IEEE TRANSACTIONS ON
EMERGING TOPICS
IN COMPUTING

Received 19 June 2014; revised 2 October 2014; accepted 14 January 2015. Date of publication 00 xxxx 0000;
date of current version 00 xxxx 0000.

Digital Object Identifier 10.1109/TETC.2015.2398198

Impact of Network Load on the Performance of a Polling MAC With Wireless Recharging of Nodes

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ABSTRACT Wireless radio frequency (RF) recharging is a promising approach to prolong the lifetime of wireless sensor networks. In this paper, we describe a polling-based MAC protocol with a round robin, one-limited service policy. Upon a specific request from one or more nodes, the coordinator sends an RF recharging pulse during which regular communication is suspended. We develop a complete probabilistic model of the energy depletion process within the proposed MAC protocol as well as a queuing model of the node behavior, and use it to investigate the behavior of the time interval between successive recharging events and the packet waiting time under varying traffic load and number of nodes in the network.

INDEX TERMS Wireless sensor networks, RF recharging, energy harvesting.

I. INTRODUCTION

Wireless sensor networks (WSNs) are often expected to perform for prolonged periods of time without human intervention [16]. As one of the most frequent reasons for maintenance is replacement or manual recharging of batteries, periodic recharging of node batteries can significantly extend the WSN lifetime [19].

Recharging may be accomplished using energy harvesting from the network surrounding [7], which is unreliable since there is no guarantee that the environment will be capable of supplying the required amount of energy when needed. Alternatively, node batteries may be recharged through RF pulses [1] emitted by the network coordinator or base station [18], [19], which results in more predictable operation since the energy increment provided by a single recharging pulse depends only on the attenuation of wireless signal between the coordinator and the node.

However, the performance of the latter solution depends on the construction of network nodes: if they have a single antenna and RF transceiver, which simplifies the design and reduces the cost, a single RF band must be used for both recharging and data communications in which case network operation will be interrupted by the recharging process. Then, achieving both maintenance-free operation and the desired level of communications performance necessitates a carefully designed and thoroughly evaluated medium access control (MAC) protocol.

In this paper we propose a polling-based MAC protocol that uses round robin, 1-limited service policy. The protocol allows nodes to explicitly request recharging when their energy level drops below a predefined threshold. As nodes are equipped with a single antenna, recharging will interrupt data communications since both occur in the same RF band, similar to the solution described in [14]. However, the sensing process is active all the time and data packets are being collected even while recharging. The performance of the network using this protocol is then evaluated through probabilistic analysis and a dedicated queuing model, with a focus on the evaluation of the battery depleting process and the impact of recharging interval on data communications in the network.

The paper is organized as follows: Section II provides an overview of related work, followed by a detailed description of the MAC protocol and the recharging process in Section III. Section IV models the energy depletion process of the node and derives the probability distribution of the time interval between successive recharging events. Section V presents a models the time between successive medium accesses by the node and queuing delay experienced by data packets. Section VI presents performance results for the proposed MAC including recharging probability, total offered load, and queuing delay. Finally, Section VII concludes the paper and highlights some future research.

II. RELATED WORK

Generic mathematical model of energy replenishment which includes battery replacement or generic recharging was presented in [8]. The work focuses on generic concepts of 'battery replacement' or 'recharging' which occurs at a certain replenishment rate, rather than on harvesting the energy from the environment or recharging through RF pulses.

Energy harvesting offers a theoretically infinite but, at the same time, unreliable power source [4], and energy allocation must be carefully planned and optimized to ensure uninterrupted operation of the network.

A number of MAC protocols for WSNs have been designed for energy harvesting from the environment, for example using solar batteries or fluorescent lamps, both of which offer nearly continuous energy replenishment [12]. Energy harvesting is usually assumed to occur independently of data communications, although some approaches do allow for the possibility of the interplay between wireless communication protocols and RF energy transfer.

A comparative analysis of a number of energy harvesting algorithms, including practical measurements, was reported in [3].

Another detailed study of a number of medium access protocols, including TDMA, framed-ALOHA and Dynamic Framed ALOHA, for networks with continuous energy harvesting was reported in [5]. The paper assumes that the power sources of individual sensor nodes use continuous energy harvesting from ambiental sources such as sunlight, fluorescent lamps, and even the heat from heat sinks of CPUs in desktop computers.

While RF energy transfer does extend the useful lifetime of sensor networks almost to the point of making them 'immortal' [19], regular data communications in a wireless sensor network will be affected to some extent by the activities related to energy transfer [14]. Yet detailed studies of the interaction between the two are still scarce, and more work is needed to decide on the optimal scheduling of energy transfers and the adjustment of network parameters needed to account for these interactions. This interaction may be avoided if recharging uses a different RF band from data communications, sometimes referred to as 'heterogeneous frequency harvesting' [13], but this solution is more expensive due to the need for two RF transceivers and two antennas.

A number of CSMA- and polling-based medium access protocols have been analyzed and compared using both analytical modeling and simulation in [2], and a polling-based protocol was found to offer better performance than its CSMA-based counterparts.

Sleep-wake policies that minimize a hybrid performance measure based on the mean queue length and mean data loss rate are discussed in [6].

We note that our earlier work in this area has considered another polling MAC in which recharging occurs in a different RF band and, thus, does not interfere with data communications [11].

III. POLLING MAC AND RECHARGING

A. MAC PROTOCOL

We assume the network consists of m nodes, one of which, hereafter referred to as the coordinator, is equipped with a suitable power source that allows it to emit RF recharging pulses. The remaining $m-1$ nodes are identical nodes with a built-in sensor unit used to sense and generate data which are then sent to the coordinator; they are also equipped with a RF transceiver that can recharge the on-board battery from the recharging pulse.

