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Modeling of RF Recharging in a Wireless Sensor Network with Coordinated Node Sleep

Mohammad Shahnoor Islam Khan, Jelena Mišić, and Vojislav B. Mišić
Department of Computer Science, Ryerson University, Toronto, ON, Canada M5B 2K3
Email: {m329khan, vmisic}@ryerson.ca; jmisic@scs.ryerson.ca

Abstract —Radio-Frequency (RF) recharging of sensor nodes is a promising way to minimize maintenance and prolong the operational life of wireless sensor networks. In this paper, we present a simple MAC protocol based on polling that includes provisions for on-demand recharging using the same RF band as normal data communications, and we develop a probabilistic performance model to evaluate the impact of the recharging process on data communications under a range of values for bit error rate and traffic load.

Index Terms—Wireless sensor networks, Radio-Frequency (RF) recharging, MAC protocol, coordinated sleep, performance evaluation

I. INTRODUCTION

Periodic recharging of sensor nodes is a promising way to minimize maintenance and prolong the operational life of Wireless Sensor Networks (WSNs) [1]. Recharging can use energy from the environment in a process commonly referred to as 'energy harvesting' [2] or it can be performed via high energy pulses from the network master or base station [3]. The former approach does not require an external power source with appropriate capacity, but the latter offers greater reliability and controllability as it does not depend on the availability of sufficient energy in the environment to replenish the nodes' power source when needed [4], [5].

Two main issues determine the performance of RF recharging. First, it may take place periodically, in regular intervals determined beforehand, or on-demand, i.e., when a sensor node reports that its available energy has dropped below a predefined threshold value. The former approach is simpler, but the frequency of recharging may be difficult to adjust: doing it too frequently may be inefficient, while doing it too seldom can lead to death of some nodes due to depletion of their power source.

Second, RF recharging and regular data communications can use the same RF band or two different RF bands. The use of a single RF band is attractive on account of hardware simplicity, but careful tailoring of the protocol and detailed analysis of its performance are needed to assess the impact of the interplay between recharging and data communications. On the other hand, using different bands allows uninterrupted data communications throughout recharging [6] but requires two antennas and two RF transceivers [3].

Performance analysis of MAC protocols along with recharging has focused on CSMA approach and its many variants [1] although ALOHA-like protocols with continuous energy harvesting have been developed and analyzed as well [7]. General treatment of energy replenishment including battery replacement or conventional recharging was presented in [8]. A MAC protocol that explicitly requests energy replenishment through a subsequent RF pulse has been studied in [3]. Performance analysis for MAC protocol has been investigated for uninterrupted transmission in which recharging is done through a high power RF pulse in separate band [6].

In this paper, we propose a simple MAC protocol in which the master sequentially polls ordinary sensor nodes and performs in-band recharging when explicitly requested by a sensor node. Polling is done in a round robin fashion and each node is allowed to send a single data packet upon polling (i.e., a 1-limited service policy is used). Furthermore, the nodes sleep between successive polling events in order to conserve energy. The performance of data communications in this setup, in particular the interplay between recharging, sleep, and data communications, are evaluated through a detailed probabilistic model.

The paper is organized as follows: the operation of the proposed MAC protocol, including the RF recharging process, is described in Section II. Probabilistic model for energy depletion of a node and probability distribution of the time period between two consecutive charging points are discussed in Section III, followed by the model for the time duration between consecutive medium accesses by the same node in Section IV. Performance of the proposed MAC protocol is analyzed in Section V. Finally, Section VI concludes the paper and highlights some promising avenues for future research.

II. THE OPERATION OF THE POLLING MAC

Let us consider a sensor network consisting of N nodes as shown in Fig. 1. A special node, hereafter referred to

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Corresponding author email: vmisic@ryerson.ca.

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as the master, is equipped with a power source that can emit RF recharging pulses upon request. The remaining $N-1$ nodes are equipped with sensor units and RF transceivers capable of data communications as well as recharging.

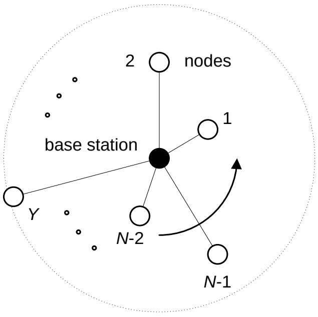


Fig. 1. Logical presentation of the network.

