldots, c_{N-k-3}}}^{N} (-1)^{c_{N-2}+N} x_{c_{N-2},N}] \right] \cdots \right]$$

The number of left transitions in the model represents the actual number of discharges. Hence, the total number of left transitions by a battery starting from state N is given by,

$$T_{left} = \textstyle\sum_{i=1}^{N} \times \sum_{j=1}^{i-1} P_{i,j}$$

where $P_{i,j}$ corresponds to the entry at the ith row and jth column. T_{left} corresponds to the total number of left transitions of the model which is nothing but the total number of discharges. Discharge of a nodes' battery occurs due to packet transmissions or receptions. In order to calculate the total number of packets transmitted, the value T_{left}, which corresponds to both transmissions and receptions of packets, has to be calculated. Then, based on the traffic pattern, the total number of discharges caused due to transmissions alone can be derived. We now explain a method to calculate the number of packets transmitted, for one such traffic pattern.

In our theoretical model, two discharges of a battery correspond to either a packet transmission or reception of 2 packets. Calculation of total number of packet transmission depends on the value of $q_{\triangle t}$. For example, if we assume that in nk time units spent by the battery in Rx state, each node receives (k) packets from one out of n neighbors, the probability that a packet is received in one time unit of Rx state is given by $q_{\triangle t} = \frac{k}{nk} = \frac{1}{n}$. Thus, the total number of packets transmitted, in this case, is given by,

$$Total \;\; number \;\; of \;\; transmissions = \frac{2 \times T_{left}}{3} \tag{6}$$

Similarly, if a node does not receive any packet in nk time units, the total number of packets transmitted is equal to $\frac{T_{left}}{2}$. Hence, the total number of packets transmitted can be calculated based on the value of T_{left} and the traffic pattern.

4. PERFORMANCE ANALYSIS

The proposed BAMAC(k) protocol was implemented using GloMoSim simulator. All the nodes were assumed to be homogeneous, sending packets with same transmission power. The parameters used in our simulation are shown in Table 1. The routing protocol used was Dynamic Source Routing (DSR) protocol. All the results that we have shown contain data points averaged over 10 runs. We have compared our protocol with the IEEE 802.11 and DWOP [20] (see Section 6) MAC protocols. In the following discussion capacity of a battery refers to nominal battery capacity unless otherwise specified. We have assumed a data packet size of 512 bytes.

4.1 Basic Assumptions

We now discuss the basic assumptions made in the design of BAMAC(k) protocol. In Section 5, we have provided a detailed analysis of the simulation results on relaxing these assumptions. Following assumptions were made in our protocol design.

- We consider that for every data packet transmission, the battery discharges two units of its charge and for every data packet reception, it discharges one unit of the charge. Thus we make an assumption that receiving takes half the amount of power spent as that of transmission.
- We, at this point of time, neglect the power spent by the nodes for control packets (*RTS, CTS, Data, and ACK*) transmission and reception.
- We assume that listening to the channel consumes negligible amount of power.

Table 1: SIMULATION PARAMETERS

Description	Value
Simulation area	2000m × 2000m
Number of nodes	10-40
Transmission power	12dB
Channel bandwidth	2Mbps
Routing protocol	DSR
Pathloss model	Two-Ray
Theoretical capacity of the battery	2000
Nominal capacity of the battery	250
Battery parameter (g)	0.05

- We also assume that if the battery idles for one unit of time (recovery slot time), that is, if the node neither transmits nor receives a packet in one time slot, the battery recovers one unit of charge with probability $R_{i,j}$.

- The recovery slot time, that is the minimum amount of time required for the idle battery to recover one charge, is assumed to be equal to the sum of the transmission time slot and the average back-off value.

- We assume the availability of a small alternate battery to power up the electronic components of the node while the node resides in the idle mode. Since, the power required by these electronic components is very minimal compared to the power spent in transmission and reception, we do not consider the effect of this battery on the nodes' lifetime calculation.

- We assume the existence of a Smart Battery System (SBS) which provides the state of the nodes' battery and hence, enables the control of its behavior such as charging and discharging. Such systems can provide a constant output voltage, irrespective of the fluctuations in the input voltage. These details can be used in calculating the current accurate battery state. For example, given a 5V battery with a maximum theoretical capacity of 200, a decrement of one unit of theoretical capacity corresponds to a decrease of 0.025V of the battery. Similarly, a remaining voltage of 3V corresponds to a theoretical capacity of 120. Hence, this ensures that at any point of time the state of the battery can be accurately determined based on the measured voltage.

We have provided the results for the following two main cases of study.