We consider a round robin polling MAC protocol where the coordinator polls each node sequentially by sending a polling (POLL) packet, similar to the MAC used in Bluetooth [10]. The MAC address of the recipient is tagged in the header of the POLL packet. Occasionally, the coordinator will send a downlink data packet instead of a POLL one; such packets may be sent to a specific node, or to all nodes as a broadcast. Each node listens to all POLL packets to check whether it is the recipient, in which case it replies with an uplink DATA packet or, if it has no data to send, an empty (NULL) packet. When polled, each node is allowed to send a single packet of unit time length. We will refer to the time elapsed between two successive visits to any node in the target network as the polling cycle.

The network layout is depicted in Fig. 1; note that different nodes are located at different distances from the coordinator.

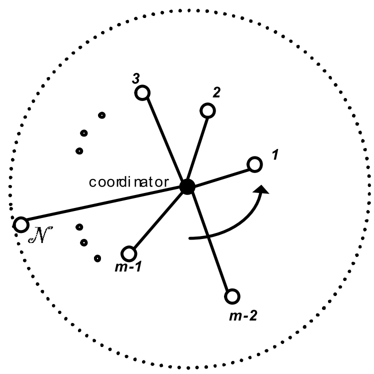


FIGURE 1. Logical representation of the network.

Bit and packet errors are quantified by their respective probabilities p_{BER} and $p_{PER} = 1-(1-p_{BER})^S$, where S is the total number of bits in a packet. If a DATA packet is correctly received, a dedicated field of the next POLL packet header towards the same recipient node will contain an acknowledgement. In the absence of acknowledgement, the node will repeat the last packet sent, up to n_{rt} times.

B. RECHARGING PROCESS

We assume that each node has the same initial energy level of E_{max}, equal to its battery capacity, which can't be exceeded when recharged. During data communications period, energy is used to support sensing, listening to and/or receiving POLL packets, and transmitting (and, possibly, retransmitting) DATA and NULL packets. The rate of energy expenditure will depend on packet generation rate λ, retransmit limit n_{rt}, bit error rate p_{BER}, and size of the network, i.e., the number of nodes m.

When the available energy has dropped below a predefined threshold, the node requests a recharge via a dedicated information field in the header of its DATA or uplink NULL packet. The coordinator will then announce the upcoming recharge pulse in the next POLL packet. The recharging pulse follows the announcement after a suitable timeout which allows the nodes to activate the recharging circuitry. Upon recharging, the network resumes normal operation. This process is schematically depicted in Fig. 2.

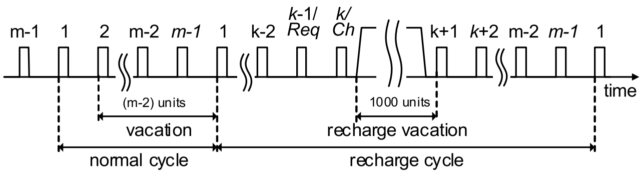
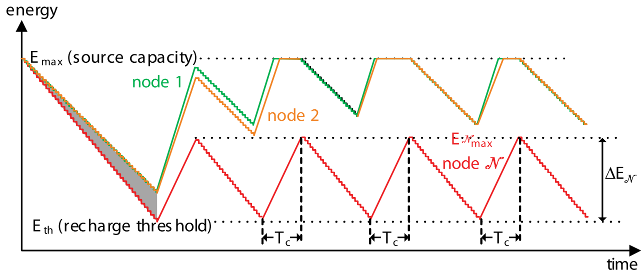


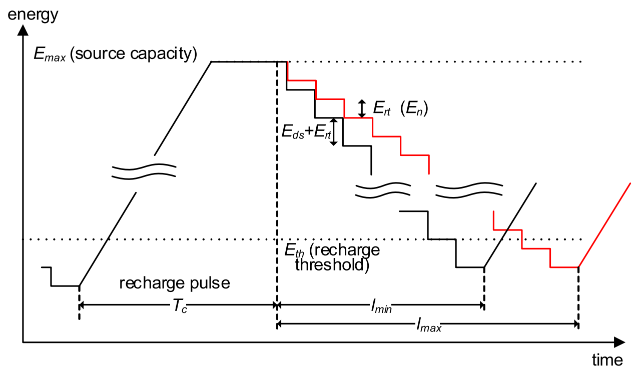
FIGURE 2. Format of network operation and recharging.

The recharging pulse has a power P_c and lasts for T_c time units. The received RF power at node i is calculated using the Friis' transmission equation [15]: $P_{ri} = \eta G_{ri} G_t \left(\frac{\lambda_w}{4\pi R_i}\right)^2 P_c$, where η is the coefficient of efficiency of RF power conversion, G_{ri} and G_t are the antenna gains at the receiver (i.e., node) and transmitter (i.e., coordinator), respectively, λ_w is the wavelength, and $R_i \gg \lambda_w$ is the distance between the coordinator and node i. The maximum possible energy increment for node i is, then, $\Delta E_i = P_{ri} \cdot T_c$, and the node energy level will be replenished to the level $\min(E_{max}, E_{th} + \Delta E_i)$. This process is schematically shown in Fig. 3(a).

Under uniformly distributed traffic load, fixed network size and constant reliability, the energy expenditure rate will vary due to randomness of packet arrivals and packet retransmission. However, mean energy consumption rate and, by extension, mean time to reach the energy threshold will be the same for all nodes since DATA and NULL packets require similar amounts of energy to send. At the same time, nodes are not recharged equally: the least amount of energy, in the first as well as subsequent recharging periods, will be received by the node at the greatest distance from the coordinator, labeled $\mathcal{N}$, due to maximum path loss. As the result, in all recharging periods (except, possibly the first one), it is the node $\mathcal{N}$ that will be the first to reach energy threshold and the first to request a recharge. Other nodes will receive larger energy increments in the recharging process and their energy will



(a)



(b)

FIGURE 3. Pertaining to energy expenditure and replenishment. (a) Energy levels during recharging and normal operation. (b) Energy levels – initial detail.

never fall to the threshold value. In fact, they will be recharged to capacity in second and subsequent recharging cycles.