We assume that the master node sequentially sends POLL messages, each of which targets a specific node [9]. All nodes must listen to the header part of each POLL message but only the addressed node responds: it sends back a single DATA or NULL packet, depending on whether it has data to send or not. After serving all $N-1$ nodes sequentially, the master instructs all nodes to go to sleep for a fixed duration of T_{sleep} cycles by broadcasting a special POLL message. The time elapsed between two consecutive visits to any node in the target network will be referred to as a polling cycle; it consists of $N-1$ POLL and DATA/NULL packets, followed by a sleep interval, as shown in Fig. 2.

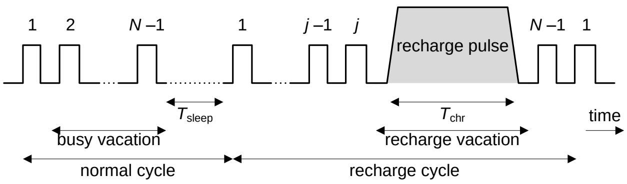


Fig. 2. Format of the polling cycle in recharging process.

A DATA packet reception may fail due to noise and interference with the probability $p_{err} = 1-(1-p_{ber})^n$, where p_{ber} stands for bit error rate (BER) and n is the total number of bits in the packet including headers. Packets that were successfully received are acknowledged in the POLL packet sent by the master node in the next polling cycle; if the reception was not successful, the node will resend the packet up to n_{ret} times before dropping the packet in question.

Initially, all the nodes are charged to the maximum energy level E_{max}. Nodes consume energy for data sensing and processing, listening to POLL packets, and transmitting DATA and NULL packets, as per rates listed in Table I.

TABLE I: ENERGY CONSUMPTION OF A NODE

Basic Tasks	
sensing a DATA packet	E_s
listening a POLL packet	E_{poll}
listening to POLL packet	E_h
transmitting a DATA packet	E_{td}
transmitting a NULL packet	E_{tn}
High Level Tasks	
NULL packet	$E_n = E_{poll} + E_{tn} + 2(N-2)E_h$
DATA packet transmission	$E_t = E_s + E_{poll} + E_{td} + (N-2)E_h$
DATA packet retransmission	$E_{rt} = E_{poll} + E_{td} + (N-2)E_h$

When the energy of a node goes below a predefined threshold value E_{thr} – a condition referred to as energy outage – the node waits until polled and sends a recharge request to the master node by enabling the appropriate bit in the header field of its next DATA or NULL packet. The energy threshold should be sufficiently high to allow the current DATA packet to be transmitted in up to n_{ret} retransmission attempts:

$$E_{thr}(N) \geq (E_t + E_{poll} + (N\text{-}2)E_h)(n_{ret}+1) \qquad (1)$$

Upon receiving a recharge request, the master node broadcasts a special POLL packet informing all the nodes about the pending recharge pulse. This pulse is sent immediately after the announcement; its power is P_{chr} and its duration is T_{chr} cycles. According to Friis' transmission equation, RF power received by node j is $P_{(r,j)} = \eta G_t G_r \left(\frac{\lambda_{\mathrm{RF}}}{4\pi R_j^2}\right) P_{chr}$, where R_j is the distance from the master, η is the coefficient of efficiency for RF power conversion, G_t and G_r are antenna gains for the transmitter and receiver, respectively, and λ_{RF} is the RF wavelength. For simplicity, we assume free space loss, so the path loss coefficient is set to 2. Maximum possible energy gain for node j is $\Delta E_j = P_{(r,j)} T_{chr}$, but the actual node energy level after recharge will be $\min(E_{max}, E_{thr} + \Delta E_j)$, as the rated battery capacity E_{max} can't be exceeded. The process of charging and discharging of node battery through regular operation is schematically shown in Fig. 3.

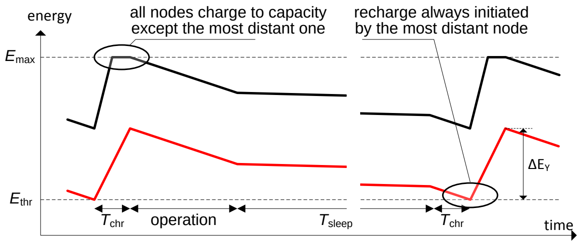


Fig. 3. Energy expenditure and recharging periods.

As the same RF band is employed for both recharging process and data communication, the latter will be interrupted by the former. For clarity, a polling cycle interrupted by the recharge pulse will be referred to as a recharge polling cycle.

