Performance of the MAC Protocol in Wireless Recharging under E-limited Scheduling

Mohammad Shahnoor Islam Khan[a], Jelena Mišić[a], Vojislav B. Mišić[a,*]

[a]*Department of Computer Science, Ryerson University, Toronto, ON, Canada*

Abstract

Recharging through radio frequency (RF) pulses is a promising approach to enhance the lifetime of wireless sensor networks (WSNs). In this paper, we propose a polling-based MAC protocol with round robin scheduling under E-limited service policy. In this model, the WSN coordinator sends a recharging pulse upon reception of a recharging request from one of the nodes. As both recharging and data communication use the same RF band, the latter process is interrupted by the former. A probabilistic model for energy depletion within the proposed MAC along with queueing delay model is evaluated as well. Later, we assess the behaviour of time interval between two consecutive recharging events and packet waiting time under varying network size and traffic load.

Keywords: wireless sensor networks, wireless recharging, MAC layer protocol, E-limited scheduling

---

1. Introduction

Extending the time interval in which no maintenance is needed is among the foremost design goals for wireless sensor networks (WSNs). One of the promising techniques to extend this time is automated recharging of node batteries [1]. Recharging may be accomplished by harvesting the energy from the environment, but such techniques are unpredictable and can't guarantee that sufficient energy will be available when needed; recharging through RF pulses sent by the WSN coordinator is a more reliable technique [2, 3]. Recharging and data communications may occur in different RF bands, provided that individual nodes are equipped with two radios and two antennas. Alternatively, a single RF band can be used for both recharging and data communications, which lowers

---

[☆] This is an expanded and revised version of the paper 'MAC protocol for wireless sensor networks with on-demand RF recharging of sensor nodes' presented at *2015 International Conference on Computing, Networking and Communications (ICNC 2015)* held in Anaheim, CA, in February 2015.

[*] Corresponding author

Email addresses: `m329khan@ryerson.ca` (Mohammad Shahnoor Islam Khan), `jmisic@scs.ryerson.ca` (Jelena Mišić), `vmisic@ryerson.ca` (Vojislav B. Mišić) the cost of wireless sensor nodes [4]. In the latter case, data communications and recharging must be interleaved and careful design of the medium access (MAC) protocol is needed to extend the maintenance-free lifetime as much as possible without compromising data communications performance.

In our earlier work, we have proposed a polling-based MAC protocol with in-band RF recharging [5] in which individual nodes are serviced using 1-limited service policy – i.e., each node was allowed to send at most a single data packet to the coordinator when polled. While this service policy ensures fairness and leads to best performance at very high loads [6, 7], it is unsuitable for scenarios where traffic load is not too high and/or different nodes have different mean packet arrival rates. In particular, the interleaving of data communications and recharging periods imposed by in-band RF recharging limits the traffic load that a WSN with RF recharging can handle.

In this paper, we present an improved MAC protocol which uses round robin scheduling of individual sensor nodes under the control of a dedicated coordinator powered by an energy supply of sufficient capacity. Recharging pulse is sent by the coordinator upon explicit request from a node which has detected that its available energy has dropped below a predefined threshold. During recharging, data communications are suspended, as both are performed in the same RF band, but the sensing unit of the node can still collect data throughout the interval. Nodes are serviced using an E-limited service policy [8] in which each node is allowed to transmit up to M data packets when polled, leads to better performance in terms of offered load, vacation time and queueing delay, compared to 1-limited service policy [9].

We evaluate the performance of this protocol using probabilistic analysis and a dedicated uplink queueing model which focuses on the battery depleting process and models the impact of the recharging interval on data communication performance.

The paper is organized as follows. Section 2 gives an overview of related work. Section 3 describes basic operation of MAC for E-limited service system. Section 4 presents the model for the energy depletion process and derives the probability distribution of the time interval between consecutive recharging events of a node. Section 5 models the vacation period of a node and queueing delay experienced by data packets. Performance of the proposed MAC protocol is presented and discussed in Section 6. Finally, Section 7 concludes the paper and highlights some future research directions.

2. Related Work

A generic model for energy replenishable sensor nodes which include battery replacement or generic recharging was presented in [10]. The work mainly focuses on generic recharging that happens at a certain replacement rate, rather than on energy harvesting from the environment or through RF recharging. More often than not, energy harvesting and data communication occur independently but some approaches consider the interplay between them as well [11]. Energy harvesting draws from a theoretically infinite power source but it

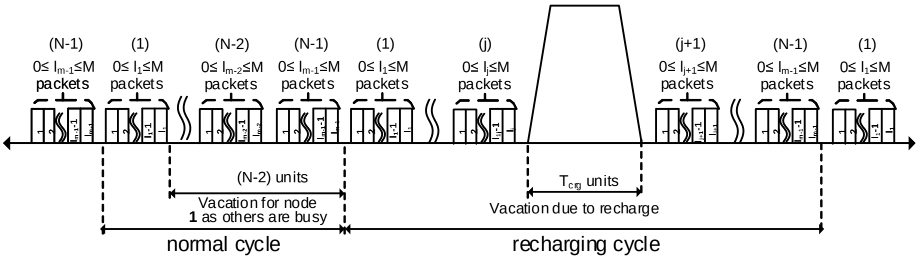


Figure 1: Packet Transmissions of nodes in a polling cycle.

is unreliable [12] due to its dependence on ambient conditions. This means that energy expenditure and subsequent use must be planned and carefully optimized in order to guarantee uninterrupted network operation. A comparative analysis of different energy harvesting techniques, including practical measurements, has been outlined in [13].

RF recharging may extend the lifetime of sensor nodes to effectively render them 'immortal' [14], but normal data operation can be affected to a large extent by the actions related to energy transfer as they require a temporary suspension of data communication activities – i.e., a vacation period [2]. Vacation period has significant impact on the queuing delay as well [15]. To reduce mean queue length and data loss, a MAC-based sleep-awake policy was proposed in [16]. However, more work is required to figure out the optimal scheduling of energy transfers and the adjustment of different parameters accountable for these interactions.