The initial operation cycle is shown in more detail in Fig. 3(b). Due to randomness of packet loss, the period between two successive recharging is a random variable which can be described with a suitable probability distribution. Energy expenditure for a polling cycle will be obtained by counting the number of cycles needed for the farthest node $\mathcal{N}$ to use up its energy budget. Consequently, we need to find the joint probability distribution of the number of polling cycles and consumed energy during this period.

IV. RECHARGING MODEL

The notation used to describe different variables in subsequent evaluations are listed in Table 1. Energy consumption corresponding to atomic activities of a node are listed in Table 2. Using these values we can calculate the energy consumption of a node during a polling cycle, which depends on the type of activity that the node engages in a given cycle.

- Upon receiving a POLL packet, the node may have data in its buffer, which occurs with the probability of ρ_b, hereafter referred to as the effective utilization of the node (its actual value will be calculated later).
- Transmission of a DATA packet uses up energy E_{poll} to receive the POLL packet and energy E_{dt} for the actual transmission.
- If the data has been sensed in the current polling cycle, E_{ds} of energy was used to sense that data, otherwise the

TABLE 1. Table of notations.

symbol	definition
p_{PER}	probability of error in a received packet
E_{max}	maximum energy capacity of a node
E_{th}	threshold energy level of a node below which a node sends energy request
$\Delta E_i(i)$	energy gain of a node i after single recharging by the coordinator
$sum_{mini}(i)$	coefficient of $x^i\sigma^j$ including equivalent energy units conversion
$sum_{small}(i)$	coefficient of x^i including equivalent energy units conversion
$E_{X_p(x,y,\sigma,t)}$	joint PGF function for different energy units (sensing packet, transmitting DATA and NULL packets) time cycles with in a single recharging period
$E_{Xv(v,t)}$	PGF function after converting energy variables x, y and σ into a single unit v
τ_{max}	maximum number of packets sent between successive recharging points
τ_{min}	minimum number of packets sent between successive recharging points
η_Δ	representing floating point energy value $\Delta E_{\mathcal{N}}$ to the nearest integer value which is a multiple of E_{ds}
η_{rt}	ratio of DATA packet transmission energy and DATA sensing energy
η_n	ratio of NULL packet transmission energy and DATA sensing energy
$T(t)$	PGF of polling cycles for which energy expenditure of a node is exceeded
$E[T]$	mean number of polling cycles between consecutive recharging points
$V_{prd}(x)$	vacation a node enjoys while other $(m-2)$ nodes are in service
$V_{rcg}(x)$	vacation while the coordinator sends recharging pulse
$V(x)$	total vacation period enjoyed by a node
$E[V]$	average vacation period
ρ_b	total offered load
$\Pi(x)$	number of packets left in the queue after the departing packet without reliability
$\Pi_g(x)$	number of packets left in the queue after the departing packet with reliability
$W*(s)$	packet waiting time in the queue

TABLE 2. Energy consumption of atomic activities.

Activity	Variable
data sensing	E_{ds}
receiving a POLL packet	E_{poll}
listening to the header of a POLL packet	E_h
transmission of a DATA packet	E_{dt}
transmission of a NULL packet	E_{nt}

data still resides in the buffer from a previous polling cycle.

- If the node has no data to send, the probability of which is $1-\rho_b$, no energy was used for sensing, and the node will use up energy E_{poll} to receive the POLL packet and energy E_{nt} for the actual transmission of a NULL packet.
- Finally, the term $(m-2)E_h$ corresponds to the fact that, in each cycle, the node must listen to the headers of POLL packets addressed to $m-2$ other nodes (i.e., all nodes except itself and the coordinator).

Energy consumption of a single node during a polling cycle is summarized in Table 3.

We will the analytical model of recharging period along with the delay model at the node queue, assuming uniform distribution of load among the nodes.

Probability generating function (PGF) for the energy consumption along with the number of polling cycles required for a single DATA packet transmission is

$$Ep(x,y,t) = \frac{xyt\sum_{k=0}^{n_{rt}}(xt)^k {p_{PER}}^k}{\sum_{k=0}^{n_{rt}} {p_{PER}}^k} \tag{1}$$

where variables y, x, and t refer to energy consumption for data sensing, transmission of a DATA packet, and the polling cycle of the network, respectively. The numerator in the last equation means that a DATA packet consumes energy for one unit of sensing, y, and one unit of transmission, x, in a unit time period t. The transmission succeeds with the probability $1-p_{PER}$. If unsuccessful, first retransmission (for which sensing is not required) will be attempted at $t=2$; it will succeed with the probability $(1-p_{PER})p_{PER}$. Retransmission is attempted until successful, at most n_{rt} times; if this count is reached and retransmission is still unsuccessful, the packet will be dropped. Denominator in that same equation normalizes the PGF function that combines energy and time units, because probability values must add up to one.

To account for the cycles where a NULL packet is sent instead of a DATA one, the above PGF must be modified to read

$$E_{all}(x,y,\sigma,t) = \rho_b Ep(x,y,t) + (1-\rho_b)\sigma t \tag{2}$$

where the additional variable σ denotes the energy consumption for the transmission of a NULL packet.

