Zoning and relaying-based MAC protocol with RF recharging

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***Abstract*—Radio frequency (RF) recharging can extend maintenance-free operation of wireless sensor networks. However, the period between recharging is limited by the distance between the most distant sensor node and the master which sends out recharging pulses. To increase this period, we propose a zoning scheme in which nodes are logically grouped into circular zones centered at the master, so that nodes in a given zone send their data to their neighbors in the next closer zone which act as relays. We describe and analyze a polling MAC protocol that supports zoning and relaying through a probabilistic model of the energy depletion process as well as a queueing model of packet transmission process. Our results indicate that zoning extends the time interval between recharge pulses and leads to equalization of node lifetimes, but also limits the available data transmission bandwidth.**

***Index Terms*—RF recharging, MAC protocol, performance evaluation**

I. Introduction

Periodic recharging of node batteries is an attractive way to reduce operational costs whilst expanding the operational life of wireless sensor networks (WSNs) [2]. WSNs can obtain energy by collecting energy from the surrounding environment, referred as 'energy harvesting' [3]. This approach is attractive as it does not require nodes with independent energy source except for the network sink that collects data from individual sensor nodes. However, energy harvesting is very much dependent on the availability of sufficient energy in the ambient which is essentially unpredictable [15], [16]. As the result, prolonged periods in which ambiental energy is unavailable may lead to energy depletion of some nodes and the resulting loss of performance, or even to end of network operation. An attractive alternative is to recharge nodes via radio frequency (RF) pulses emitted from the master node (also referred to as access point, coordinator, or base station). This may be accomplished in regular intervals or on demand, i.e., when one of the nodes reports that its remaining energy has reached a predefined threshold [10], which avoids the problem of node battery exhaustion mentioned above.

Performance of energy replenishment through battery replacement or regular recharging was discussed in [6]. An important question is whether the RF band is shared between recharging and data communication, or not. Using two different bands simplifies the design of the MAC protocol and ensures uninterrupted data flow, but these benefits are obtained at the expense of hardware complexity as two antenna systems and two RF transceivers are required [9], [10]. On the other hand, the single RF band based approach requires careful design of the network protocols as data communication and recharging are interleaved in the same RF band; nonetheless, it appears to be more popular due to its hardware simplicity (it requires a single antenna and transceiver system) and the ability to operate with less bandwidth [8]. In this work, we use single RF band-based recharging.

Probably the most important problem with recharging through RF pulses is that the amount of energy obtained through recharging depends on distance: nodes which are farther away from the master receive smaller amounts of energy due to path loss. As the result, the period between successive recharge requests is determined by nodes farthest away from the master [4]; closer nodes get recharged more often than necessary and their batteries never reach the energy threshold [8]. As path loss can't be eliminated, the only feasible way in which network lifetime could be prolonged is by adapting the energy consumption so that nodes closer to the recharging source consume more energy whilst farther ones consume less. Equalization of energy consumption rate for different nodes is, thus, the key to extending the period between successive recharges and, consequently, increasing the network lifetime.

A promising way toward such equalization is to apply zoning to the sensor field – i.e., to divide the nodes into circular zones or coronas centered at the master. Zoning was first described in an analysis of distance-dependent energy exhaustion of nodes in a sensor field [11]; however, the paper did not elaborate on the MAC protocol. Zoning was also proposed in the context of separation of local and global traffic [5], but without considering the impact of distance on energy consumption or replenishment rate of nodes in different zones.

In this paper we describe a zoning approach in which nodes in a given zone act as relays for the packets sent by their counterparts in the zones farther away from the master. (Of course, nodes in the zone closest to the master transmit their packets directly, while nodes in the most distant zone perform no relaying.) We propose a MAC protocol based on polling that fully supports zoning and relaying, and describe a network formation protocol that creates the zones.

The main benefit of this approach stems from the fact that transmissions need only reach a node in the closer zone rather than the master. As the result, transmitter nodes can reduce their transmission power which will reduce their energy consumption; this will provide the most benefit to the nodes in the most distant zone as they receive the least amount of energy during recharge [4].