Several CSMA-based MAC protocols have been proposed to prolong battery lifetime for WSNs [17] [18]. These protocols mainly focus on energy conservation by enabling sleeping of one node while others are transmitting data. However, such MAC protocols can't guarantee per-node fairness and may result in higher latency time for some of the nodes. On the other hand, polling-based MAC protocols improve real time performance and provide fairness among nodes by implementing different types of scheduling [19].

Evaluation of MAC protocols with provisions for recharging has been done mostly for energy harvesting using solar batteries or fluorescent lamps which offer continuous energy replenishment. Several analytical and simulation-based models have been described for both CSMA- and polling-based MAC protocols [20][21]. ALOHA-like protocols with continuous energy harvesting have been proposed as well [22]. These results show that polling-based MAC protocols outperform CSMA-based ones in terms of network performance.

Routing under the constraints imposed by wireless recharging is another open issue that has not received adequate attention so far. A survey of recent work has been presented in [23] while an energy-efficient routing protocol has been described and analyzed in [24].

3. MAC Protocol

The network consists of $N-1$ sensor nodes and a coordinator. Each of the nodes has a sensing unit to collect sensing data which is then delivered to the coordinator. The coordinator sequentially polls each sensor node in a round robin fashion by sending POLL packets which may or may not contain data, similar to Bluetooth [25].

Upon receiving a POLL packet, the sensor node sends a DATA or NULL packet, depending on whether it has data to send or not, in the uplink to the coordinator. After receiving a DATA packet, the coordinator will send a new POLL packet to the same sensor node. After receiving a NULL packet, or after receiving a total of M DATA packets, the coordinator will move on to poll the next sensor node. This service policy corresponds to E-limited policy [8] which is non-gated, as the data sensed during the delivery of a DATA packet can be included, as long as the maximum of M packet is not exceeded.

All sensor nodes are listening to the header part of each POLL packet in order to find out which node is to respond. We define a *polling cycle* as the time interval between two consecutive visits to the same node. Therefore, in a polling cycle shown in Fig. 1, each node gets the opportunity to send at most M DATA packets to the coordinator.

We assume that the packet arrival rate follows Poisson distribution with mean arrival rate λ for all nodes. Packets are assumed to have a fixed size of L bits; the corresponding probability generating function (PGF) will be $G_p(z) = z^L$, and its Laplace-Stieltjes transform will be $G_p^*(s) = e^{-sL}$.

Our analysis will follow the theory of $M/G/1$ queuing systems with vacations. The number of packets at the uplink queue of a sensor node can be modelled with set of embedded Markov points that correspond to the moments when a node vacation is terminated due to the arrival of data, and the moments when a packet from a node is served in its entirety.

Let q_i be the joint probability that a Markov point in the uplink transmission from a sensor node is a vacation termination time and there are $i = 0, 1, 2 \ldots$ packets in the uplink queue of a node. Variables a_i and f_i represent the probability of i packet arrivals during the service time of a single packet and during each vacation period, respectively, while π_i^m denotes that the number of packets in the system after the completion of the m^{th} packet service, $m = 1 \mathinner{..} M$, is i. The following equations then hold:

$$\pi_i^1 = \sum_{k=0}^{i+1} q_k a_{i-k+1} \tag{1a}$$

$$\pi_i^m = \sum_{k=0}^{i+1} \pi_k^{m-1} a_{i-k+1}, \qquad m = 2 \mathinner{..} M \tag{1b}$$

$$q_i = \left(\sum_{m=1}^{M-1} \pi_0^m + q_0 \right) f_i + \sum_{k=0}^{i} \pi_k^M f_{i-k}, i = 0, 1, \ldots \tag{1c}$$

The PGFs for number of packets after each packet service and queue are

$$\Pi_m(z) = \sum_{i=0}^{\infty} \pi_i^m z^i \quad m = 1\,..\,M \tag{2a}$$

$$Q(z) = \sum_{i=0}^{\infty} q_i \dot{z}^i \tag{2b}$$

During the service period of one node, the other $N-2$ nodes are forced to undertake a vacation. The PGF and LST of vacation time are denoted with $V(z)$ and $V^*(s)$, respectively, while the number of packets arrival during a single vacation period is $V(\lambda-\lambda z)$. Then, the PGF of packet arrivals during a vacation is

$$V(\lambda - \lambda z) = \sum_{i=0}^{\infty} a_i z^i \tag{3}$$

Using (1) and (3), we can simplify the PGFs from (2) to

$$\Pi_1(z) = \frac{[Q(z) - q_0]B^*(\lambda - \lambda z)}{z} \tag{4a}$$

$$\Pi_m(z) = \frac{\Pi_{m-1}(z) - \pi_0^{m-1} B^*(\lambda - \lambda z)}{z}, \quad m = 2\,..\,M \tag{4b}$$

$$Q(z) = \left[\sum_{m=1}^{M-1} \pi_0^m + q_0 + \Pi_M(z)\right] V^*(\lambda - \lambda z) \tag{4c}$$

The impact of noise and interference is often measured through bit error rate ER_b, or the equivalent packet error rate $\sigma = 1 - (1 - ER_b)^L$ (since the data packet has a fixed size of L bits). Transmission reliability is implemented through Automatic Repeat Request (ARQ) protocol which retransmits corrupted packets up to n_{ret} times. Taking retransmissions into account, we can revise the PGF $Q(z)$ to

$$Q_\sigma(z) = \frac{(1-\sigma)\displaystyle\sum_{i=0}^{n_{ret}} (\sigma z)^i \left(\sum_{m=1}^{M-i-1} \pi_0^m + q_0 + \Pi_{M-i}(z)\right)}{(1-\sigma)\displaystyle\sum_{i=0}^{n_{ret}} \sigma^i} \cdot V^*(\lambda - \lambda z) \tag{5}$$

The PGF $Q_\sigma(z)$ must be normalized by dividing it into $Q_\sigma(1) = 1 - \Pi(1)$.