Upon recharge, the energy of the furthest node $\mathcal{N}$ will be well above the threshold value: $E_{max}^{\mathcal{N}} = E_{th} + \Delta E_{\mathcal{N}}$. Due to stochastic character of data sensing and the impact of noise and interference on packet transmission and retransmission, the energy of this node will drop to the threshold level at a random time between $\tau_{min} = E_{max}^{\mathcal{N}}/(E_{ds} + (n_{rt}+1)E_{rt})$ and $\tau_{max} = E_{max}^{\mathcal{N}}/E_n$ packet transmissions. The above limits depend on the intensity of traffic, transmission errors which lead to retransmission, and maximum number of retransmission attempts allowed. The lower limit, τ_{min}, corresponds to the case where the node has some data to send at all times and each of the packets takes a maximum number n_{rt} retransmissions to be successfully sent. The upper limit, τ_{max}, is reached when the node buffer is empty throughout the recharge cycle, so that the node sends only NULL packets. We note that the probability of reaching either limit is small but non-zero nevertheless.

The next step is to combine the possible numbers of DATA and NULL packet transmissions as well as DATA packet retransmissions to form a joint probability distribution of total energy expenditure and required number of polling cycles between successive recharging pulses. The resulting PGF is

$$E_{X_p(x,y,\sigma,t)} = \frac{\sum_{k=\tau_{min}}^{\tau_{max}} E_{all}(x,y,\sigma,t)^k}{\tau_{max}-\tau_{min}+1} \tag{3}$$

where we have multiplied the PGFs to obtain the sum of corresponding random variables representing the transmission time of k packets where k, the total number of transmitted packets in a recharging period, ranges from τ_{min} to τ_{max}. Then we have added those products with equal weight, and normalized the resulting sum by their number $\tau_{max}-\tau_{min}+1$.

To simplify the link to energy consumption values from Tables 2 and 3, it is convenient to normalize the energy for transmitting a DATA or NULL packet to the amount needed

TABLE 3. Energy consumption at the level of the polling cycle.

Node activity in the cycle	Amount
first attempt to transmit a DATA packet	$E_t = E_{ds} + E_{poll} + (m-2)E_h + E_{dt}$
attempt to re-transmit a DATA packet	$E_{rt} = E_{poll} + (m-2)E_h + E_{dt}$
transmitting a NULL packet	$E_n = E_{poll} + (m-2)E_h + E_{nt}$

for sensing a single data value, i.e.,

$$\eta_{rt} = E_{rt}/E_{ds} \tag{4}$$

$$\eta_n = E_n/E_{ds} \tag{5}$$

and map $x = y^{\eta_{rt}}$ and $\sigma = y^{\eta_n}$ in (3). Since data packet transmission (described by the variable x) requires the highest energy value, all the coefficients of energy units are collected, combined and finally rounded up to the next integer value for obtaining greater accuracy; the new combined energy unit, dimensionally equal to y, will be labeled v. The actual process of merging the energy variables x, σ and y into variable v is shown in Algorithm 1.

The final PGF $E_{Xv(v,t)}$ contains a single energy variable v with an integer multiple of E_{ds} as its power, and a cycle variable t. Minimum and maximum degrees of v in $E_{Xv(v,t)}$ are expressed as d_v^{min} and d_v^{max}, respectively. As described earlier, for uniform traffic distribution, recharging requests will be triggered by the node $\mathcal{N}$ that is farthest away from the coordinator. Energy increment can be expressed through the ratio $\eta_\Delta = \Delta E_{\mathcal{N}}/E_{ds}$, similar to (4) and (5).

The condition that the energy resource is exceeded can be described with the polynomial

$$Tr(t) = \sum_{i=\eta_\Delta}^{d_v^{max}} f_t(i) \tag{6}$$

where $f_t(i)$ (which is polynomial in t) denotes the coefficients of the PGF $E_{Xv(v,t)}$ associated with energy variable v and its power i:

$$f_t(i) = \text{coeff}(E_{Xv(v,t)}, v, i) \tag{7}$$

Since variable t denotes the number of polling cycles, $Tr(t)$ represents the conditional PGF for the number of polling cycles required for which energy expenditure of the furthest node will be exceeded. To qualify as a probability distribution of the number of polling cycles between two successive recharging requests, $Tr(t)$ must be unconditioned to

$$T(t) = \frac{Tr(t)}{Tr(1)} \tag{8}$$

Mean number of polling cycles between two successive recharging requests is, then, $E[T] = T'(1)$. Since the proposed 1-limited MAC protocol supports only single packet transmission in a polling cycle, the probability of recharge is as $P_r = \dfrac{1}{E[T]}$.

Algorithm 1 Energy Transformation for Each Time Unit Within the PGF Function

Data: $E_{Xp(x,y,\sigma,t)}$, transmission ratios η_{rt} and η_n
Result: PGF of combined energy usage, in units of E_{ds}, and the number of polling cycles between successive recharging periods.

```
Calculate minimum d_x^min and maximum d_x^max degree of variable x in E_Xp(x,y,σ,t);
for i ← d_x^min to d_x^max do
    Get coefficient x(i) of x^i in E_Xp(x,y,σ,t) (x(i) is a polynomial on y, σ and t excluding the variable x);
    Evaluate minimum d_σ^min and maximum d_σ^max degree for variable σ in x(i);
    for j ← d_σ^min to d_σ^max do
        Get coefficient xσ(i,j) for σ^j in x(i) (xσ(i,j) is polynomial on y and t);
        Find minimum d_y^min and maximum d_y^max degree of variable y in xσ(i,j);
        for k ← d_y^min to d_y^max do
            Find coefficient xσy(i,j,k) of y^k in xσ(i,j) (xσ(i,j) is a polynomial on t only);
            Combined coefficient of energy x, σ and y consumption;
            E_com(i,j,k) = ⌈i·η_rt + j·η_n + k⌉;
            form new element of new polynomial as xσy(i,j,k)v^{E_com(i,j,k)}
        Third level summation on unified energy units
            sum_mini(i,j) ← Σ_{k=d_y^min}^{d_y^max} xσy(i,j,k)u^{E_com(i,j,k)};
    Second level summation
        sum_small(i) ← Σ_{j=d_σ^min}^{d_σ^max} sum_mini(i,j);
New PGF for on combined energy unit as
    E_Xv(v,t) ← Σ_{i=d_x^min}^{d_x^max} sum_small(i);
```

V. QUEUING AND VACATION MODEL

The MAC protocol described above utilizes round robin scheduling of nodes with 1-limited service policy. Therefore, it can be modeled as a M/G/1 gated limited system with vacations [17].