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Zoning also requires that nodes closer to the master receive and retransmit other nodes' packets which will increase their power consumption. However, this increase is less critical since the energy increment received during recharge by the nodes in closer zones is much higher due to shorter distance to the master. Moreover, those nodes will be able to reduce their transmission power which will offset the increase in consumption to some extent. Overall, this approach should result in a more balanced power consumption and an increase in the time interval between successive recharging pulses.

The rest of the paper is organized as follows: Section II describes the operation of the MAC protocol. Section III models the energy depletion process of the node and derives the probability distribution of the period between successive recharging events. In Section IV, we model total time between successive medium accesses by a node as well as queuing delay, and derive performance descriptors for packet waiting time. Section V presents performance results for the proposed MAC including recharging interval described through mean, standard deviation and, in fact, complete probability distribution, as well as packet delay described through mean value, standard deviation, and coefficient of variation. Finally, Section VI concludes the paper and highlights some future research.

II. THE MAC PROTOCOL

We assume that sensor nodes are randomly positioned, following uniform spatial distribution, in a circle of diameter $2D$ centered at the master. Nodes are logically divided into n_z zones shaped as concentric disks or coronas centered at the master, as shown in Fig. 1(a). Assuming that the master is located in zone 0 with the radius of zero, the outer radius of each zone $j = 0..n_z$ is d_j, where $d_0 = 0$ and $d_{n_z} = D$. Nodes in zone 1 send their packets directly to the master; nodes in zones $j > 1$ send their packets to a relay node in the next lower zone $j - 1$, as will be explained below.

To balance the load for nodes that act as relays, we assume that the sensor field is also divided into logical sectors such that each sector contains at most one node for each zone. In this manner, each node has a contiguous path to the master through nodes in the same sector but in lower-numbered zones. This setup is schematically presented in Fig. 1(a) for a network with three zones and five sectors.

The setup described above requires that each zone contains approximately equal number of nodes. Given uniform spatial distribution of nodes, this can be achieved if zone areas are equal, as per following system of equations:

$$d_j^2 - d_{j-1}^2 = d_{j-1}^2 - d_{j-2}^2, \qquad j = 2..n_z \tag{1}$$

A. Network formation

In order to establish zones and sectors, the master needs to conduct network formation algorithm. We assume that master knows the network diameter D, the number of zones n_z it wants to establish, and the outer radius of each zone which can be obtained from the system of equations above.

The algorithm consists of three phases: paging, zone establishment, and sector establishment.

In the *paging phase*, the master learns the IDs and approximate distances of m network nodes. To this end, the master transmits periodic beacon packets to which nodes reply with their IDs. Collisions may be minimized by using an appropriate random wait procedure. If nodes reply with constant power, master will be able to estimate their distance on the basis of received signal strength (RSS) [7].

In the *zone establishment phase*, the master groups the nodes into zones according to their distance. It transmits beacon packets containing tuples of node ID and zone number as well as estimated power level for that zone. Each zone $j \in 1..n_z$ contains m_j nodes, hence $m = \sum_{j=1}^{n_z} m_j$. To ensure that the next phase, sector establishment, creates the required contiguous packet paths towards the master, the following relations must hold:

$$m_{n_z} \leq m_{n_z-1} \ldots \leq m_2 \leq m_1 \tag{2}$$

$$m_1 = \left\lceil \frac{m}{n_z} \right\rceil \tag{3}$$

They should not be difficult to achieve in case of uniform spatial distribution of nodes.

Finally, in the *sector establishment phase*, the master helps nodes establish sectors. This phase consists of a total of n_z rounds, one per each zone, starting from the most distant one.

First, the master sends a special POLL packet with sector inquiry to each node in zone n_z, which then respond with a packet to their counterparts in the next lower zone $n_z - 1$. Alternatively, a single POLL packet may be used for the entire zone, in which case the nodes transmit according to a schedule derived from their IDs or after a suitable random delay.

The response packet is transmitted at the power level established in the previous phase for the zone n_z. It is received by one or more nodes in zone $n_z - 1$ which record the sender ID and the RSS of the packet.

In the next round, the master sends the sector inquiry to each node in zone $n_z - 1$. These node respond by forwarding the response packets received from nodes in the next higher zone and the corresponding RSS values; as before, the nodes in the next lower zone $n_z - 2$ record the received packets and corresponding RSS values.