Overall, the operation of the network can be expressed through the $M(N-1)$ equations above; by solving these equations, we can derive probability values in the normalized PGF $\frac{Q\sigma(z)}{Q(1)}$.

The uplink transmission is terminated after sending M packets or when the queue is empty. The PGF for the duration of uplink service period (including

NULL packets) is

$$\begin{aligned} S^u(z) =& \frac{1}{Q_\sigma(z)} \Bigg[z + \sum_{i=M}^{\infty} q_i (G_p(z))^M + z(G_p(z))^M \sum_{i=1}^{M-i} q_i \\ & + \sum_{i=1}^{M-1} q_i \sum_{l=1}^{M-k} (z - z(G_p(z))^l) \psi^*_{M-l,i}(G_p(z)) \Bigg] \end{aligned} \tag{6}$$

where

$$\psi^*_{l,i}(z) = \frac{iw^l}{l(l-i)!} \cdot \frac{d^{l-i}}{dy^{l-i}} (zG^*_p(\lambda - \lambda z))^{2n} \tag{7}$$

In the downlink, the coordinator sends only POLL packets, to each of which the sensor responds by a single uplink DATA or NULL packet. Let S denote the service time for a downlink and uplink transmission. The corresponding PGF may be written as

$$\begin{aligned} S(z) =& \frac{1}{Q_\sigma(z)} \Bigg[z + \sum_{i=M}^{\infty} q_i (zG_p(z))^M + z(zG_p(z))^M \sum_{i=1}^{M-i} q_i \\ & + \sum_{i=1}^{M-1} q_i \sum_{l=1}^{M-k} (z - z(zG_p(z))^l) \psi^*_{M-l,i}(zG_p(z)) \Bigg] \end{aligned} \tag{8}$$

Probability of sending a NULL packet in the uplink is

$$s^u_0 = S^u(0) \tag{9}$$

while the PGF for the service time spent transmitting DATA packets is

$$S^u_+(z) = S^u(z) - s^u_0 \tag{10}$$

4. Recharging model

We assume that all nodes are initially charged to the maximum battery capacity of E_{max} which can't be exceeded. Energy is used to sense, process, send and resend data, including NULL packets, but also to listen to POLL packets sent to the node in question as well as to all other nodes. Table 1 represents units for energy expenditures for various events considered in the model.

When the energy level of a node drops below a predefined threshold E_δ, the node sends a recharge request by piggybacking the appropriate message onto a DATA or NULL packet it sends to the coordinator. Upon receiving such a request, the coordinator sends a special POLL packet informing all the nodes about a pending recharge RF pulse. This packet also contains the information about the power of the recharging pulse and its duration, P_{crg} and T_{crg}, respectively.

Table 1: Elementary energy consumption units.

Energy expenditure	label
Data sensing	E_{ds}
Listening to the POLL packet	E_{poll}
Listening to the header of POLL packet	E_{pa}
Data packet transmission	E_{dt}
Null packet transmission	E_{nt}

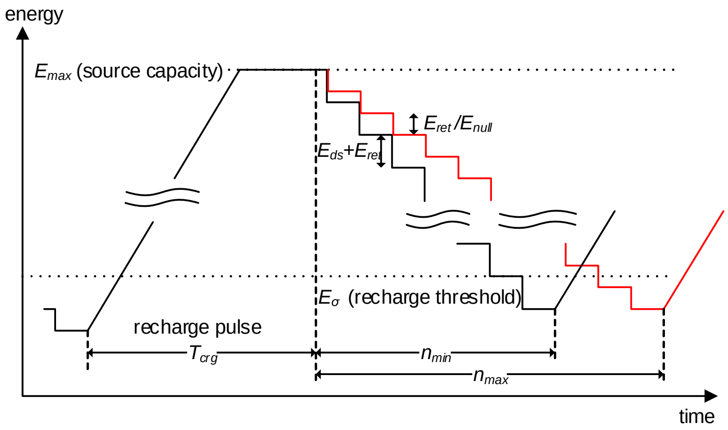


Figure 2: Details of energy consumption rate and its variation [5].

While recharging is initiated by the node with the energy below the threshold, all nodes will benefit from it and replenish their energy sources. As different nodes are located at different distance from the coordinator, the amount of energy they will receive from the recharge pulse will be proportional to the path loss LP_i between the coordinator and the node i as per Friis' transmission equation, $LP_i^r = \eta G_i^r G_t \left(\frac{\lambda_w}{4\pi r_i}\right)^2 P_{crg}$, where η is the coefficient of efficiency for RF power conversion, G_i^r and G_t are antenna gains for the receiver (sensor node) and the transmitter (coordinator), respectively, λ_w is the wavelength of the RF signal, and r_i is the distance between the receiver and transmitter [26]. The energy level of node i is, then, changed to $\min(E_{max}, E_{delta} + P_{crg}T_{crg}LP_i$.

At the end of recharging operation, normal data communication resumes, with the coordinator polling the next node in the round robin sequence. Although, a particular node i sends energy request when its energy falls bellow E_δ but all the nodes are recharged simultaneously while the coordinator sends charging pulse. Due to the different path loss values, the nodes will possess different energy levels after the recharging operation.

Table 2: Energy consumption units at polling cycle level .

Energy expenditure in a cycle	label
with no data packet	$E_{null} = E_{poll} + (m-2)E_{pa} + E_{null}$
with first transmission attempt	$E_{tr} = E_{ds} + E_{poll} + (m-2)E_{pa}/\overline{S^u_+}(z) + E_{dt}$
with packet re-transmission	$E_{ret} = E_{poll} + (m-2)E_{pa}/\overline{S^u_+}(z) + E_{dt}$

It is worth noting that the initial recharging request can be triggered by any sensor node as all nodes experience data traffic with the same probability distribution. However, after a few cycles, energy requests will always be issued by the node at the largest distance from the coordinator, as its energy will be replenished the least due to path loss [5].

The energy expenditure of a node during a time period between successive recharge pulses will fluctuate due to randomness of traffic arrivals and data packet retransmissions. As the result, the time intervals between two recharging points is a random variable. Fig. 2 shows two possible energy consumption processes of a node starting from maximum energy level E_{max}.