In this scenario, the vacation has two components. First of them, cyclical or periodical vacation, is due to the transmission and reception of packets by other nodes in a polling cycle. This vacation consists of service times of the other $m-2$ nodes, i.e., it excludes the target node and the coordinator, and its PGF is

$$V_{prd}(x) = (\rho_b G_{up}(x)x + (1-\rho_b)x^2)^{m-2} \tag{9}$$

Second type of vacation is the vacation caused by recharging (during which no data transmission can take place), and its PGF is

$$V_{rcg}(x) = P_{rt}x^{T_c} + (1-P_{rt}) \tag{10}$$

Combined PGF of the total vacation can be calculated as

$$V(x) = V_{rcg}(x)V_{prd}(x) \tag{11}$$

Mean and standard deviation of the total vacation are

$$E[V] = V'(1) \tag{12}$$

$$V_{sd} = \sqrt{(V''(1) - (V'(1))^2 + V'(1))} \tag{13}$$

We assume that POLL, DATA, and NULL packets last for one unit time slot each. Data packets are generated by sensing at a rate of λ per node, following a Poisson process. PGFs for uplink (DATA and NULL) packets and downlink (POLL) packets are $G_{up}(x)$ and $G_{dp}(x) = x$, respectively. Total mean packet time for a node (total denoting both uplink and downlink together) is $G'_{up}(1) + G'_{dp}(1)$. Offered load for each node is, then, $\rho = \lambda(G'_{up}(1) + G'_{dp}(1))$. However, the actual load will be higher due to vacations:

$$\rho_v = \rho + \lambda E[V] \tag{14}$$

where $E[V]$ represents the average duration of the vacation period. The use of retransmissions to achieve reliable transmission effectively converts a single packet transmission into a burst with the PGF of

$$G_b(x) = \frac{x\sum_{k=0}^{n_{rt}} x^k {p_{PER}}^k}{\sum_{k=0}^{n_{rt}} {p_{PER}}^k} \tag{15}$$

and its mean value is $E[G_b] = G'_b(1)$.

Hence, the total offered load in the uplink is

$$\rho_b = (\rho + \lambda_u E[V])E[G_b] \tag{16}$$

As total offered load depends on mean vacation time while cyclical vacation depends on total offered load, we need to simultaneously solve equations (16) and (12) to get these two values.

Assuming a FIFO servicing discipline, we can model 1-limited M/G/1 queues without transmission errors by considering a packet followed by a vacation as a virtual packet with the PGF of $B_1(x) = G_{up}(x)G_{dp}(x)V(x)$. This allows us to use the standard expression for the number of packets left after the departing uplink packet as

$$\Pi(x) = \frac{(1-\rho_v)(1-V^*(\lambda-\lambda x))B_1^*(\lambda-\lambda x)}{\lambda E[V](B_1^*(\lambda-\lambda x)-x)} \tag{17}$$

$$= (1-\lambda(E[G_{up}]+E[G_{dp}]+E[V]))(1-V^*(\lambda-\lambda x)) \cdot \frac{G^*_{up}(\lambda-\lambda x)G^*_{dp}(\lambda-\lambda x)V^*(\lambda-\lambda x)}{\lambda E[V](G^*_{up}(\lambda-\lambda x)G^*_{dp}(\lambda-\lambda x)V^*(\lambda-\lambda x)-x)} \tag{18}$$

where we have converted the PGFs for packet time and vacation time into Laplace-Stieltjes Transforms (LST) by replacing variable x with e^{-s}. For simplicity, each node is assumed to have a buffer of infinite size; the error introduced by this approximation is negligible at small to moderate load.

In the presence of transmission errors and retransmissions, each packet becomes a burst of random length. If the number of retransmissions is limited to n_{rt}, as assumed above, the PGF for the burst size is given by (15), and the overall PGF for the distribution of packets left after a single departing packet is

$$\Pi_g(x) = \frac{(1-\rho_b)(1-V^*(\lambda-\lambda x))G_b(B_1^*(\lambda-\lambda x))}{\lambda E[V]G_b(B_1^*(\lambda-\lambda x)-x)} \tag{19}$$

where $G_b(B_1^*(\lambda-\lambda x)$ represents the PGF of a burst where argument x is replaced with $B_1^*(\lambda-\lambda x)$, which is further replaced with $B_1^*(\lambda-\lambda x) = G^*_{up}(\lambda-\lambda x)G^*_{dp}(\lambda-\lambda x)V^*(\lambda-\lambda x)$.