This procedure is repeated for each zone in descending order. Upon receiving all forwarded packets from zone 1, the master can group nodes into m_1 sectors and inform them accordingly. Grouping is done so that each sector contains a connected path of n_z nodes, one from each zone, ending with the master. Within a given sector, a node in a given zone acts as the relay for the node in the next higher zone and, indirectly, for nodes in all higher zones. Note that some paths may not begin at the most distant zone, depending on the total number of nodes, but they must be contiguous nonetheless.

B. MAC operation: polling

Once zones and sectors are established, normal operation may commence. It consists of poll cycles conducted sequentially over sectors. In each polling cycle master sends one POLL packet per each sector which contains the sector number. All nodes listen to the header of the POLL packet:

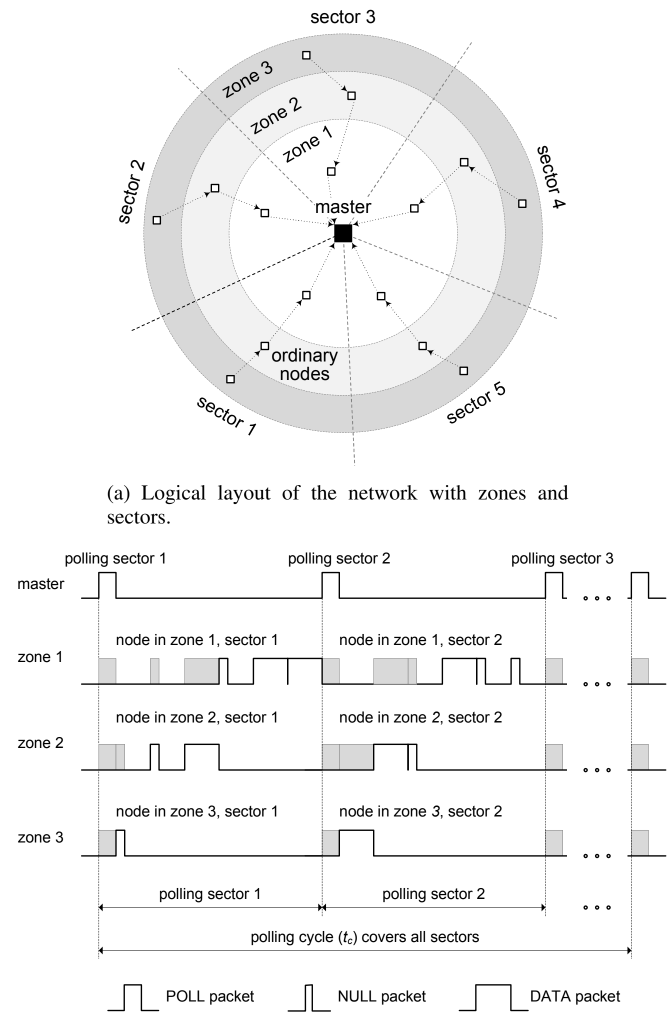
nodes that don't hear their sector number may go back to sleep immediately, while nodes that hear their sector number will calculate the times for their receive and transmit activities, as follows. Nodes in a given sector communicate only when their sector is polled and sleep at other times. However, they need to listen to headers of POLL packets for other sectors, as explained below.

After hearing the POLL packet, the node in the most distant zone n_z transmits a packet to a node in the next lower zone, and immediately goes to sleep. If there was data to send, the node sends a DATA packet to the node from the same sector but in the next lower zone $n_z - 1$; otherwise, it sends a NULL packet to that same node.

The designated relay node receives and subsequently retransmits the packet to a node in the next lower zone, followed by a DATA or NULL packet of its own. This process continues until the node in zone 1 sends all the packets from its sector to the master, which then proceeds to poll the next sector.

Note that NULL packets contain no data and, thus, can be shorter than DATA packets. While this can be used to shorten the data transmission, it also complicates scheduling as all nodes in a given sector would have to listen for longer time – from the sector POLL packet until receiving all packets from higher zones. In this work we have adopted a simpler solution in which the poll period is divided into fixed duration transmission/reception slots. Thus the node in zone $i = 1..n_z - 1$ can turn its radio on after $(n_z - i - 1)(n_z - i)/2$ packet slots following the POLL packet. It can switch to transmission after listening to exactly $n_z - i$ packets, some of which may be NULL, and retransmit the received packets, followed by a packet of its own, to the next lower zone or the master, in case $i = 1$.