As noted above, noise and interference can damage a DATA packet transmission and cause up to n_{ret} retransmissions (which may still fail). Unsuccessful transmission of a packet with recharge request may cause the node to exhaust its energy in which case it is effectively lost for all subsequent network activities.

III. MODELING THE RECHARGING PROCESS

Energy expenditure of a given node will differ from one polling cycle to another due to unpredictability of packet arrivals and packet retransmissions, although the mean time to consume the energy increment $E_{max} - E_{thr}$ will be same for each node. Moreover, the node at the greatest distance from the master (node Y) will receive the least amount of energy at the time of recharging. Initially, the recharge request may come from any node; but in the long run, node Y will always be the one to initiate the recharge process and, consequently, determine the time period between two consecutive recharge requests (and ensuing recharge pulses). This time period is a random variable and its probability distribution needs to be derived. Focusing on energy expenditure of the most distant node, we may calculate the time interval between two recharge requests in units of polling cycles. Hence, we need to find the joint probability distribution of the number of polling cycles and energy consumed in each polling cycle.

The Probability Generating Function (PGF) of the energy and time cycles needed for successful transmission of a DATA packet is

$$E_d(s,r,t) = \frac{srt\sum_{k=0}^{n_{ret}}(rt)^k p_{err}^k}{\sum_{k=0}^{n_{ret}} p_{err}^k} \tag{2}$$

where variables s and$r$ stand for sensing and transmitting a DATA packet, respectively, and parameter t is used for counting polling cycles. Note that data sensing is required in the first attempt to transmit data but not in subsequent retransmission attempts, which is why the variable s is not considered in the retransmission part of (2).

However, a DATA packet is sent only when the node has data to send, otherwise the node sends a NULL packet. The probability of these events is ρ_{tot} and $1 - \rho_{\text{tot}}$, respectively, where ρ_{tot} is the total offered load. Therefore, we use an additional variable, ϕ, for tracking power consumption during NULL packet cycles, which gives the updated PGF as

$$E_{d/n}(s,r,\phi,t) = \rho_{tot}E_d(s,r,t) + (1-\rho_{tot})\phi t \tag{3}$$

After the completion of packet transmissions from all nodes, the master node broadcasts a POLL message which instructs each node to sleep for T_{sleep} cycles. According to the data for a typical Bluetooth LE chipset [10], power consumption during sleep is negligibly low compared to the power consumption during other activities shown in Table I.

In the presence of transmission errors, PGF for the sleeping time upon a successful transmission of a packet is

$$E_{sleep}(s,r,\phi,t) = (1-p_{err})st^{T_{sleep}}\sum_{i=0}^{n_{ret}}(p_{per}st^{T_{sleep}})^i \tag{4}$$

However, the probability of occurrence of this sleep time is $\frac{1}{2(\mathrm{N}-1)}$, and the PGF for energy consumption has to be normalized accordingly to

$$E_s(s,r,\phi,t) = \frac{E_{sleep}(s,r,\phi,t)}{2(N-1)} + \left(1 - \frac{1}{2(N-1)}\right) \tag{5}$$

As retransmission is not required for sending NULL packets, the PGF for sleeping time when sending NULL packets is

$$E_{s/n}(s,r,\phi,t) = \frac{st^{T_{sleep}}}{2(N-1)} + \left(1 - \frac{1}{2(N-1)}\right) \tag{6}$$

Total PGF for successful transmission of a DATA or NULL packet, including the sleeping period, then becomes

$$E_{total}(s,r,\phi,t) = \rho_{tot}Ep(s,r,t)E_s(s,r,\phi,t) + (1-\rho_{tot})\phi t E_{s/n}(s,r,\phi,t) \tag{7}$$

To compute the range of polling cycles between consecutive recharge points, we need to find the maximum and minimum number of transmitted packets. Maximum number of packet transmissions q_{max} occurs when there is no data to send at all during the entire polling cycle, hence only NULL packets are sent. Conversely, the number of packet transmissions is at its minimum q_{min} when the node has fresh DATA packets in each cycle and each of these is retransmitted n_{ret} times. These numbers can be calculated as

$$\begin{aligned} q_{max} &= \left\lceil \frac{E_{thr}+\Delta_Y}{E_n + \frac{s}{2(N-1)}} \right\rceil \\ q_{min} &= \left\lfloor \frac{E_{thr}+\Delta_Y}{(n_{ret}+1)E_r + E_{sd} + s\frac{(n_{ret}+1)}{2(N-1)}} \right\rfloor \end{aligned} \tag{8}$$

and the PGF for the number of packet transmissions sustained by the energy increment for the most distant node Y is

$$E_{S_p}(r,s,\phi,t) = \frac{\sum_{k=q_{min}}^{q_{max}} E_{total}(r,s,\phi,t)^k}{q_{max} - q_{min} + 1} \tag{9}$$