To analyze the impact of recharging on data performance, let us find the total number of polling cycles along with energy expenditure for the farthest node starting from a recharge point until its energy level falls below E_δ. To this end, we need the joint probability distribution of consumed energy for E-limited system along with the required time. Table 1 shows the total energy needed to transmit a DATA packet (which includes sensing, listening to a POLL packet, and actual transmission); a NULL packet (in which case sensing is not needed, and the actual transmission is presumably shorter than for a full DATA packet); and to retransmit a previously corrupted DATA packet (which also does not require new data sensing).

Let us now calculate the PGF for energy consumption along with the required number of time units for successful transmission of packets by a node in a polling cycle. Let v and w denote the energy units for transmitting or retransmitting a data packet, respectively, and let t denote the time unit. By replacing $z = (v^{\frac{1}{\sum_{i=0}^{n_{ret}} \delta i}} \cdot w \cdot t^L)$ in (10), we obtain the PGF for the combined energy expenditure and time as

$$E_{data}(w,v,t) = S_u^+(v^{\frac{1}{\sum_{i=0}^{n_{ret}} \sigma i}} \cdot w \cdot t^L) \tag{11}$$

Let Φ denote the energy unit for transmitting a NULL packet. Note that, under E-limited service policy, only one NULL packet is sent in a polling cycle. Then, the complete PGF for sending DATA and NULL packets can be expressed as

$$E_{all}(w,v,\phi,t) = E_{data}(w,v,t) + (1 - s_0^u)\phi t \tag{12}$$

where $s_0^u = 1 - \rho_{tot}$ is the probability that the node buffer is empty, and ρ_{tot} denotes the total offered load (effective utilization) of a node.

Let us consider that the farthest node Y has the energy consumption budget of Δ_Y after it is recharged. By inspecting dynamics of DATA and NULL packet transmission, we conclude that Δ_Y amount of energy consumption is finished between $n_{min} = \Delta_Y/((n_{ret}+1)E_{ret}+E_{ds})$ and $n_{max} = \Delta_Y/(E_{null})$ packet transmissions. The minimum number of packet transmissions corresponds to the scenario where a node has packets all the time and each packet needs n_{ret} attempts to be sent successfully, while the maximum number corresponds to the scenario in which the node queue is always empty and only NULL packets are sent. The probability of sending packets between these two boundaries has non zero values.

Now, we need model the joint probability distribution of energy consumption along with time duration in order to send all the combinations of DATA and NULL packets between two charging points. The PGF $EEp(w,v,\phi,t)$ considering all possibilities can be written as

$$EEp(w,v,\phi,t) = \frac{\sum\limits_{j=n_{min}}^{n_{max}} E_{all}(w,v,\phi,t)^j}{n_{max}-n_{min}+1} \tag{13}$$

As our model requires to determine total energy expenditure, we require to combine all the energy consumption units. According to Tables 1 and 2 we define translation ratios between re-transmission and NULL packet transmission energies with sensing energy as

$$nT = E_{null}/E_{ds} \tag{14}$$

$$rT = E_{ret}/E_{ds} \tag{15}$$

Further we need to use these ratios to map $w = v^{rT}$ and $\phi = v^{nT}$ in (13). However since variable v already appears with high powers, it is possible to collect the coefficients, round the powers and combine them in joint energy consumption variable u (which is equivalent to v by dimension but we have considered different variable name for clarity). The algorithm 1 shows merging the variables w,ϕ,v into variable u (which has same unit as v).

After combining all energy units, the new PGF $EE_u(u,t)$ has only one energy unit u with an integer multiple of E_{ds} in its exponent. Minimum and maximum exponent value of variable u in $EE_u(u,t)$ are expressed as min_{exp} and max_{exp}, respectively. As explained earlier, recharge is initiated by the furthest node Y from the coordinator. Node Y gains Δ_Y of energy during recharge, and when its energy level reaches E_δ due to energy consumption new recharging request is sent. We will express the energy budget in multiples of sensing energy quantum, $n_{ds} = \frac{\Delta_Y}{E_{ds}}$, so as to have it match the matches unit of variable u in the PGF $EE_u(u,t)$.

Let $u_{cef}(i)$ be the coefficient of u^i in $EE_u(u,t)$. In that case, $u_{cef}(i)$ will be a polynomial function in t. Then, the polynomial conditioned to the event that

Algorithm 1: PGF for combined energy unit and time unit.

```
Data: $EE_{all}(w, v, \phi, t)$, conversion ratios $nT$ and $rT$
Result: PGF for energy consumption representing in $E_{ds}$ quanta along
        with number of polling cycles between two consecutive charging
        points.
Find minimal $min_w$ and maximal $max_w$ exponent of variable $w$ in
  $EE_{all}(w, v, \phi, t)$ ;
for $i \leftarrow min_w$ to $max_w$ do
    Derive coefficient $w_{cof}$[i]of $w^i$ (polynomial on $v$, $\phi$ and $t$) ;
    Find minimal $min_\phi$ and maximal $max_\phi$ exponent of variable $\phi$ in
      $w_{cof}[i]$;
    for $k \leftarrow min_\phi$ to $max_\phi$ do
        Calculate coefficient $\phi w[i, k]$ of $\phi^k$ in $w_{cof}$[i] (polynomial on $v$ and
          $t$) ;
        Find minimal $min_v$ and maximal $max_v$ exponent of variable $v$ in
          $\phi w[i, k]$;
        for $j \leftarrow min_v$ to $max_v$ do
            Find coefficient $v\phi w[i, k, j]$ of $v^k$ in $\phi w$[i,k] (polynomial on $t$);
            calculate combined integer energy consumption coefficient a
              $exp[i, k, j] = \lceil i \cdot rT + k \cdot zT + j \rceil$;
            form new element of new polynomial as $v\phi w[i, k, j]u^{exp[i,k,j]}$
        Sum third level $sum_{mini}$[i,k] ← $\sum_{jj=min_\phi}^{\max_\phi} v\phi w[i, k, jj]u^{exp[i,k,j]}$;
    Sum second level $sum_{small}$[i] ← $\sum_{kk=min_\phi}^{max_\phi} sum_{mini}$[i, kk] ;
form new PGF as $EE_u(u, t) \leftarrow \sum_{ii=min_w}^{max_w} sum_{small}$[ii] ;
```

energy consumption is exceeded can be derived as

$$T_r(t) = \sum_{i=n_{ds}}^{max_{exp}} u_{cef}(i) \tag{16}$$

Since t represents the time for polling cycles, polynomial $T_r(t)$ is the conditional PGF for polling cycle numbers for which energy budget of a node is exceeded. $T_r(t)$ has to be unconditioned in order to become a complete probability distribution for the number of polling cycles.