Probability distribution of the number of packets left after a packet departure can be converted into the probability distribution of packet delay. This is usually accomplished by observing that the number of packets left after a packet departure is equal to the number of packets that have arrived during the time the departing packet was in the system. If response time for a packet is T_r, the last observation can be expressed as

$$\Pi_g(x) = T_r^*(\lambda-\lambda x) \tag{20}$$

In the presence of transmission errors and re-transmissions, the response time for a packet consists of waiting time until that packet is transmitted correctly. Waiting time includes waiting for all previous packets as well as the time needed for unsuccessful transmissions of the target packet. Therefore the probability distribution of waiting time can be described with

$$\Pi_g(x) = W^*(\lambda-\lambda x)G^*_{up}(\lambda-\lambda x) \tag{21}$$

Upon substitution $s = \lambda-\lambda x$, the probability distribution of the packet delay becomes

$$\begin{aligned} W^*(s) &= \frac{1}{G^*_{up}(s)}\Pi_g(1-\frac{s}{\lambda}) \\ &= \frac{(1-\rho_b)(1-V^*(s))G_b(G^*_{up}(s)G^*_{dp}(s)V^*(s))}{\lambda E[V](G_b(G^*_{up}(s)G^*_{dp}(s)V^*(s))-1+s/\lambda)G^*_{up}(s)} \\ &= \frac{(1-\rho_b)(1-V^*(s))G_b(G^*_{up}(s)G^*_{dp}(s)V^*(s))}{G^*_{up}(s)E[V](\lambda G_b(G^*_{up}(s)G^*_{dp}(s)V^*(s))-\lambda+s)} \end{aligned} \tag{22}$$

Moments of packet delay can be obtained as $(-1)^k W^{*(k)}(0)$ where k denotes the order of the moment (e.g. first moment has $k=1$, second moment has $k=2$ etc) and (k) denotes the k-th derivative of the LST $W^*(s)$. However, multiple applications of l'Hôpital's rule are necessary to obtain higher moments. In most cases, it suffices to find first moment (mean) and second central moment (standard deviation); the latter is obtained as

$$W_{sd} = \sqrt{(W^{*(2)}(0) - W^{*(1)}(0)^2)}. \tag{23}$$

VI. PERFORMANCE RESULTS

We consider the network with $m = 3$ to 11 nodes. Ordinary nodes generate packets at a rate of $\lambda = 0.007 \, .. \, 0.019$ with an increment value of 0.002 packets per time unit per node. Bit error rate is assumed to be constant with a probability of $p_{BER} = 10^{-5}$. The packet retransmission limit was set to $n_{rt} = 3$. Both downlink (POLL) and uplink (DATA or NULL) packets last for one time slot. When requested, the coordinator sends a recharging pulse of power 0.1W that lasts for 1000 slots. All the nodes are located within a disc at the distance of 1 . . 10 meters from the coordinator. In our experiment, we have considered energy consumption values for different events, i.e., sensing packets, transmitting, according to the [20]. We have solved the system of equations described above using Maple 13 from Maplesoft, Inc. [9]. For added verification, we have also implemented a discrete event simulator in C++. In the diagrams below, analytical results are shown with lines while simulation results are depicted with squares.

Our first set of experiments shows the main performance descriptors of network load and recharging as functions of packet generation rate λ and network size m.

Fig. 4(a) shows the total offered load from (16). As can be seen, the offered load is approximately linearly dependent on the packet generation rate and network size, as described by (9).

Mean recharging period, expressed in polling cycles, is shown in Fig. 4(b). As can be seen, larger network size leads to faster battery depletion, since all nodes have to listen to all POLL packets and the duration of the polling cycle is directly proportional to network size. The packet arrival rate is small enough throughout the observed range, hence the probability of having no data to send (i.e., of sending a NULL packet) is very high when m is small. As a NULL packet requires less power to transmit than a DATA one, the recharging period is higher at smaller values of m. On the other hand, larger network size leads to a longer vacation time during which more packets arrive, hence the probability that the node queues are empty decreases. More packet arrivals also means there will be fewer NULL packets which decreases the recharging period as well, although the difference is minor compared to the other factors.

The packet generation rate λ has both a positive and negative impact on the recharging period. Namely, higher packet rate results in more DATA packets and fewer NULL packets, which leads to a shorter recharging period. At the same time, higher packet rate triggers more packet retransmissions which requires slightly less energy than regular packet transmissions (E_{rt} vs. $E_{rt} + E_{ds}$) which has the opposite effect. The difference in energy consumption when sending DATA and NULL packets is small as the size of DATA packets is small. Moreover, most of the energy of a node is consumed for

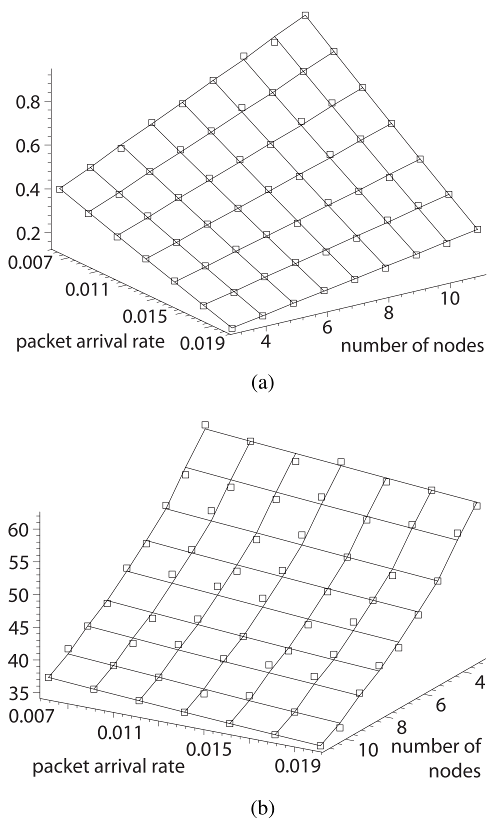


FIGURE 4. Descriptors of load and recharging. (a) Total offered load. (b) Mean recharging period (in polling cycles).