To find the total energy consumed in different time slots we need to convert different energy units to a single one – in this case the energy for sensing E_{s}, which is the smallest of basic units listed in Table 1. Conversion is accomplished by defining the ratios of energy for DATA packet retransmission and NULL packet transmission to the data sensing energy unit as follows:

$$\begin{aligned} r_{rt} &= E_{rt}/E_s \\ r_\phi &= E_n/E_s \end{aligned} \tag{10}$$

After mapping $r = z^{\mathrm{r_{rt}}}$ and $\phi = z^{\mathrm{r_\phi}}$ in (9) to use the ratios defined above, the updated PGF will use a single energy unit v only:

$$E_{S_v}(v,t) = E_{S_p}(r,s,\phi,t) \qquad (11)$$

and the new PGF $E_{S_v}(v,t)$ will have only two variables: the exponent of variable v depicts the total energy used as multiples of s units, and the exponent of variable t represents the total number of time slots required to consume this energy.

The resulting PGF can be represented as

$$E_{S_v}(v,t) = \sum_{k=0}^{v^{(max)}} f_k(t) v^k \qquad (12)$$

where the coefficients $f_k(t)$ are polynomials in t only. Let $v^{min} = \frac{\Delta E_Y}{E_S}$ be the minimum number of energy consumption unit(s) that causes the energy level to fall below E_{thr}, and let the maximum exponent $v^{(\mathrm{max})}$ of energy unit v in $E_{S_v}(v,t)$ correspond to the maximum energy consumption of a node during a single recharge cycle. The PGF for this scenario is

$$T_{(out/p,Y)}(t) = \sum_{k=v^{min}}^{v^{(max)}} f_k(t) \qquad (13)$$

As $T_{(out/p,Y)}(t)$ contains only a part of sample space, it has to be normalized to become a proper PGF:

$$T_{(out,Y)}(t) = \frac{T_{(out/p,Y)}(t)}{T_{(out/p,Y)}(1)} \qquad (14)$$

from which we can get the average number of polling cycles between two consecutive recharging requests sent from the same node as

$$\overline{T_{(out,Y)}} = T'_{(out,Y)}(t)|_{t=1} \qquad (15)$$

Since a node can only send a single packet in any given polling cycle (i.e., the service discipline is 1-limited), the outage probability can be calculated as$p_{out} = \frac{1}{\overline{T_{(out,Y)}}}$.

IV. VACATION AND QUEUING MODELS

Assuming that the data packet arrivals follow a Poisson process with the arrival rate λ, the MAC protocol described above can be modelled as a $M/G/1$ gated limited system with vacations [11]. We assume that POLL, DATA, and NULL packets take one unit time slot each. Let the PGFs for uplink DATA/NULL packet and downlink POLL packets be defined as $G_u(z) = z$ and $G_d(z) = z$, respectively. Mean service time of a node in both directions (uplink and downlink) is obtained as $G_u(1) + G_d(1)$, while the offered load of a node is $\rho = \lambda(G_u'(z)|_{z=1} + G_d'(z)|_{z=1})$.

A. Vacation Model

However, the actual offered load is $\rho_s = \rho + \lambda\overline{V}$ due to the presence of vacations, $\overline{V}$ being the mean vacation period. Furthermore, the use of packet retransmissions to achieve reliability transforms a single packet transmission into a burst with the PGF of

$$G_b(z) = \frac{z\sum_{k=0}^{n_{ret}} z^k p_{err}^k}{\sum_{k=0}^{n_{ret}} p_{err}^k} \qquad (16)$$

and mean burst length of $\overline{G_b(z)} = G_{b'}(z)|_{z=1}$.