4.2 BAMAC(1)

In the following discussion, we have provided the simulation results and analysis of BAMAC(k) protocol where $k = 1$. In the subsequent sections we will discuss the effect of k value on the performance. Figure 5 shows that our protocol performs better compared to IEEE 802.11 and DWOP protocols in terms of the number of packets transmitted. In the simulations studies, inter-arrival time of 1 ms corresponds to 0.5 Mbps load per node. Since DWOP protocol is also a MAC scheduling protocol trying to provide fairness to the nodes, it also performs much better compared to IEEE 802.11. However, since DWOP does not take battery into consideration, as shown in Figure 6, the remaining battery capacity at the end of the simulation remains very small. We observe from the above mentioned figures that, the number of packets transmitted is 50% for BAMAC(1) protocol. This is the maximum acheivable number of packet transmissions, because any node can only transmit 50% of its theoretical capacity due to the first assumption made (transmission of a packet consumes two units of battery charge). In Figures 7 and 8, we have shown the results assuming infinite theoretical capacity. This shows that, in the case BAMAC protocol, the death of a battery and hence the path of a node is not caused due to the lack of nominal capacity, whereas this is not true in the case of other MAC potocols at high traffic. At high traffic, nodes which use IEEE 802.11 and DWOP MAC protocols finish their nominal capacity and transmit lesser number of packets than our protocol.

As the inter-arrival time of packets increases, even if node transmits continuously, it may gain enough time slots for recovering the charges lost due to the earlier transmissions. This is the reason behind an increase in the number of packets transmitted and an increase in the remaining battery capacity for the nodes as the inter-arrival time of packets increases.

Since, in IEEE 802.11 nodes try to acquire the channel in a greedy manner without considering either fairness or the remaining battery capacity, it may have higher average throughput as shown in Figure 9. However, the nodes' batteries finish faster. Though, the throughput of IEEE 802.11 is higher, it is not fair across all the nodes which can be seen from Figure 10 which shows the standard deviation of the throughput across all the flows. The BAMAC protocol explained above ensures short-term fairness among the nodes in terms of access to the common channel. This ultimately increases the lifetime of the nodes in the network. The standard deviation curve shows higher deviation for IEEE 802.11 and DWOP. So, the average throughput, for IEEE 802.11 and DWOP protocols is mainly because of the higher value of throughput for a certain set of nodes than the remaining. As mentioned earlier, in ad hoc wireless networks, a single node failure can lead to the partition of the network. Thus, though the throughput of the network degrades, the lifetime and hence the number of packets transmitted by the nodes remain high in BAMAC(1) protocol compared to DWOP and IEEE 802.11 MAC protocols. Hence, in the case of highly energy constrained networks such as ad hoc networks, having lesser throughput variation, for a longer time duration, across the nodes of the network is important in addition to having higher average throughput for a short duration of time. However, at lighter loads, since the inter-arrival time of packets is high, the throughput across the nodes remains constant.

Figure 11 shows the discharge of nominal capacities of the batteries at different points of time during the simulation. Since, in BAMAC(k) protocol, each node receives enough time for idling, which is more than the time required for regaining the charge spent on transmission of a packet, the nominal capacity of the battery remains higher even after transmission of many packets. As shown in the figure, the nominal capacity of the batteries in BAMAC protocol remains high throughout the simulation, whereas it discharges at a much higher rate in the case of IEEE 802.11 and DWOP protocols. Hence, DWOP and IEEE 802.11 transmit only 400 and 800 packets, respectively. Figure 12 shows the percentage nominal capacity per packet at different points of time in the simulation. When the percentage nominal capacity was averaged out for the whole session of the simulation, on an average 96% and 60% improvement was observed for BAMAC protocol compared with IEEE 802.11 and DWOP MAC protocols respectively, in terms of percentage nominal capacity spent per packet.

4.3 BAMAC(k)

Now we will see the effect of k value on the performance on the system. We have also analyzed the factors that lead to the calculation of optimal k value. Figures 13 and 14 show the number of packets transmitted as k value increases from 1 to 20 and 1 to 250, respectively. The corresponding graphs obtained using theoretical analysis are provided in Figures 15 and 16. As shown in the Figure 13-16, an increase in the number of neighbors (n) corresponds to an increase in the number of recovery slots, which is evident from Equation 3. This ultimately increases the number of packets transmitted. The main advantage of increasing the value of k can be observed in Figures 17 and 18, which show that as k increases the throughput also increases. The increase in throughput does not degrade the total number of packets transmitted till it reaches an optimal value.

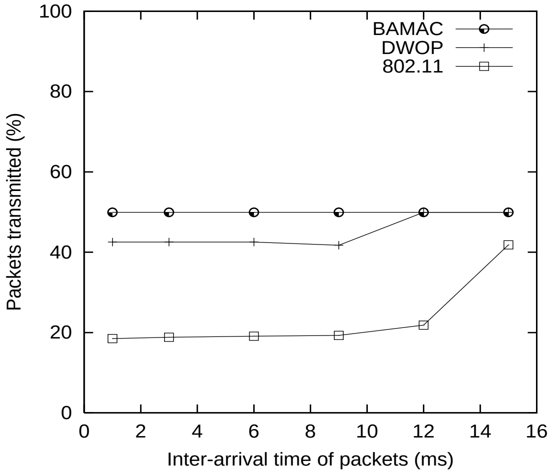


Figure 5: Packets transmitted.