$$T(t) = \frac{T_r(t)}{T_r(1)} \tag{17}$$

The mean number of polling cycles between two consecutive recharging appeals is, then, $\overline{T} = T'(1)$.

A node i will be in outage if it needs more energy than the available Δ_i. The probability of this event is $p_{out} = \frac{1}{T}$, which will be referred to as outage probability or even recharging probability $p_{rec} = p_o$, since the node requests a recharge before the onset of an outage.

5. Vacation model

A node is forced to undertake vacation (during which it can't perform data transmit/receive operation) when other nodes are transmitting packets or when it receives recharging pulse from the coordinator. Let us now find the probability distribution of this vacation period. We assume that time is expressed in basic slots, with POLL and NULL packets consuming one slot each while a DATA packet consumes L time slots. $S(z)$ presents the node service time: the time for sending packets in the uplink and receiving POLL messages in the downlink.

The node receives uplink packet with λ arrival rate. Without the impact of vacation, a node's offered load will be $\rho = \lambda \cdot \overline{S}$. However, a node may be required to undergo a vacation. Let $V(z)$ be the PGF of the vacation period and $\overline{V}$ be the average vacation time. During the vacation period, the node is not allowed to send data but it continues to receive traffic at the rate of λ which increases the load to

$$\rho_{tot} = \rho + \lambda\overline{V} \tag{18}$$

The total vacation period can be split into two components:

1. Cyclical vacation consists of service times of other $N-2$ nodes and its PGF is

$$V_{cyc}(z) = (S(z))^{m-2} \tag{19}$$

2. Recharging vacation is the duration of the recharge pulse, and its PGF is

$$V_{rec}(z) = P_{out}z^{T_{crg}} + (1 - P_{out}) \tag{20}$$

PGF for the total vacation time is

$$V(z) = V_{rec}(z)V_{cyc}(z) \tag{21}$$

and its mean and standard deviation can be found as

$$\overline{V} = V'(1) \tag{22}$$

$$V_{stdev} = \sqrt{}(V''(1) - (V'(1))^2 + V'(1)) \tag{23}$$

Note that total offered load depends on the mean vacation period, while the cyclical vacation depends on total offered load. Therefore, (18) and (22) need to be solved together as a system.

5.1. Queuing model

The PGF (5) contains $\Pi_M(z)$ and π_O^k, $1 \leq k \leq M-1$, values, and we need to decompose this compound PGF (i.e., a PGF that has other PGFs as elements) into simpler, separate PGFs. Note that under E-limited service, after serving a packet a node with a non-empty queue may or may not undergo a vacation, depending on how many packets have been served. Therefore, the beginning of a vacation period is a function of the number of packets served by the node. We can model the E-limited system as a $M/G/1$ system with Bernoulli scheduling, where service continues with the probability of $p_s = 1 - p_v$ (where p_v is the vacation probability). In this case, q_i can be re-written as

$$q_i = (q_0 + \pi_0)f_i + p_v \sum_{k=1}^{i} \pi_k f_{i-k} \quad i = 1, 2, \cdots \tag{24a}$$

$$\pi_i = \sum_{k=1}^{i+1} q_k a_{i-k+1} + p_s \sum_{k=1}^{i+1} \pi_k a_{i-k+1} \quad i = 0, 1, \cdots \tag{24b}$$

$$\sum_{i=0}^{\infty}(q_i + p_i) = 1 \tag{24c}$$

while the PGFs for the queue and the number of packets remaining after service can be written as

$$Q(z) = [q_0 + p_s\pi_0 + p_v\Pi(z)]V * (\lambda - \lambda z) \tag{25a}$$

$$\Pi(z) = [Q(z) + p_s\Pi(z) - (q_0 + p\pi_0)]\frac{S_u(z)}{z} \tag{25b}$$

$$Q(z) + \Pi(z) = 1 \tag{25c}$$

From (25a), (25b), we obtain separate PGFs as

$$Q(z) = \frac{(q_0 + p_s\pi_0)[(z - S_u(\lambda - \lambda z)]V^*(\lambda - \lambda z)}{z - [p_s + p_v V * (\lambda - \lambda z)]S_u(\lambda - \lambda z)} \tag{26a}$$

$$\Pi(z) = \frac{(q_0 + p_s\pi_0)[(V^*(\lambda - \lambda z) - 1]S_u(\lambda - \lambda z)}{z - [p_s + p_v V^*(\lambda - \lambda z)]S_u(\lambda - \lambda z)} \tag{26b}$$

$$q_0 + p_s\pi_0 = \frac{1 - \rho_{tot} - p_s\lambda\overline{V}}{1 - \rho_{tot} - \lambda\overline{V}} \tag{26c}$$

At this time, p_v value can easily be calculated as other terms in (26c) are known. In particular, the number of the packets in the queue is

$$Q\sigma(z) = [(1 - \sigma) + \sigma z]Q(z) \tag{27}$$

$\frac{Q\sigma(z)}{Q(1)}$ and $\frac{\Pi(z)}{\Pi(1)}$ are normalized PGF functions.