Therefore, the total scaled offered load becomes

$$\rho_{tot} = (\rho + \lambda\overline{V})\overline{G_b(z)} \qquad (17)$$

In our model, vacation has two parts. The cyclical or periodic vacation occurs in each polling cycle due to the activity of other nodes and its duration is the sum of service times of the other $N-2$ ordinary nodes, which results in the PGF of

$$V_{cyc}(z) = (\rho_{tot} G_u(z) z + (1-\rho_{tot}) z^2)^{N-2} \qquad (18)$$

Another type of vacation is caused by the in-band recharge pulse during which there can be no data communication. The recharging vacation takes place when a node goes in energy outage; its probability of occurrence is p_{out} and it lasts for fixed T_{chr} time cycles. The PGF for the duration of this vacation is

$$V_{rec}(z) = p_{out} z^{T_{chr}} + (1-p_{out}) \qquad (19)$$

The PGF of combined vacation periods can be obtained as

$$V(z) = V_{cyc}(z) V_{crg}(z) \qquad (20)$$

Mean and standard deviation of the vacation period are

$$\begin{aligned} \overline{V} &= V'(z)|_{z=1} \\ V_{sd} &= \sqrt{V''(z)|_{z=1} + V'(z)|_{z=1} - (V'(z)|_{z=1})^2} \end{aligned} \qquad (21)$$

Note that the mean vacation period and total offered load are inter-dependent, which means that (17) and (21) have to be solved together as a system.

B. Queueing Model

We assume that packets are served according to a FIFO discipline. We can model 1-limited $M/G/1$ queues by considering a packet followed by a vacation as a virtual packet with the PGF of $B_v(z) = G_u(z) G_d(z) V(z)$ (when there is no transmission error). In this case, the PGF for the number of packets remaining in the queue upon a packet departure is

$$\begin{aligned} \mathit{\Pi}(z) &= \frac{(1-\rho_{tot})(1-V^*(\lambda-\lambda z))B_v^*(\lambda-\lambda z)}{\lambda\overline{V}(B_v^*(\lambda-\lambda z)-z)} \\ &= (1-\lambda(\overline{G_u(z)} + \overline{G_d(z)} + \overline{V}))(1-V^*(\lambda-\lambda z)) \quad (22) \\ &\cdot \frac{G_u^*(\lambda-\lambda z) G_d^*(\lambda-\lambda z) V^*(\lambda-\lambda z)}{\lambda\overline{V}(G_u^*(\lambda-\lambda z) G_d^*(\lambda-\lambda z) V^*(\lambda-\lambda z)-z)} \end{aligned}$$

For computational simplicity, we assume that the queue buffer is of infinite size; the margin of error due to this approximation is negligible in case of small to moderate load. Taking into account that the use of packet retransmissions to achieve reliability effectively transforms a single packet transmission into a burst, the size of which is given by (16), the PGF for the number of packets in the queue upon a packet departure becomes

$$\Pi_b(z) = \frac{(1-\rho_{tot})(1-V^*(\lambda-\lambda z)) G_b(B_v^*(\lambda-\lambda z))}{\lambda\overline{V} G_b(B_v^*(\lambda-\lambda z)-z)} \qquad (23)$$

where $B_v^*(\lambda-\lambda z)$ from (22) is replaced by the burst service time $G_b(B_v^*(\lambda-\lambda z))$.

Probability distribution of the number of packets in the queue after the departure of a packet can be transformed into the probability distribution of packet delay. A single packet stays in the system during a time interval equal to the sum of the queueing time and service time. The number of packet arrivals during that time will be equal to the number of packets remaining in the queue after the departure of that packet. Thus, if the response time for a packet is $T_r(z)$,(23) can be rewritten as

$$\Pi_{\mathrm{b}}(z) = T_r^*(\lambda - \lambda z) \tag{24}$$

Waiting time $W(\mathrm{z})$ includes the waiting for all earlier packets, as well as the time required for unsuccessful transmissions of the target packet, and its probability distribution is

$$\Pi_b(z) = W^*(\lambda - \lambda z) G_u^*(\lambda - \lambda z) \tag{25}$$

By substituting $\mathrm{s} = \lambda - \lambda\mathrm{z}$ in the above expression, we can express the probability distribution of packet waiting time as

$$\begin{aligned} W^*(s) &= \frac{1}{G_u^*(s)} \Pi_b(1 - s/\lambda) \\ &= \frac{(1-\rho_{tot})(1-V^*(s)) G_b(G_u^*(s) G_d^*(s) V^*(s))}{\lambda \overline{V}(G_b(G_u^*(s) G_d^*(s) V^*(s)) - 1 + s/\lambda) G_u^*(s)} \\ &= \frac{(1-\rho_{tot})(1-V^*(s)) G_b(G_u^*(s) G_d^*(s) V^*(s))}{G_u^*(s) \overline{V}(\lambda G_b(G_u^*(s) G_d^*(s) V^*(s)) - \lambda + s)} \end{aligned} \tag{26}$$