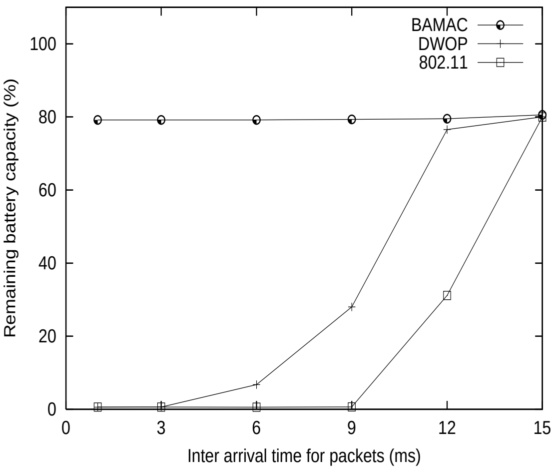


Figure 6: Remaining battery capacity at the end of the simulation.

Thus, if longer battery lifetime and higher number of packet transmissions are favored, a smaller value of k, that is $k = 1$, is preferred. Whereas, if higher throughput is preferred, higher values of k is chosen. However, as explained earlier, as k value increases, the throughput increases without significant decrease in the number of packets transmitted, till an optimal value is reached. Though, the optimal k value does not follow a specific pattern for different n values, in our simulation we found that it falls at around $k = 50$ and the theoretical analysis shows the optimal value to be around 100 to 150. The discrepancy between the theoretical and the simulation results is mainly due to the following: (a) in the theoretical analysis, a perfect round-robin scheduling of the nodes is assumed, (b) hence, there exists exactly nk recovery slots and k transmission slots, whereas, in the simulations, since we assume a random back-off, we can achieve only a near round-robin scheduling and hence each node may not gain perfect nk recovery slots and k transmission slots. Various other factors influencing the optimal value for k are the number of neighbors (n), battery parameters, and the recovery slot time.

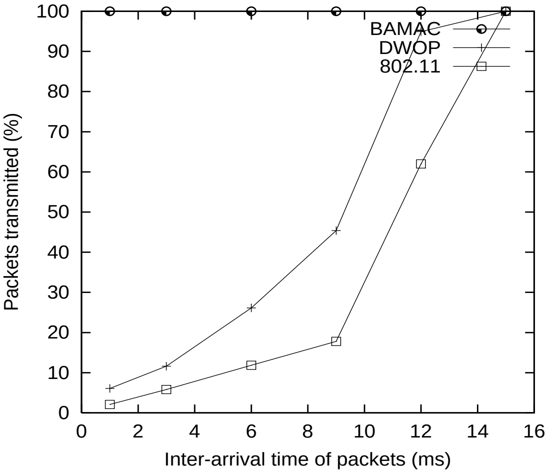


Figure 7: Packets transmitted assuming infinite theoretical capacity.

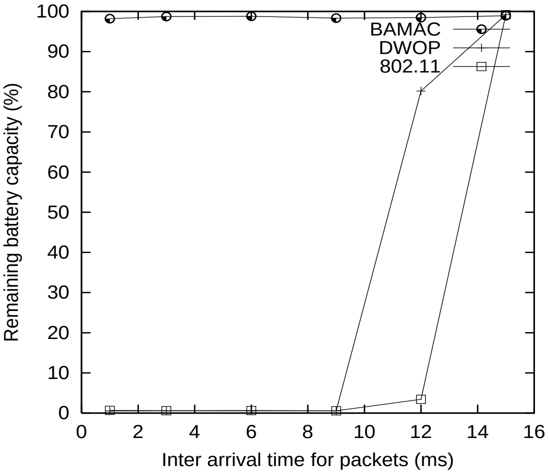


Figure 8: Remaining battery capacity at the end of the simulation assuming infinite theoretical capacity.

5. FACTORS INFLUENCING THE PERFORMANCE OF BAMAC(k)

Major factors that influence the above mentioned performance of our protocol can be stated as follows:

- **Power spent in the control packets (*RTS, CTS, and ACK*) transmission:** The set of results provided above neglect the power consumed by the control packets. In Figures 19 and 20, we have provided the results for number of packets transmitted and the remaining battery charge of the nodes, assuming each control packet transmission takes 10% of the power consumed by a data packet transmission. The results show that there is a degradation of 2%, 20%, and 1% in the number of packets transmitted by the nodes using BAMAC, DWOP and IEEE 802.11 MAC protocols, respectively. This is mainly due to the major proportion of power spent in transmitting the control packets, which can be observed from Figure 20; the figure shows

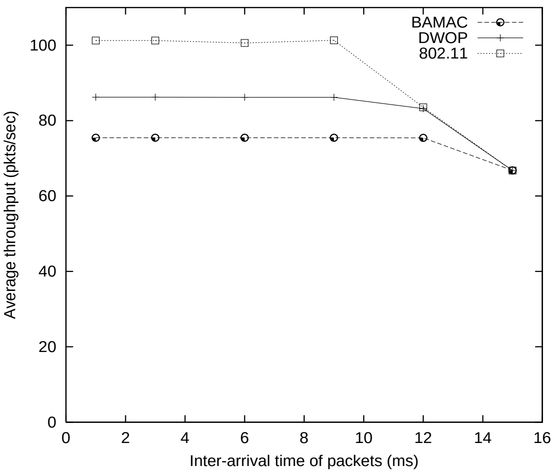


Figure 9: Average throughput.