Consequently, the sector service time consists of POLL packet time and $n_z(n_z + 1)/2$ packet slots. The entire polling cycle contains m_1 sector service times.



(a) Logical layout of the network with zones and sectors.

(b) Polling MAC operation. Shaded rectangles depict listening/receiving packets.

Fig. 1. Pertaining to the principle of zoning and operation of the MAC protocol.

C. MAC operation: recharging

When a node detects that its energy has dropped below a certain threshold E_{thr}, it will request a recharge by appending the appropriate information to the header of its own DATA or NULL packet. Upon receiving such a request (which will be piggybacked on one of the packets relayed by the node in zone 1 of the current sector), the master completes the current sector poll and announces the upcoming recharge pulse in the next sector POLL packet. This is the reason why all nodes must listen to POLL packet regardless of the sector. Polling continues after the recharge pulse at the point it was interrupted.

Recharging is effected by the master through a pulse of power P_w and duration T_p. The energy increment received by a given node i is $\Delta_i = P_w T_p Pl_i$, where Pl_i is the path loss that is inversely proportional to the distance to the master raised to the power of path loss exponent, typically 2 to 4 [12].

Energy consumption of a node depends on its zone and the total number of zones. Nodes in zone j should adjust their transmit power so as to make sure their packets are correctly received by the relay nodes in zone $j - 1$, which in the worst case amounts to the distance of $d_j - d_{j-2}$. On the other hand, receiving power is always the same and does not depend on distance [1], [14]. As the number of packets received and transmitted grows linearly as the zone index decreases, nodes close to the master spend more energy on packet relaying than nodes closer to the network edge.

The operation of the MAC protocol in a network with three zones is schematically shown in Fig. 1(b).

III. Modeling the MAC protocol

Let us now describe the analytical model for the MAC protocol, including both time and energy considerations. For simplicity, we will assume that all time intervals are expressed in multiples of the basic slot T, whereas all energy values are multiples of basic energy quantum E_u. Motivated by the data for a typical Bluetooth LE (low energy) chipset solution [1], we will assume $T_s = 25\mu s$ and $E_u = 0.25\mu J$. Assuming packet sizes of 20, 40 and 80 bytes for NULL, sector POLL and DATA packet, respectively, that fit one, two and four slots, respectively, we obtain raw data rate of 6.4 Mpbs.

We assume that each data packet has length L_d in bits. If bit error rate is BER, packet error rate will be $PER = 1-(1-BER)^{L_d}$. MAC protocol has partial reliability implemented through Automatic Repeat Request (ARQ) technique with up to n_r retries for packet. To reduce energy consumption, DATA packets sent from a node are acknowledged by setting a dedicated field in the header of the POLL packet targeting that node in the next cycle.

During normal network operation, node uses its energy for data sensing, listening and transmitting. Listening consists of POLL/DATA packet reception and listening to the headers of other sector POLL packets. Transmission consists of relaying and transmission/retransmission of DATA and NULL packets. Energy consumption depends on the actual zone, total number of zones and sectors, traffic intensity, bit error rate, and maximum number of retries n_r. When the energy of node i drops to E_{thr}, the node will request recharging. When recharging is finished, the energy level will be $\min(E_c, E_{thr}+\Delta_i)$, where $E_c \approx E_{thr} + \max\Delta_i, i = 1\,..\,m$, is the battery capacity.

Energy budget for packet transmission depends on the maximum distance between adjacent zones i.e. on $d_j - d_{j-1}$, $j = 2\,..\,n_z$. Transmission power in all zones should be scaled such that signal in adjacent zone is received with same RSS and, consequently, same SINR. The reference RSS is the one measured after receiving POLL signal by nodes in zone n_z. If master transmits POLL packet with power P_{poll} and path loss exponent is l, then nodes in zone j should transmit with power $Pt_j = P_{poll}\frac{(d_j-d_{j-2})^l}{D^l}$.