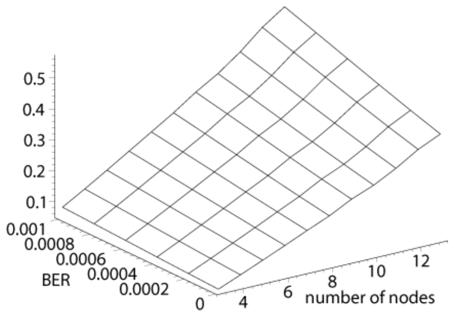
The k^{th} moment of packet delay can be calculated as the k^{th} derivative of LST $\mathrm{W}^*(\mathrm{s})$, $(-1)^{\mathrm{k}} \mathrm{W}^{*(\mathrm{k})}(0)$. Mean waiting time and standard deviation can be calculated as

$$\begin{aligned} \overline{W} &= -W^{*(1)}(s)|_{s=0} \\ W_{sd} &= \sqrt{W^{*(2)}(s)|_{s=0} - (W^{*(1)}(s)|_{s=0})^2} \end{aligned} \tag{27}$$

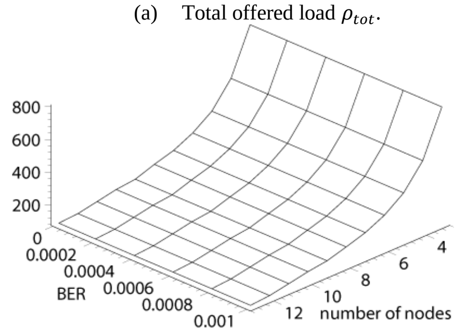
V. PERFORMANCE EVALUATION

To assess the performance of the proposed MAC protocol, we solved the system of equations outlined above using Maple 16 from Maplesoft, Inc. [12]. We have considered networks with $N = 3$ to 13 nodes located within a 1 to 10 meter distance from the master node. Packet arrival rate was $\lambda = 0.011$ packets per node per time unit, which was set to $100\mu\mathrm{s}$. All packets (POLL, DATA, and NULL) are assumed to take one time unit. DATA packets have 50 bytes (400 bits) while the bit error rate was varied from 10^{-5} to 10^{-3}. Maximum number of packet retransmissions n_{ret} was three; unsuccessful packets were dropped afterwards. Recharging period T_{chr} has a fixed duration of 1000 time cycles while the recharging power was 1W. Mandatory sleeping period T_{sleep} of 50 cycles was imposed at the end of each polling cycle. Numerical values for energy units listed in Table I were taken from the datasheet for Texas Instruments' CC2540 chipset [13].

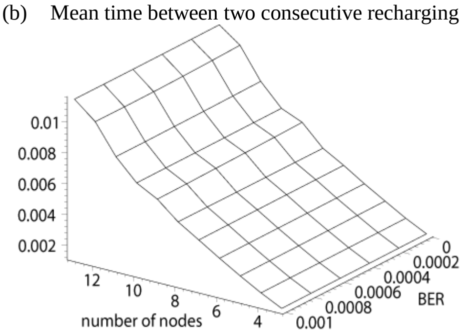
Our first experiment involves variable number of nodes and bit error rate. Total offered load ρ_{tot} is shown in Fig. 4(a): it depends very much on the number of nodes (i.e., network size) but only slightly on the bit error rate. Apart from the sheer increase in the number of packets, the number of nodes also indirectly affects the offered load through the duration of cyclic vacation which is an exponential function of the network size $N - 2$, as per (18). Longer cyclic vacation results in more packet arrivals so any given node has proportionally less time to send data which eventually intensifies the offered load. On the other hand, increasing bit error rate causes a higher retransmission rate which subsequently increases the load, but the dependency is not as pronounced and the rate of increase is sub-exponential.



(a) Total offered load ρ_{tot}.



(b) Mean time between two consecutive recharging events.

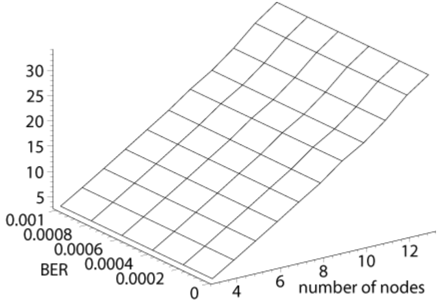


(c) Outage probability.