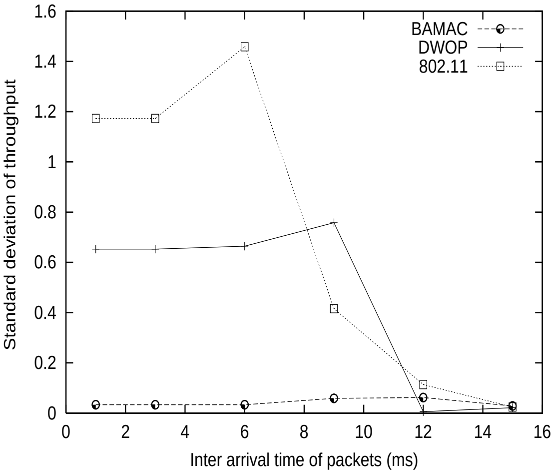


Figure 10: Throughput fairness.

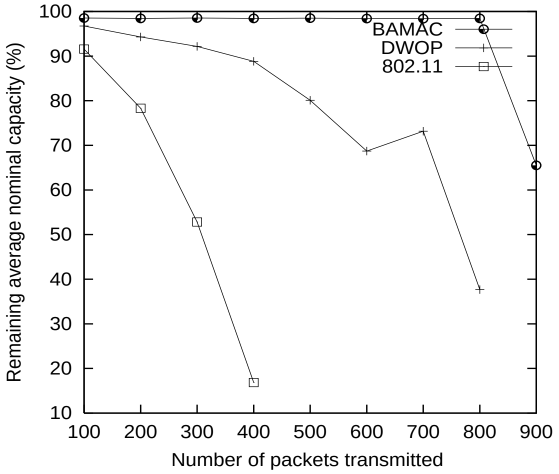


Figure 11: Remaining nominal capacity at different instances of the simulation.

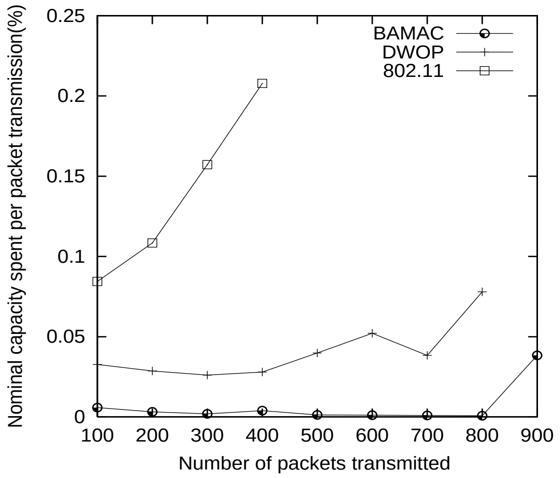


Figure 12: Nominal capacity spent per packet transmission at different instances of the simulation.

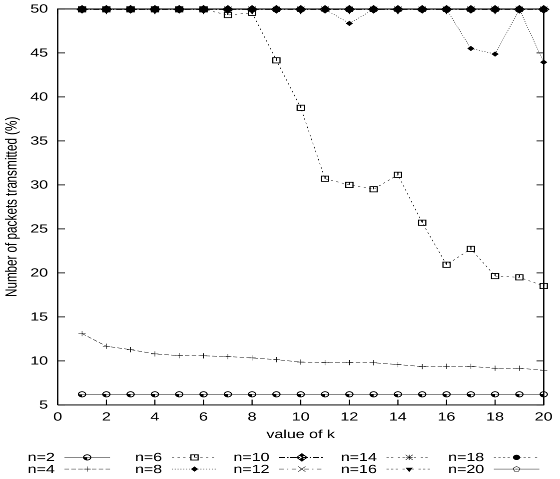


Figure 13: Number of packets transmitted calculated through simulations for k values 1 to 20.

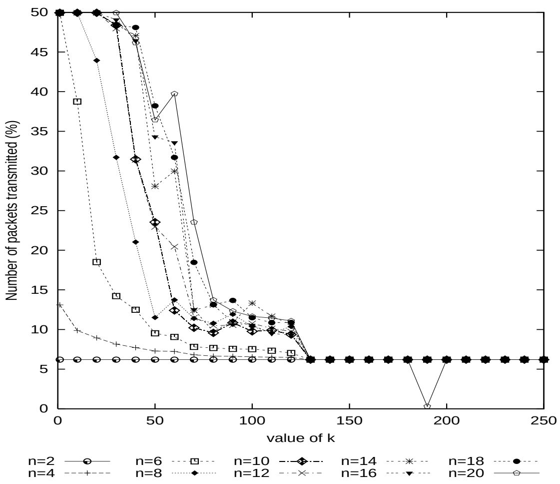


Figure 14: Number of packets transmitted calculated through simulations for k values 1 to 250.