Time between two consecutive recharging pulses is a random variable which depends on the number of zones and sectors, node traffic, and bit error rate. We assume uniform traffic load over all nodes. Obviously nodes in different zones will send recharging requests at different times due to different distances and relaying load. Our task is to analyze recharging periods in different zones and evaluate its impact on network capacity and packet delay.

A. Joint probability distribution of polling cycle time and consumed energy per cycle

In calculating the joint probability distribution of polling cycle time and consumed energy per cycle, we will use energy consumption variables, absolute and relative to the energy unit E_u, listed in Tables I and II for listening and transmission, respectively. (Note that the latter values depend on the zone in which the node resides.) In the development of the required Probability Generating Functions (PGFs), variable y will model the polling cycle, while variable z will denote energy consumption expressed in basic energy units; time periods (in base time slots) will be denoted with variable x.

PGF for the energy consumption of a single data packet sent from a node in zone j is

$$Epd(y,z) = \frac{z^{k_s} z^{k_{td,j}} y(1-PER)\sum_{i=0}^{n_r} y(z^{k_{td,j}})^i PER^i}{(1-PER)\sum_{i=0}^{n_r} PER^i} \tag{4}$$

TABLE I
BASIC ENERGY UNITS FOR SENSING AND LISTENING.

Energy expenditure	label	E_u multiple
energy unit	E_u	1
sensing	E_s	k_s
listening to the POLL packet	E_{lp}	k_{lp}
listening to the header of POLL packet	E_a	k_{la}
listening to data packet	E_{ld}	k_{ld}
listening to null packet	E_{ln}	k_{ln}

TABLE II
BASIC ENERGY UNITS FOR TRANSMISSION IN ZONE j.

Energy expenditure	label	E_u multiple
energy unit	E_u	1
transmitting null packet	$E_{tn,j}$	$k_{tn,j}$
transmitting data packet	$E_{td,j}$	$k_{td,j}$

For simplicity we have assumed that a NULL packet will be always decoded correctly; if this does not hold, the required model extension is straightforward. Mean value of $Epd(y,z)$ with respect to the number of cycles is $\overline{Epd_c} = \frac{d}{dy}Epd(y,z)\Big|_{y=1,z=1}$ which, for simplicity, will be written as $\overline{Epd_c} = \frac{d}{dy}Epd(1,1)$. From (4), we can find the probability of initial transmission attempt, including sensing, for a node in zone j as

$$Pf_j = 1/\overline{Epd_c} \tag{5}$$

If $Epn_j(z) = z^{k_{tn,j}}$ denotes the PGF for the transmission of a null packet in zone j and $\rho_{b,j}$ denotes the effective utilization of a node, the PGF for transmission energy for a single packet by the node in zone j becomes

$$Ep_j(y,z) = \rho_{b,j} z^{k_{td,j}}(Pf_j z^{k_s} + 1 - Pf_j) + (1-\rho_{b,j})z^{k_{tn,j}} \tag{6}$$

Using (6) we can derive the PGF for energy expenditure for all activities of a node in zone j as

$$\begin{aligned} Ez_j(y,z) = {} & y z^{k_{lp}} z^{k_{la}(m_1-1)} \\ & \cdot(\rho_{b,j} z^{k_{ld}} + (1-\rho_{b,j})z^{k_{ln}})^{n_z-j} \\ & \cdot(\rho_{b,j} z^{k_{td,j}} + (1-\rho_{b,j})z^{k_{tn,j}})^{n_z-j} Ep_j(y,z) \end{aligned} \tag{7}$$

where m_1 denotes the number of sectors. Maximum and minimum energy expenditure of a node during sector poll in zone j are, then,

$$\begin{aligned} Ez_j^{(max)} &= k_{lp} + (m_1-1)k_{la} + k_{ld}(n_z-j) + k_s \\ &\quad + k_{td,j}(n_z-j+1) \\ Ez_j^{(min)} &= k_{lp} + (m_1-1)k_{la} + k_{ln}(n_z-j) \\ &\quad + k_{tn,j}(nz-j+1) \end{aligned}$$

This allows us to set the threshold for requesting recharging to a multiple of maximum energy expenditure of a node in zone 1 (closest to the master). Upon recharging, nodes in zone j will have energy budget of

$$Eb_j = E_{thr} + \Delta_j = E_{thr} + P_w T_p Pl_i \tag{8}$$

Algorithm 1: Creation of PGF for recharging period.