Let us now find the probability distributions of packet delay from the probability distribution of the number of packets left after a packet has been served. If $T^*(s)$ is the LST of the time during which a packet is in the system, the number of packet arrivals during that time is

$$\frac{\Pi(z)}{\Pi(1)} = T^*(\lambda - \lambda z) \tag{28}$$

Packet waiting time, the LST of which is denoted with $W^*(s)$, includes waiting for all previous packets, as well as for previous unsuccessful transmissions of that same packet; its probability distribution can be written as

$$\frac{\Pi(z)}{\Pi(1)} = W^*(\lambda - \lambda z) S_u(\lambda - \lambda z) \tag{29}$$

Finally, we can substitute $s = \lambda - \lambda z$ or equivalently $z = 1 - \frac{s}{\lambda}$ to calculate the value of $W^*(s)$. The probability distribution of packet delay becomes

$$W^*(s) = \frac{s(1 - 2\lambda\overline{S})}{s - \lambda + \lambda(G_p^*(s))^2} \cdot \frac{1 - V^*(s)}{s\overline{V}} \cdot \frac{q_0^u}{Q\sigma(1)V^*(s)} \tag{30}$$

Mean value of the queuing delay is obtained as

$$\overline{W} = \frac{\lambda(\overline{L^2} + \overline{L}^2)}{1 - 2\lambda L} \cdot \frac{\overline{L}}{1 - 2\lambda\overline{\overline{L}}} + \frac{\overline{V^2}}{2\overline{\overline{V}}} - \overline{V} + \frac{Q'(1)}{\lambda Q(1)} \tag{31}$$

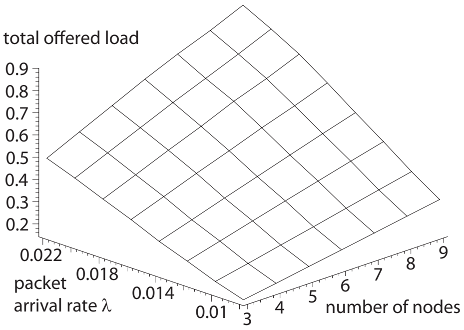
6. Performance results

We have assumed that individual sensor nodes are randomly located within a circle of 10 metre radius, with the coordinator in its centre. Network size N is varied between 3 to 9 nodes including the coordinator. We have assumed free space loss (i.e., path loss coefficient was set to 2). The bit error rate was fixed at $ER_b = 10^{-5}$. For E-limited service policy, a sensor node was allowed to transmit up to $M = 2$ packets, while the number of retransmissions for a corrupted packet was $n_{ret} = 3$.

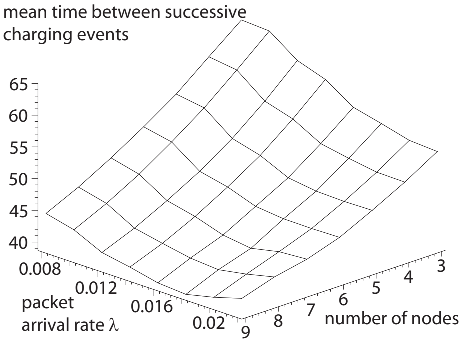
The mean packet arrival rate per node λ was varied between 0.008 and 0.022 in 0.002 step increments. In the downlink, the network has only POLL packets. Packet transmission time is constant and equal to one time slot while the duration of the charging pulse duration was 1000 slots. Using these values, we have solved the system of equations described above using Maple 16 from Maplesoft, Inc. [27].

Fig. 3(a) presents total offered load, as defined by (18). As can be seen, the offered load increases with both network size N and traffic arrival rate λ. The later relationship is self-explanatory, as higher packet arrival rate will obviously lead to higher load. On the other hand, more nodes in the network mean that a given node is given less time and, consequently, less chance to send data. Moreover, it undergoes longer vacation period due to longer cyclical vacation component, as per (19). At the same time, new packets keep coming during the vacation period. As the result, the effective offered load per node increases.

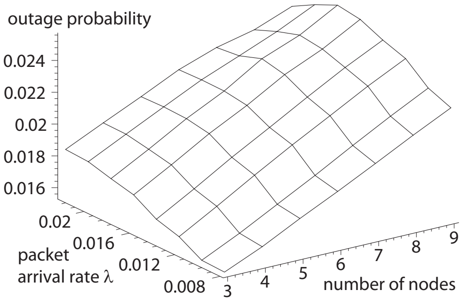
Mean recharging period is shown in Fig. 3(b). At first, it may look counter-intuitive to have the mean recharging period decrease with the number of nodes as each node actually receives a smaller fraction of active time. Note that a larger network translates into a longer vacation time for an individual sensor node. Larger network size also leads to faster depletion of energy since all the nodes have to listen to all POLL messages, both their own and other nodes' ones. On account of this, mean recharging period is inversely proportional to network size.



(a) Total offered load.



(b) Re-charging period (in piconet cycles).



(c) Outage probability.

Figure 3: Descriptors of load and re-charging.

At the same time, recharging period decreases at higher traffic intensity as more energy is required to send a DATA packet compared to a NULL packet. The recharging probability shown in Fig. 3(c) is the inverse of recharging period, and its behaviour is exactly opposite to that of the recharging period.

Descriptors of vacation time are shown in Fig. 4. Mean vacation time increases gradually with increasing traffic intensity, since a node consumes energy at a faster rate. On account of higher energy consumption, recharging probability also increases – i.e., more frequent recharging vacation V_{rec} occurs. On the other hand, larger network size N lead to longer cyclical vacation V_{cyc} which is an exponential function of the network size. In turn, longer V_{cyc} increases the total vacation time.

Standard deviation of mean vacation time exhibits similar behavior but at a somewhat reduced rate, on account of the fact that higher arrival rates decrease the number of NULL packets. Standard deviation also increases more rapidly with the number of nodes as this injects more variability in the transmission process. For this reason, the coefficient of variation of the vacation time, $V_{stdev}/\overline{V}$, decreases with higher packet arrival rate but grows with increasing network size. It is worth noting that the coefficient of variation of the vacation time is above one, i.e., vacation time exhibits hyper-exponential behavior.