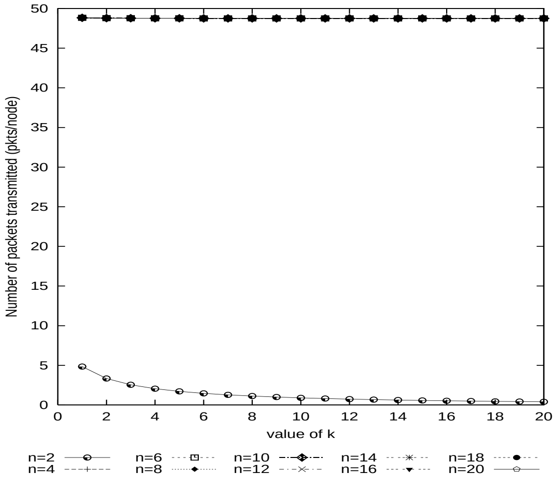


Figure 15: Theoretical analysis of number of packets transmitted for k values 1 to 20.

that on the inclusion of power consumption for control packets, the remaining nominal battery capacity at the end of the simulation degrades by 0%, 36%, and 20% corresponding to BAMAC, DWOP and IEEE 802.11 MAC protocols, respectively. This indicates the existence of a large number of continuous control packet transmissions in the case of DWOP protocol, to attain a fair share scheduling of the nodes in the network.

- **Effect of battery parameters:** We now discuss the impact of certain battery parameters on the performance.
  - Value of ϕ: As, mentioned earlier, in Equation 2, $\phi(T_i)$ is a piecewise constant function of number of charge units delivered which are specific to the cell's chemical properties. The values assumed in our protocol are shown in Figure 1(b). As ϕ decreases, the probability of recovery of a charge increases. The values used in our simulation indicate that the probability of recovery remains higher till the remaining theoretical capacity reaches 2.5% of its initial capacity. This assumption was taken from the research work of Adamou and Sarkar in [21]. Since, probability of recovery also depends on the remaining nominal capacity, the results show a better short-term performance of IEEE 802.11 and DWOP MAC protocols at longer packet inter-arrival times. In such cases, all the three protocols, gain on an average more than two slots for recovery after every packet transmission. However, an ideal round-robin scheduler will have a uniformly distributed recovery time between two successive transmissions. Since, our protocol tries to attain a round-robin scheduling of nodes for transmission, compared to other protocols, better performance, in terms of remaining battery, is observed for BAMAC protocol in the presence of both higher and lower traffic.

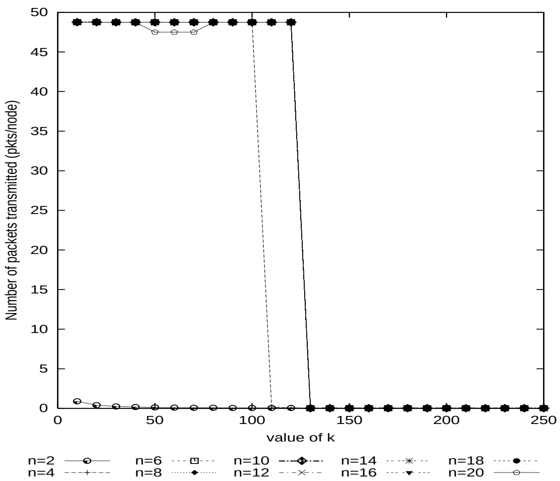


Figure 16: Theoretical analysis of number of packets transmitted for k values 1 to 250.

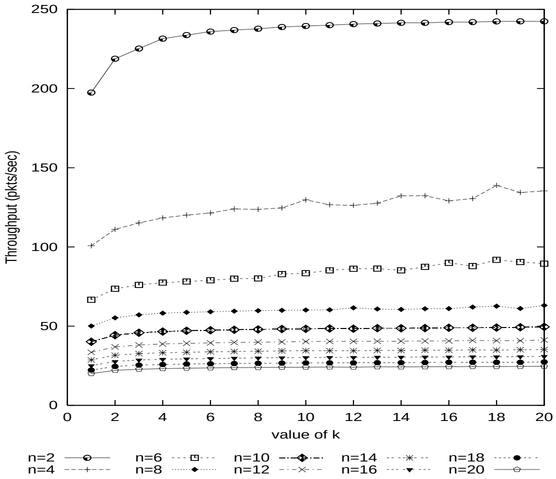


Figure 17: Throughput calculated through simulations for k values 1 to 20.

- Recovery slot duration: In [22], based on the battery behavior, the authors have assumed that one charge recovery may occur if the battery remains idle for one recovery slot duration, which is assumed to be equal to the time taken for one packet transmission. We, in our protocol, have assumed it to be sum of a packet transmission time and average back-off time. This ensures that if there are two nodes in the network transmitting alternatively, on an average each node gains one recovery slot. As the recovery slot time increases, the battery needs proportional idle time for recovery. Even in such cases a round-robin schedule of transmitting nodes will show a better performance due to the uniform discharge of batteries across nodes.