Data: $SE_j(y,z)$
Result: PGF for the recharging period (in polling cycles) in zone j

find minimal $Sminy_j$ and maximal $Smaxy_j$ degree of variable y in $SE_j(y,z)$;
for $i \leftarrow Sminy_j$ **to** $Smaxy_j$ **do**
    $cc[i,j](z) =$ coefficient$(SE_j(y,z), y, i)$;
    find minimal $minz_j$ and maximal $maxz_j$ degree of variable z in $cc[i,j](z)$;
    for $k \leftarrow minz_j$ **to** $maxz_j$ **do**
        $cic[k] =$ coefficient$(cc[i,j](z), z, k)$;
    form mass probability that energy resource will be exceeded in i-th cycle $Pm_{j,i} \leftarrow \sum_{k=E_{a,j}}^{maxz_j} cic[k]$;
form polynomial of recharging period as $T_{recp,j}(y) \leftarrow \sum_{i=miny_j}^{maxy_j} Pm_{j,i} y^i$;
form PGF of recharging period as $T_{rec,j}(y) \leftarrow T_{recp,j}(y)/T_{recp,j}(1) = \sum_{i=miny_j}^{maxy_j} P_{t(j,i)} y^i$;

The recharging request from this zone will be sent at a point in time between $l_{min,j} = \Delta_j/Ez_j^{(max)}$ and $l_{max,j} = \Delta_j/Ez_j^{(max)}$ polling cycles, depending on the zone, traffic intensity, error rate, and allowed number of retries. Shortest period between successive recharging requests occurs when each of the nodes in the sector has a new data packet at all times, while the longest period (and, consequently, maximum number of polling cycles) corresponds to the scenario where node buffers in the sector are always empty so that only NULL packets are transmitted.

Joint PGF of energy consumption when the number of polling cycles ranges between $l_{min,j}$ and $l_{max,j}$ is

$$SE_j(y,z) = \frac{\sum_{i=l_{min,j}}^{l_{max,j}} Ez_j(y,z)^i}{l_{max,j} - l_{min,j} + 1} \tag{9}$$

We can manipulate coefficients in the last expression in order to derive PGF of the recharging period in zone j, as shown in Algorithm 1.

Mean and standard deviation of the number of polling cycles between two successive recharging events in zone j are

$$\begin{aligned} \overline{T_{rec,j}} &= \frac{d}{dy} T_{rec,j}(1) \\ \sigma(T_{rec,j}) &= \sqrt{\frac{d^2}{dy^2} T_{rec,j}(1) - \overline{T_{rec,j}} + \overline{T_{rec,j}}^2} \end{aligned} \tag{10}$$

while the coefficient of variation is $Cv(T_{rec,j}) = \frac{\sigma(T_{rec,j})}{\overline{T_{rec,j}}}$. Finally, recharging probability can be calculated as

$$P_{r,j} = \frac{1}{\overline{T_{rec,j}}} \tag{11}$$

B. Network cycle time

In the proposed MAC protocol, sectors are polled sequentially, while nodes within a sector transmit in the descending order of zones. Therefore, we need to model sector transmission time before following with the model of network cycle time.

Assuming that variable x denotes a basic time slot, packet sizes for NULL, sector POLL and DATA packets can be represented with PGFs $Gn(x) = x$, $Gp(x) = x^2$ and $Gd(x) = x^4(x)$, respectively. As both NULL and DATA packets are sent in a fixed-size transmission slot, duration of node service time in zone j can be calculated as

$$S_j(x) = Gd(x)^{2(n_z-j)+1} \tag{12}$$

The total sector service time is then

$$S(x) = Gp(x)Gd(x)^{(n_z(n_z+1)/2)} \tag{13}$$

and network cycle time is

$$T_{cyc}(x) = S(x)^{m_1} \tag{14}$$

The PGF of the recharging time was previously calculated as function of polling cycles in algorithm 1; its PGF expressed in slots is $T_{rec,j}(T_{cyc}(x))$.