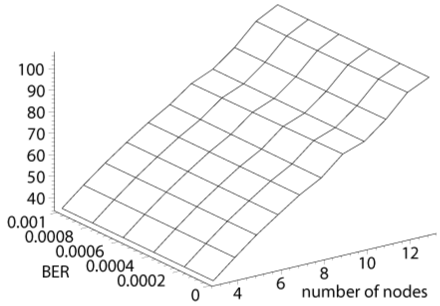
Fig. 4. Representations of total offered load and recharging operation.

Mean number of cycles between consecutive recharging events is shown in Fig. 4(b). Again, the number of nodes is the major determining factor for these variables. With more nodes, any given node needs to listen to more POLL packet headers and, thus, consumes more energy. As the result, the mean period between successive recharge points is inversely proportional to the network size N. By the same token, higher bit error rate causes more retransmissions, and DATA packets consume more energy than their NULL counterparts. Still, the dependency is not as pronounced, so that mean period decreases only slowly with BER. Energy outage probability shown in Fig. 4(c) is simply reciprocal of the mean period.

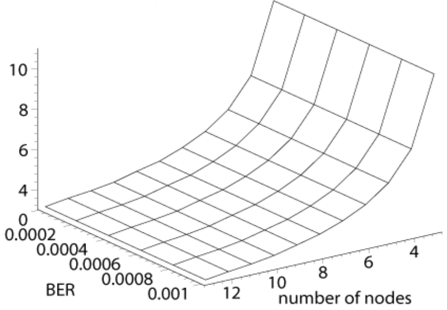
In the same setting, the descriptors of the vacation time are shown in Fig. 5. All three descriptors – mean, standard deviation, and coefficient of variation (defined as the ratio of the other two) – are strongly dependent on the number of nodes, as defined by (18); at the same time, they are virtually independent on the bit error rate. This last observation may be somewhat unexpected, as different intermediate variables are indeed affected by the bit error rate. However, one should keep in mind that the duration of both types of vacation periods in the MAC protocol are determined by the protocol itself rather than by the network and traffic parameters. We note that the coefficient of variation of the vacation time, Fig. 5(c), decreases when the number of nodes increases, but shows strong hyper-exponential behavior throughout the observed range of parameter values.



(a) Mean value.



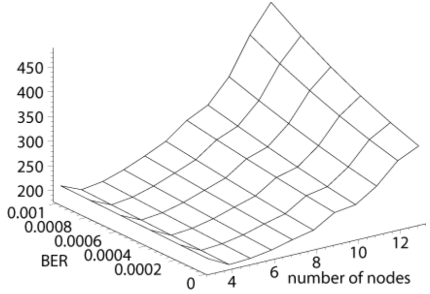
(b) Standard deviation.



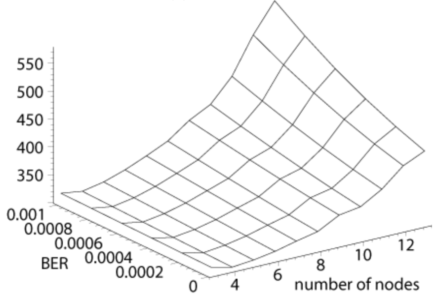
(c) Coefficient of variation.

Fig. 5. Descriptors of vacation time.

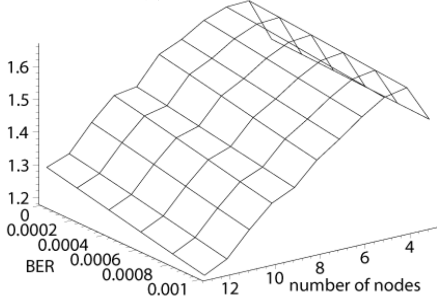
Finally, the diagrams in Fig. 6 show the mean, standard deviation and coefficient of variation of the packet delay at the node queue. As could be expected, mean packet delay in Fig. 6 increases with the number of nodes as the polling cycle gets longer. It also increases with bit error rate, but only at larger network size where the impact of packet retransmissions begins to show. Standard deviation of delay time, Fig. 6, exhibits similar behavior. However, coefficient of variation decreases when the number of nodes increases, as the variations in delay caused by different number of retransmissions from different nodes tend to cancel each other. It is worth noting that the value of the coefficient of variation is between 1.2 and 1.7 – i.e., mildly hyper-exponential – in the observed range of independent variables.



(a) Mean value.