- **Effect of traffic pattern in the network:** We have seen from the results that a round-robin node scheduling is the best way to schedule the nodes in order to increase the battery lifetime which in turn increases the network lifetime. Since DWOP MAC protocol essentially tries to perform a fair scheduling of the flows of the network, it does not perform well in terms of battery lifetime. In our protocol a round-robin node scheduling is carried out and hence battery lifetime is extended. As part of the future work, we try to include ideal battery aware flow scheduling.

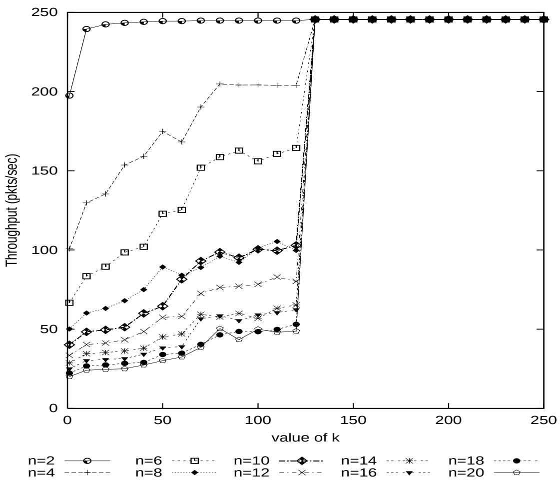


Figure 18: Throughput calculated through simulations for k values 1 to 250.

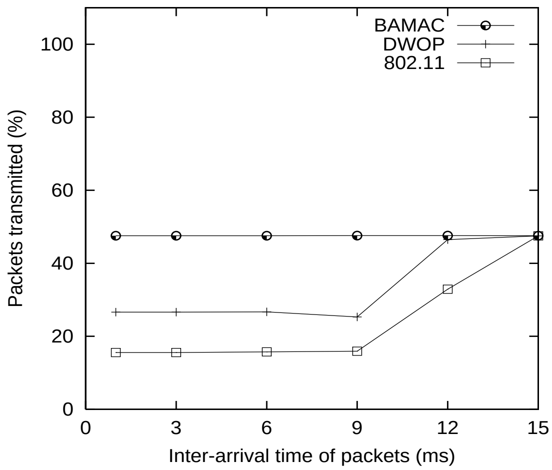


Figure 19: Number of packets transmitted when the power reduction for control packets is included.

6. RELATED WORK

Recent work in [1]-[17] suggest that a proper selection of power levels for nodes in an ad hoc wireless network leads to saving of power and unnecessary wastage of energy. There is ongoing research work in the field of chemistry trying to increase the lifetime of the batteries. Recent work [23]-[26] in energy efficiency for ad hoc networks shows that the battery lifetime can be considerably improved by introducing techniques which make efficient utilization of the battery power by making use of its internal characteristics.

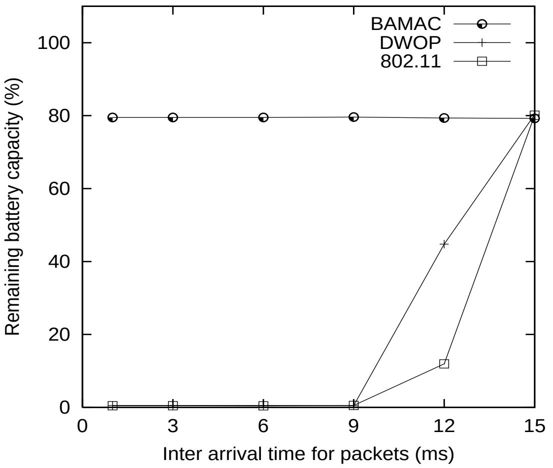


Figure 20: Remaining battery capacity at the end of the simulation when the power reduction for control packets is included.

The authors of [22], [23], and [24] have shown that the pulsed discharge current applied for bursty stochastic transmissions improves the battery lifetime than that of the constant current discharge. In [23], Chiasserini and Rao studied the battery behavior under two different modes of pulsed discharge – Binary and Generalized pulsed discharge of the batteries.

In [25], they provided an accurate model of the cell behavior. They have also proposed a leaky bucket traffic shaping scheme for shaping the discharge of the batteries by modeling the traffic generated by each node. Another strategy for discharging the cell, using stochastic dynamic programming, to extend lifetime of the batteries is provided in [21].

The authors of [18] have assumed each node to contain a battery pack with L cells and have proposed three battery scheduling policies for scheduling these L cells. On arrival of a packet, a subset of batteries is chosen for discharge based on each of these policies. In one of these schemes, whenever a packet arrives for transmission, one among the L cells is chosen in a round-robin fashion and discharged for providing energy to transmit the packet. They have found that the round-robin scheduling of the cells provides the maximum lifetime for the nodes due to the uniform discharge (recovery) of the cells. In [26], the authors have provided a heterogeneous battery scheduling scheme for a dual-battery powered portable system.