IV. Queueing model

In a single network cycle, a node can transmit at most one packet of its own; the remaining time is unavailable for service regardless of the zone in which the node resides. In terms of queueing theory, this constitutes a (cycle) vacation. As all nodes share the same network cycle, cycle vacation time will be the same for all of them: it consists of $m_1 - 1$ sector service times and all packet times in the target sector except the packet sent by target node, hence its PGF is

$$V_c(x) = S(x)^{(m_1-1)} Gp(x) Gd(x)^{n_z(n_z+1)/2-1} \tag{15}$$

Recharging vacation occurs during the recharging pulse when no transmission can take place; it is also common to all nodes in a given zone, say j, and its PGF is

$$V_{r,j}(x) = P_{r,j} x^{T_p} + (1 - P_{r,j}) \tag{16}$$

The total vacation experienced by a single node has the PGF of

$$V_j(x) = V_{r,j}(x) V_c(x) \tag{17}$$

and its mean value and standard deviation are

$$\overline{V_j} = \frac{d}{dx} V_j(1) \tag{18}$$

$$\sigma(V_j) = \sqrt{\frac{d^2}{dx^2} V_j(1) - (\overline{V_j})^2 + \overline{V_j}} \tag{19}$$

A. Offered load

As noted above, any given node can transmit at most one DATA or NULL packet in a polling cycle despite different relaying load across zones. As the network polling cycle is common to all nodes, this MAC scheme can be modeled using an approach similar to M/G/1 gated limited system with vacations [13]. For simplicity, we will assume that node buffer has infinite capacity; if needed, a finite buffer can be modeled without difficulty.

We assume that packets arrive to each node according to a Poisson process with rate λ. Basic offered load per node is $\rho = \lambda\overline{Gd}$; however, vacation after each packet transmission in zone j increases the offered load to

$$\rho_{v,j} = \rho + \lambda\overline{V_j} \tag{20}$$

where $\overline{V_j}$ denotes mean length of vacation period in zone j.

Packet retransmissions will also increase the offered load as they use bandwidth, and each retransmission is followed by a vacation as well. As the result, a single packet transmission is effectively changed into a burst transmission with the PGF of

$$Gb(x) = \frac{(1-PER)x\sum_{i=0}^{n_r} x^i PER^i}{(1-PER)\sum_{i=0}^{n_r} PER^i} \tag{21}$$

and mean value of $\overline{Gb} = \frac{d}{dx}Gb(1)$.

Thus, total effective offered load becomes

$$\rho_{b,j} = (\rho + \lambda\overline{V_j})\overline{Gb} \tag{22}$$

Note that offered load depends on mean vacation time, but the cyclical vacation depends on offered load; therefore, equations (4) up to (22) have to be solved together.

B. Waiting time

Since nodes in each zone modeled in isolation have vacations of different duration, waiting times for packets in each zone will be different. Assuming FIFO servicing discipline, we may use existing framework for limited M/G/1 queues with vacations but without transmission errors. To this end, we need to consider a packet followed by a vacation as a virtual packet with PGF of $B_{v,j}(x) = Gd(x)V_j(x)$. In that case, the number of packets left in the queue after a departing uplink packet can be expressed as

$$\Pi_j(x) = \frac{(1-\rho_{v,j})(1-V_j^*(\lambda-\lambda x))B_{v,j}^*(\lambda-\lambda x)}{\lambda\overline{V_j}(B_{v,j}^*(\lambda-\lambda x)-x)} \tag{23}$$

$$= (1-\lambda(\overline{Gd}+\overline{V_j}))(1-V_j^*(\lambda-\lambda x)) \cdot \frac{Gd^*(\lambda-\lambda x)V_j^*(\lambda-\lambda x)}{\lambda\overline{V_j}(Gd^*(\lambda-\lambda x)V_j^*(\lambda-\lambda x)-x)} \tag{24}$$

where PGFs for packet time and vacation time were converted into Laplace-Stieltjes Transforms (LSTs) by replacing variable x with e^{-s} (e.g., $V_j(x)$ was converted to $V_j^*(s)$).