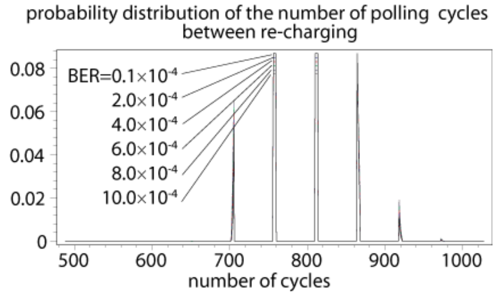


(b) Standard deviation.

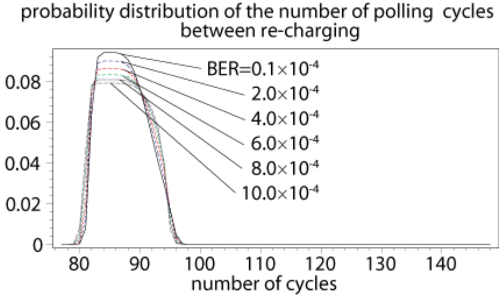


(c) Coefficient of variation.

Fig. 6. Descriptors of packet queueing delay.



(a) Network with m = 3 nodes.



(b) Network with m = 13 nodes.

Fig. 7. Probability distribution of the number of polling cycles between two consecutive recharging events.

Probability distribution of the number of polling cycles between consecutive recharging pulses is shown in Fig.

7as the function of bit error rate. When the network has three nodes (master and two ordinary ones), the probability distribution, shown in Fig. 7(a), is characterized by discrete peaks caused by the mandatory sleep period imposed after each polling cycle which has four time units (two nodes, each with a POLL packet followed by a DATA or NULL packet). The impact of bit error rate is very small, making the peaks obtained at different values almost indistinguishable from each other. In this scenario, recharging occurs after about 700 to 900 cycles, which is quite good but the improvement is obtained at the expense of short cycles with higher sleeping probability.

When the network has 13 nodes (master and twelve ordinary ones), the probability distributions are spread over a wider range of values, as can be seen in Fig. 7(b). While the curves obtained for different values of bit error rate are still close to each other, the higher values result in slightly but noticeably wider distribution shape than lower ones. This is the consequence of longer polling cycles (24 time units) but the period between recharge pulses is much shorter than in the previous case: it occurs between 80 and 96 cycles. For networks of larger size, energy consumption is faster and recharging becomes more frequent, which means the corresponding distributions will be wider and shifted toward smaller cycle values.

VI. CONCLUSION AND FUTURE WORK

In this paper we have presented a polling-based MAC protocol with 1-limited service policy that supports in-band RF recharging in wireless sensor networks. Through probabilistic analysis we have shown that the performance of the protocol is affected by the interruption of data transmission caused by the recharging process. We have also derived a quantitative characterization of the vacation periods in the network, and evaluated precisely the probability distribution of the time interval between consecutive charging events. Our results indicate that the major determinant of network performance is the size of the network, while the impact of bit error rate is of secondary importance. Our future work will focus on determining the optimum characteristics of the recharging process and the possibility of extending the time interval between recharging pulses.

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Mohammad Shahnoor Islam Khan has completed his M.Sc. degree in computer Science from Ryerson University, Canada in 2012. Currently he is a Ph. D candidate in computer science department of same university. His research interests include wireless sensor network, body area network, machine type communications and mobile cloud computing.

Jelena Mišić is a Professor of Computer Science with Ryerson University, Toronto, ON, Canada. She has authored over 90 papers in archival journals and over 120 papers at international conferences in the areas of wireless networks, in particular, wireless personal area network and wireless sensor network protocols, performance evaluation, and security. She serves on the Editorial Boards of the *IEEE Transactions on Vehicular Technology, Computer Networks*, *Ad hoc Network*s, *Security and Communication Networks*, *Ad Hoc and Sensor Wireless Networks*, *International Journal of Sensor Networks*, and *International Journal of Telemedicine and Applications*.

Vojislav B. Mišićis is a Professor of Computer Science with Ryerson University, Toronto, ON, Canada. He has authored or co-authored seven books, 20+ book chapters, and over 200 papers in archival journals and prestigious international conferences. His research interests include performance evaluation of wireless networks and systems and software engineering. He is the Editor-in-

Chief of *Cyber-Physical Systems* journal, and serves on the Editorial Boards of the *IEEE Transactions on Cloud Computing*, *Ad hoc Networks*, *Peer-to-Peer Networks and Applications*, and *International Journal of Parallel, Emergent and Distributed Systems.*