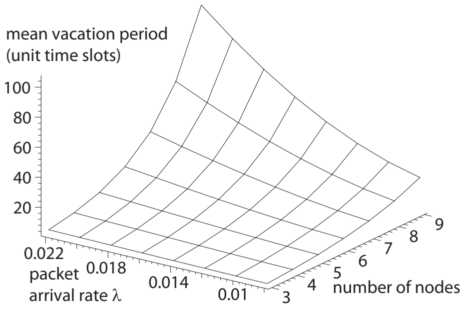
Ensembles of probability distribution of polling cycle periods between two successive recharging pulses are shown in Fig. 5(a) for the network of size $N = 4$. Both the boundary limits ('lower' and 'upper') of distribution space have smaller values at higher traffic intensity. Namely, higher traffic arrival rate increases packet retransmission probability, and packet retransmission requires less power consumption. As a result 'lower boundary' starts from smaller value range and 'upper boundary' ends up with a smaller value, compared to the analogous curve obtained at a lower traffic arrival rate.

Fig. 5(b) is shifted to the left (i.e., towards lower values) for larger network size, compared to the diagrams in Fig. 5(a). Namely, when the network size increases, nodes consume more power as they need to listen to a larger number of POLL packets targeting other nodes in the network.

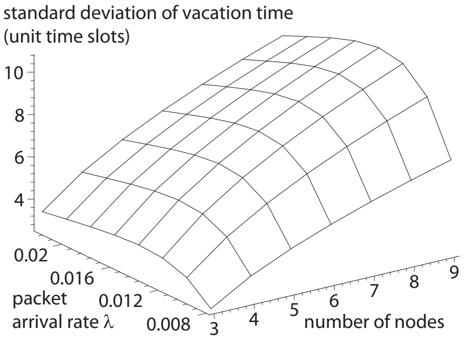
Finally, Fig. 6 shows the mean packet waiting time. Initially, this waiting time increases slowly with the packet arrival rate λ and network size N. However, at larger values of N and/or λ, a steeper increment in mean packet waiting time is observed due to the simultaneous impact of high traffic intensity and large vacation period. Note that this waiting period includes the recharging vacation, i.e., the component of vacation time due to the recharging pulse.

7. Conclusion

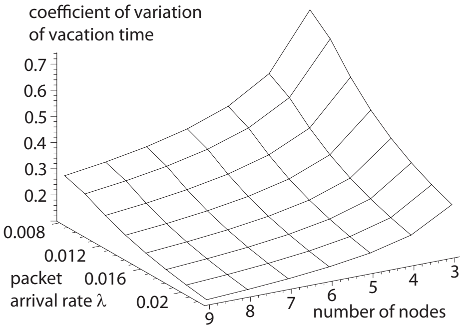
In this paper, we have proposed and evaluated a simple MAC protocol for wireless sensor networks with in-band RF recharging of node energy sources. The protocol is based on polling, and uses a non-gated E-limited service policy. We have constructed a probabilistic model of the communications and recharging processes which allowed us to calculate mean time between recharges, as



(a) Mean value.

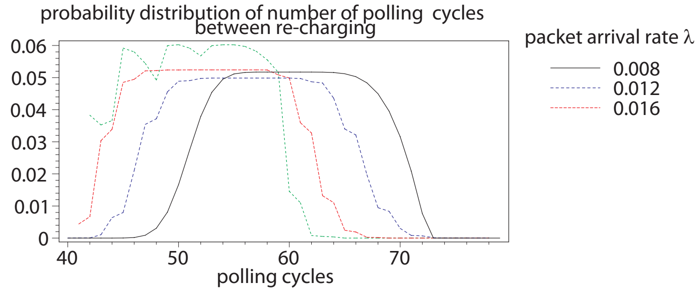


(b) Standard deviation.

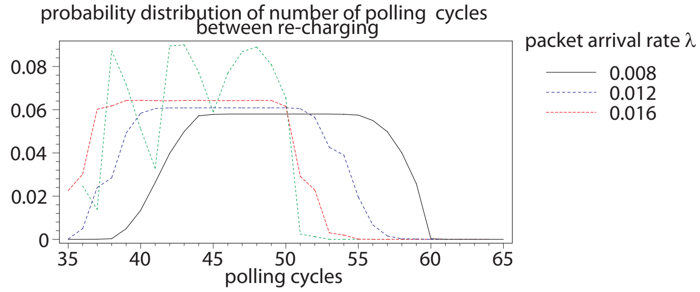


(c) Coefficient of variation.

Figure 4: Descriptors of vacation time.



(a) Ensemble of cycle distributions for $\lambda = 0.008 \cdots 0.020$ when $N = 4$.



(b) Ensemble of cycle distributions for $\lambda = 0.008 \cdots 0.020$ when $N = 7$.

Figure 5: Probability distributions of number of polling cycles between two successive re-charging for different network size.

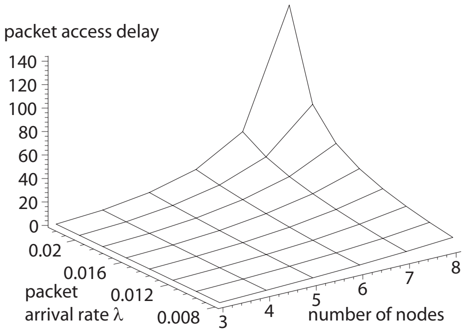


Figure 6: Descriptor of waiting time.

well as a queuing model for nodes in the network that allowed us to calculate the parameters of the packet waiting time. Our analysis shows that the performance of the proposed MAC protocol is mostly affected by the interruptions in data communications caused by RF recharging. Therefore, the parameters of the recharging pulses have to be carefully chosen in order to maintain the performance of the network within acceptable limits.

Our future work will focus on fine tuning of network parameters to optimize performance, in particular the choice of network parameters like recharging durations and power intensity values to find the values that lead to lowest packet waiting times and minimal per bit power consumption in transferring data. We will also investigate the possibility of reducing the number of POLL packets in order to reduce the power consumption of the network, as well as the modifications to the MAC protocol that will improve the network lifetime through individual and/or joint scheduling of node transmissions. This approach appears promising in particular if packet arrival rates at individual nodes differ from one node to another.