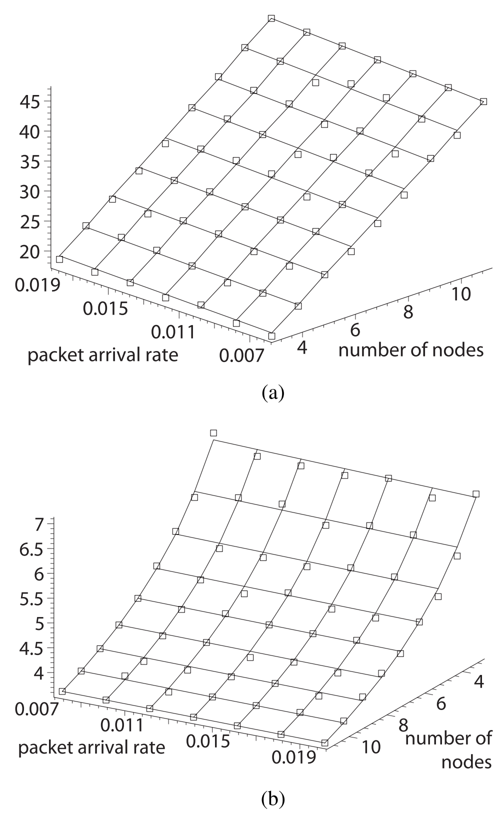


FIGURE 5. Descriptors of vacation time. (a) Mean value. (b) Coefficient of variation.

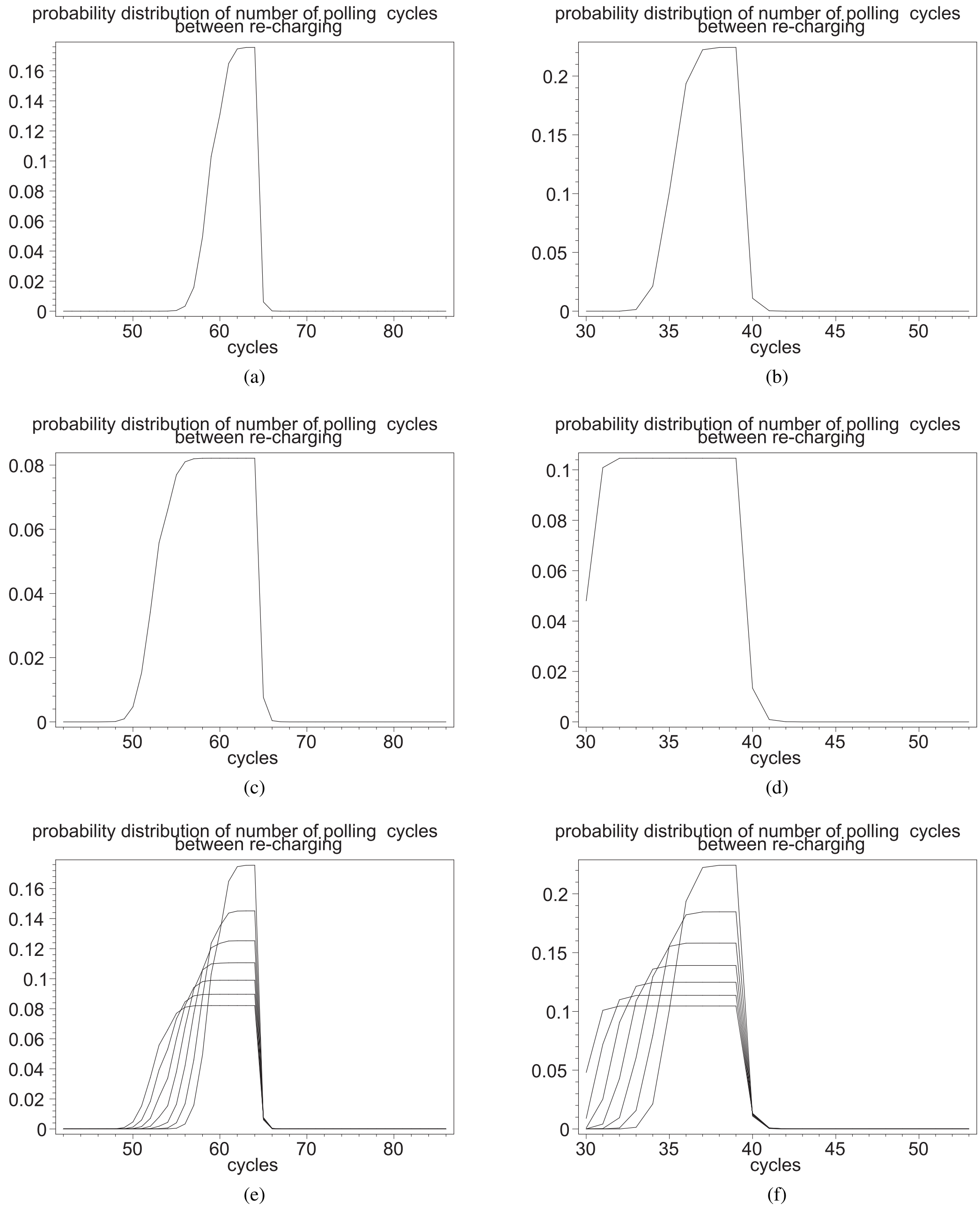


FIGURE 6. **Distributions of the number of polling cycles between two successive recharging pulses in a network with $m = 3$ nodes (left column) and $m = 11$ nodes (right column). (a) Probability distribution of the number of cycles at packet generation rate $\lambda = 0.007$, at $m = 3$. (b) Probability distribution of the number of cycles at packet generation rate $\lambda = 0.007$, at $m = 11$. (c) Probability distribution of the number of cycles at packet generation rate $\lambda = 0.019$, at $m = 3$. (d) Probability distribution of the number of cycles at packet generation rate $\lambda = 0.019$, at $m = 11$. (e) Ensemble of cycle distributions for packet generation rate from $\lambda = 0.007$ (topmost curve) to 0.019 (bottommost curve), in steps of 0.002, at $m = 3$. (f) Ensemble of cycle distributions for packet generation rate from $\lambda = 0.007$ (topmost curve) to 0.019 (bottommost curve) in steps of 0.002, at $m = 11$.**

longer vacation period. According to Fig. 4(b), recharging period is substantially reduced for larger network sizes, and it is not much dependent on the traffic load.