In [20], Kanodia *et al.* proposed DWOP, a MAC scheduling protocol which tries to provide, for the nodes of the network, a fair share access of the channel. Since this protocol schedules the nodes in a round-robin fashion, it introduces indirectly a uniform discharge of the batteries for their nodes. However, the authors do not consider the presence of a battery.

7. SUMMARY

In this paper, we proposed a novel energy efficient battery aware MAC protocol (BAMAC(k)), the main aims of which were minimal power consumption, longer life, and fairness for the nodes of ad hoc wireless network. Traditional ad hoc wireless MAC protocols are designed without considering the battery state. We found that our protocol, which provides a uniform discharge of batteries across nodes, extends the battery lifetime consuming 96% and 60% less percentage nominal capacity of the battery per packet transmission compared to the IEEE 802.11 and the DWOP MAC protocols, respectively. We also found that our protocol performs better, in terms of power consumption, fairness, and lifetime of the nodes, compared to IEEE 802.11 and DWOP MAC protocols. We found that as the chosen value of k increases in the BAMAC(k) protocol, the throughput increases without a significant degradation in the number of packets transmitted, till an optimum value of k is reached; beyond which, though the throughput still increases, the number of packet transmission starts decreasing rapidly. In this paper, we analyzed the factors affecting the optimal value of k and also provided a detailed analysis of the factors influencing the performance of our MAC protocol. A discrete-chain Markov model was used to theoretically analyze the protocol. The correctness of the theoretical model was verified through extensive simulation studies. If the time for which the batteries reside in discharge and recovery states of each cycle is provided, our model can provide the number of cycles for which the battery remains active before it reaches the dead state, in other words, our model provides the lifetime of the batteries.

8. REFERENCES

[1] R. Wattenhofer, L. Li, P. Bahl, and Y. M. Wang, "Distributed Topology Control for Power-Efficient Operation in Multi-Hop Wireless Ad Hoc Networks," *Proceedings of IEEE INFOCOM 2001*, vol. 3, pp. 1388-1397, April 2001.

[2] S. Agarwal, R. H. Katz, S. V. Krishnamurthy, and S. K. Dao, "Distributed Power Control in Ad Hoc Wireless Networks," *Proceedings of IEEE PIMRC 2001*, vol. 2, pp. 59-66, October 2001.

[3] R. Ramanathan and R. Rosales-Hain, "Topology Control of Multi-Hop Wireless Networks using Transmit Power Adjustment," *Proceedings of IEEE INFOCOM 2000*, vol. 2, pp. 404-413, March 2000.

[4] V. Kawadia, S. Narayanaswamy, R. Rozovsky, R. S. Sreenivas, and P. R. Kumar, "Protocols for Media Access Control and Power Control in Wireless Networks," *Proceedings of IEEE Conference on Decision and Control 2001*, vol. 2, pp. 1935-1940, December 2001.

[5] M. Sanchez, P. Manzoni, and Z. J. Haas, "Determination of Critical Transmission Range in Ad Hoc Networks," *Proceedings of MMT 1999*, October 1999.

[6] A. Muqattash and M. Krunz, "Power-Controlled Dual Channel Medium Access Protocol for Wireless Ad Hoc Networks," *Proceedings of IEEE INFOCOM 2003*, vol. 1, pp. 470-480, April 2003.

[7] V. Kawadia and P. R. Kumar, "Power Control and Clustering in Ad Hoc Networks," *Proceedings of IEEE INFOCOM 2003*, vol. 1, pp. 459-469, April 2003.

[8] C. K. Toh, "Maximum Battery Life Routing to Support Ubiquitous Mobile Computing in Wireless Ad Hoc Networks," *IEEE Communications Magazine*, vol. 39, no. 6, pp. 138-147, June 2001.

[9] M. Woo, S. Singh, and C. S. Raghavendra, "Power-Aware Routing in Mobile Ad Hoc Networks," *Proceedings of ACM MOBICOM 1998*, pp. 181-190, October 1998.

[10] R. L. Cruz and A. R. Santhanam, "Optimal Routing, Link Scheduling, and Power Control in Multi-Hop Wireless Networks," *Proceedings of IEEE INFOCOM 2003*, vol. 1, pp. 702-711, April 2003.

[11] A. Srinivas and E. Modiano, "Minimum Energy Disjoint Path Routing in Wireless Ad Hoc Networks," *Proceedings of ACM MOBICOM 2003*, pp. 122-133, September 2003.

[12] I. Stojmenovic and X. Lin, "Power-Aware Localized Routing in Wireless Networks," *Proceedings of IEEE IPDPS 2000*, vol. 2, no. 11, pp. 1122-1133, May 2000.

[13] C. F. Chiasserini, I. Chlamtac, P. Monti, and A. Nucci, "Energy-Efficient Design of Wireless Ad Hoc Networks," *Proceedings of Networking 2002*, pp. 376-386, May 2002.