References

[1] R. J. Vullers, R. Schaijk, H. J. Visser, J. Penders, C. V. Hoof, Energy harvesting for autonomous wireless sensor networks, IEEE Solid-State Circuits Magazine 2 (2) (2010) 29–38.

[2] L. Xie, Y. Shi, Y. T. Hou, W. Lou, H. D. Sherali, S. F. Midkiff, On renewable sensor networks with wireless energy transfer: The multi-node case, 9th Ann. IEEE Comm. Soc. Conf. Sensor, Mesh and Ad Hoc Communications and Networks (SECON 2012), Seoul, Korea, 2012, pp. 10–18.

[3] L. Xie, Y. Shi, Y. T. Hou, H. D. Sherali, Making sensor networks immortal: An energy-renewal approach with wireless power transfer, IEEE/ACM Transactions on Networking 20 (6) (2012) 1748–1761.

[4] M. Naderi, P. Nintanavongsa, K. Chowdhury, RF-MAC: A medium access control protocol for re-chargeable sensor networks powered by wireless energy harvesting, IEEE Trans. Wireless Communications, 13 (7) (2014) 3926–3937.

[5] J. Mišić, M. S. Khan, V. B. Mišić, Performance of simple polling MAC with wireless re-charging in the presence of noise, 17th ACM Int. Conf. Modeling, analysis and simulation of wireless and mobile systems, Montreal, Canada, 2014, pp. 137–143.

[6] A. Capone, R. Kapoor, M. Gerla, Efficient polling schemes for Bluetooth picocells, IEEE Int. Conf. Communications (ICC 2001), Vol. 7, Helsinki, Finland, 2001, pp. 1990–1994.

[7] H. Levy, M. Sidi, O. J. Boxma, Dominance relations in polling systems, Queueing Systems Theory and Applications 6 (2) (1990) 155–171.

[8] H. Takagi, Queueing Analysis, Vol. 1: Vacation and Priority Systems, North-Holland, Amsterdam, The Netherlands, 1991.

[9] H. Takagi, Queuing analysis of polling models, ACM Computing Surveys (CSUR) 20 (1) (1988) 5–28.

[10] J. Lei, R. Yates, L. Greenstein, A generic model for optimizing single-hop transmission policy of replenishable sensors, IEEE Trans. Wireless Communications 8 (2) (2009) 547–551.

[11] J.-D. Park, H. Lee, M. Bond, Uninterrupted thermoelectric energy harvesting using temperature-sensor-based maximum power point tracking system, Energy Conversion and Management 86 (2014) 233–240.

[12] C. K. Ho, R. Zhang, Optimal energy allocation for wireless communications with energy harvesting constraints, IEEE Trans. Signal Processing 60 (9) (2012) 4808–4818.

[13] M. Gorlatova, A. Wallwater, G. Zussman, Networking low-power energy harvesting devices: Measurements and algorithms, IEEE Trans. Mobile Computing 12 (9) (2013) 1853–1865.

[14] M. Y. Naderi, K. R. Chowdhury, S. Basagni, W. Heinzelman, S. De, S. Jana, Experimental study of concurrent data and wireless energy transfer for sensor networks, IEEE Global Telecommunications Conf. (GlobeCom 2014), Austin, TX, 2014, pp. 2543–2549.

[15] W. Yue, Q. Sun, S. Jin, Performance analysis of sensor nodes in a wsn with sleep/wakeup protocol, Int. Symp. Operations Research and its Applications, Chengdu-Jiuzhaigou, China, 2010, pp. 370–377.

[16] V. Joseph, V. Sharma, U. Mukherji, Optimal sleep-wake policies for an energy harvesting sensor node, IEEE. Int. Conf. Communications (ICC 2009), Dresden, Germany, 2009, pp. 1–6.

[17] W. Ye, J. Heidemann, D. Estrin, An energy-efficient MAC protocol for wireless sensor networks, INFOCOM 2002, 2002, pp. 1567–1576 vol.3.

[18] N. Jain, S. Das, A. Nasipuri, A multichannel CSMA MAC protocol with receiver-based channel selection for multihop wireless networks, 10th Int. Conf. Computer Communications and Networks, 2001, pp. 432–439.

[19] A. Willig, Polling-based MAC protocols for improving real-time performance in a wireless profibus, IEEE Trans. on Industrial Electronics 50 (4) (2003) 806–817.

[20] Z. A. Eu, H.-P. Tan, W. K. Seah, Design and performance analysis of MAC schemes for wireless sensor networks powered by ambient energy harvesting, Ad Hoc Networks 9 (3) (2011) 300–323.

[21] H. Levy, M. Sidi, Polling systems: applications, modeling, and optimization, IEEE Trans. Communications 38 (10) (1990) 1750–1760.

[22] F. Iannello, O. Simeone, U. Spagnolini, Medium access control protocols for wireless sensor networks with energy harvesting, IEEE Trans. Communications 60 (5) (2012) 1381–1389.

[23] J. Hao, B. Zhang, H. T. Mouftah, Routing protocols for duty cycled wireless sensor networks: A survey, IEEE Communications Magazine 50 (12) (2012) 116–123.

[24] J. Hao, Z. Yao, K. Huang, B. Zhang, C. Li, An energy-efficient routing protocol with controllable expected delay in duty-cycled wireless sensor networks, IEEE Int. Conf. Communications (ICC 2013), 2013, pp. 6215–6219.

[25] J. Mišić, V. B. Mišić, Performance Modeling and Analysis of Bluetooth Networks: Network Formation, Polling, Scheduling, and Traffic Control, CRC Press, Boca Raton, FL, 2005.

[26] H. T. Friis, A note on a simple transmission formula, Proc. IRE 34 (5) (1946) 254–256.

[27] Maplesoft, Inc., Maple 16, Waterloo, ON, Canada, 2012.