Descriptors of total vacation time are shown in Fig. 5. Mean vacation time increases with the network size due to an increase in cyclic vacation component, while mean vacation time increases only slightly with packet generation rate due to the slow increase in recharging probability. Coefficient of variation exhibits similar behavior, except that the dependency on network size is exponential as per (9). As the standard deviation of vacation time is smaller than the mean, the behavior of the distribution is hypo-exponential.

Probability distribution of the number of polling cycles between two successive recharging points derived in (8) is evaluated for varying packet generation rate; the results obtained from analytical solution are shown in Fig. 6 where diagrams on the left correspond to a network with $m = 3$ nodes while those on the right correspond to a network with $m = 11$ nodes. Top and middle rows show the distributions for the lowest ($\lambda = 0.007$ per node per time slot) and highest packet generation rate ($\lambda = 0.019$) considered, while the bottom row shows the ensembles of cycle distributions for packet arrival rates between lowest and highest value in steps of $\Delta\lambda = 0.002$.

Overall, the agreement between analytical and simulation results is quite good, which confirms the validity of our analysis.

As can be seen, lower packet generation rate results in probability distribution of the number of recharging cycles with a narrower shape. Higher packet generation rate increases packet retransmission which requires slightly less power, and by extension the lower bound of the recharging period distribution decreases. On the other hand, increased packet generation rate leads to an increase in DATA packet transmission and retransmission, but decreases the number of NULL packets; as the result, the upper bound of the distribution remains largely unaffected by this increase.

In the diagrams obtained for $m = 11$ (right column), both the lower and upper bound of the probability distribution are smaller by about 25 than their counterparts for $m = 3$ (left column). The difference is caused by the prolonged polling cycle at higher value of m. In both cases, the probability appears to be nearly flat (i.e., uniform) throughout the width of the main lobe of the distribution.

Finally, the diagrams in Fig. 7 show the mean and coefficient of variation of the packet waiting time at the node, as calculated from the probability distribution of (22). In small networks, mean waiting time increases linearly with packet generation time and vice versa. However, the increase soon becomes exponential, as more nodes and higher packet generation rate are responsible for higher rate of packet arrivals, and packets have to wait much longer. Note that recharging (with a pulse that lasts 1000 unit time slots) also contributes to this waiting time, as data is still being sensed even during recharge. The waiting time might be reduced by increasing the power of the recharging pulse which would allow for a reduction in its duration. Note that the ratio of standard deviation to mean value remains close to 1 at higher values for both m and λ: the ratio is lower (i.e., hypo-exponential) for moderate offered loads but gets closer to 1 at higher values (the range of independent variables in the diagrams corresponds to total offered load up to about $\rho_b = 0.75$).

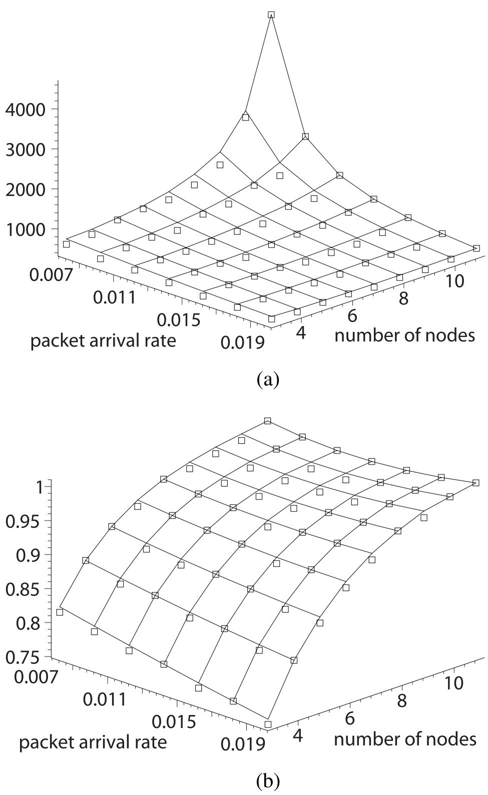


FIGURE 7. Descriptors of packet waiting time. (a) Mean packet waiting time. (b) Coefficient of variation of packet waiting time.

VII. CONCLUSION AND FUTURE WORK

In this paper we have proposed a simple round robin MAC protocol that performs RF recharging to allow a wireless sensor network to operate for extended periods of time without maintenance. As both data communications and recharging use the same RF band, the former are interrupted by the latter. To evaluate the performance of the networks operating under such a protocol, we have developed a probabilistic model for cycle duration between two successive recharging events as well as a queuing model for the node and packet waiting time. Our results indicate that recharging has a major impact on the distribution of the waiting time of the packets. As the results, careful tuning of protocol parameters is required to achieve the desired performance levels and, in particular, to prevent longer access delays for data collected by the network.

In future, we will work to find the optimal duration of recharging period and power which minimizes packet waiting times within the acceptable application-defined range. We will also extend our model to real world scenarios in which additional constraints must be added. We want to add more reliability in sending the recharging request to the coordinator, and reduce energy outage time of a node by the collaborative participations of its neighbouring nodes. We also want to investigate the effects of node mobility.

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