[14] C. F. Chiasserini and R. R. Rao, "A Distributed Power Management Policy for Wireless Ad Hoc Networks," *Proceedings of IEEE WCNC 2000*, vol. 3, pp. 1209-1213, September 2000.

[15] S. Singh and C. S. Raghavendra, "Power-Aware Multi-Access Protocol with Signaling for Ad Hoc Networks," *ACM Computer Communication Review*, vol. 28, no. 3, pp. 5-26, July 1998.

[16] R. Zheng and R. Kravets, "On-Demand Power Management for Ad Hoc Networks," *Proceedings of IEEE INFOCOM 2003*, vol. 1, pp. 481-491, April 2003.

[17] R. Zheng, J. C. Hou, and L. Sha, "Asynchronous Wakeup for Ad Hoc Networks," *Proceedings of ACM MOBIHOC 2003*, pp. 35-45, June 2003.

[18] C. F. Chiasserini and R. R. Rao, "Energy Efficient Battery Management", *Proceedings of IEEE INFOCOM 2000*, vol. 2, pp. 396-403, March 2000.

[19] C. F. Chiasserini, R. R. Rao, "A Model for Battery Pulsed Discharge with Recovery Effect," *Proceedings of IEEE WCNC 1999*, vol. 2, pp. 636-639, September 1999.

[20] V. Kanodia, C. Li, A. Sabharwal, B. Sadeghi, and E. Knightly, "Ordered Packet Scheduling in Wireless Ad Hoc Networks: Mechanisms and Performance Analysis", *Proceedings of ACM MOBIHOC 2002*, pp. 58-70, July 2002.

[21] M. Adamou and S. Sarkar, "A Framework for Optimal Battery Management for Wireless Nodes", *Proceedings of IEEE INFOCOM 2002*, vol. 3, pp. 1783-1792, June 2002.

[22] C. F. Chiasserini and R. R. Rao, "Pulsed Battery Discharge in Communication Devices", *Proceedings of ACM MOBICOM 1999*, pp. 88-95, November 1999.

[23] C. F. Chiasserini and R. R. Rao, "Improving Battery Performance by Using Traffic Shaping Techniques", *IEEE Journal on Selected Areas of Communications*, vol. 19, no. 7, pp. 1385-1394, July 2001.

[24] D. Panigrahi, C. F. Chiasserini, S. Dey, and R. R. Rao, "Battery Life Estimation of Mobile Embedded Systems", *Proceedings of IEEE VLSI Design 2001*, January 2001.

[25] C. F. Chiasserini and R. R. Rao, "A Traffic Control Scheme to Optimize the Battery Pulsed Discharge", *Proceedings of IEEE MILCOM 1999*, pp. 1419-1423, November 1999.

[26] P. Rong and M. Pedram, "Battery-Aware Power Management Based on Markovian Decision Processes", *Proceedings of ICCAD 2002*, pp. 707-713, November 2002.

9. APPENDIX

9.1 Overview of Battery Characteristics

A battery typically consists of an array of one or more electro-chemical cells. It can be characterized either by its voltages (open circuit, operating, and cut-off voltages) or by its initial and remaining capacities. In this paper we have represented the batteries based on their *nominal, theoretical and actual* capacities. The behavior of the batteries is governed by the following two major chemical effects, which are to be considered for understanding the battery's discharge properties and to define the battery capacities.

- **Rate capacity effect**: As the intensity of the discharge current increases, an insoluble component develops between the inner and outer surfaces of the cathode of the batteries. The inner surface becomes inaccessible as a result of this phenomenon, rendering the cell unusable even while a sizable amount of active materials still exists. This effect depends on the actual capacity of the cell and the discharge current.
- **Recovery capacity effect**: This effect is concerned with the recovery of charges under idle conditions. Due to this effect, on increasing the idle time of the batteries, one may be able to completely utilize the theoretical capacity of the batteries.

Now, we define the various capacities of the batteries.

- **Theoretical capacity (T):** The amount of active materials (the materials that react chemically to produce electrical energy when battery is discharged and restored charged) contained in the battery refers to its theoretical capacity and hence total number of such discharges cannot exceed the battery's theoretical capacity. Whenever the battery discharges, the theoretical capacity of the battery decreases.
- **Nominal (standard) capacity (N):** This corresponds to the capacity actually available when the battery is discharged at a specific constant current. Whenever the battery discharges, nominal capacity decreases, and increases probabilistically as the battery remains idle (also called as recovery state of the battery). This is due to the recovery capacity effect. At any time unit i, the state of the battery is represented by the tuple $< N_i, T_i >$, where N_i and T_i correspond to the current nominal and current theoretical capacities.
- **Actual capacity:** The energy delivered under a given load is said to be the actual capacity of the battery. A battery may exceed the actual capacity but not the theoretical capacity. This is due to the rate capacity effect. The lifetime of a node is the same as the actual capacity of the battery, which can be completely utilized on increasing the idle time of the battery.