As noted above, packet retransmissions will transform virtual packet into a packet burst with random length, the PGF of which is

$$Q_j(x) = Gb(B_{v,j}(x)) \tag{25}$$

and its LST becomes $Q_j^*(s) = Gb(B_{v,j}(e^{-s}))$. When this effect is included in the distribution of the number of packets left after departing packet we obtain the PGF of

$$\Pi_j(x) = \frac{(1-\rho_{b,j})(1-V_j^*(\lambda-\lambda x))Q_j^*(\lambda-\lambda x))}{\lambda\overline{V_j}(Q_j^*(\lambda-\lambda x)-x)} \tag{26}$$

Probability distribution of packet delay, expressed with LST of $W_j^*(s)$, can be found from the distribution of response time $T_j^*(s)$ and packet service time $Gd^*(s)$, since response time is the sum of waiting and packet service times, i.e., $T_j^*(s) = W_j^*(s)Gd^*(s)$. In stable state, the number of new packet arrivals during the response time of the target packet is equal to the number of packets left after the departure of the target packet, which may be written as

$$\Pi_j(x) = T_j^*(\lambda-\lambda x) \tag{27}$$

In the presence of transmission errors and retransmissions, response time for a packet consists of waiting time until the target packet is transmitted correctly; this includes waiting for all previous packets as well as for unsuccessful transmissions of the target packet. Therefore, the probability distribution of waiting time may be described with

$$\Pi_j(x) = W_j^*(\lambda-\lambda x)Gd^*(\lambda-\lambda x) \tag{28}$$

Since packet waiting time is a continuous random variable, we need to express it as a LST through the substitution $s = \lambda - \lambda x$, or, equivalently, $x = 1 - \frac{s}{\lambda}$. The probability distribution of the packet delay becomes

$$\begin{aligned} W_j^*(s) &= \frac{1}{Gd^*(s)}\Pi_j(1-\frac{s}{\lambda}) \\ &= \frac{(1-\rho_{b,j})(1-V_j^*(s))Q_j^*(s)}{\lambda\overline{V_j}Gd^*(s)(Q_j^*(s)-1+s/\lambda)} \\ &= \frac{(1-\rho_{b,j})(1-V_j^*(s))Q_j^*(s)}{Gd^*(s)\overline{V_j}(\lambda Q_j^*(s)-\lambda+s)} \end{aligned} \tag{29}$$

k-th moment of packet delay can be obtained as $(-1)^k W_j^{*(k)}(0)$. For example, standard deviation of waiting time is obtained as

$$W_{j,stdev} = \sqrt{W_j^{*(2)}(0) - W_j^{*(1)}(0)^2} \tag{30}$$

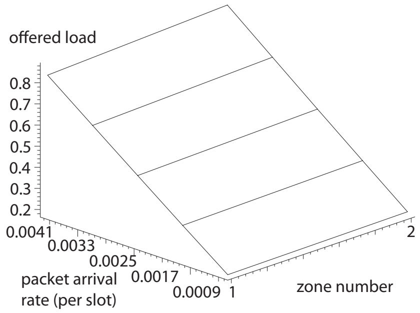
V. Performance results

We have varied the number of zones between $n_z = 2$ to $n_z = 5$. We assume that networks has $m = 25$ nodes including the master, except for the case when $n_z = 5$ where for simplicity we have adopted $m = 26$. Number of sectors is $m_1 = (m-1)/n_z$. Bit error rate is set to $BER = 10^{-5}$ and number of packet retransmissions is $n_r = 3$.

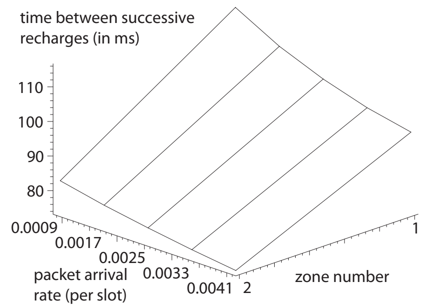
Charging pulse lasts for $T_p = 20ms$ (i.e., 800 slots) and its power is 1W. Network diameter is set to $D = 10$m. Path loss exponent is set to the free-space value of 2. Energy consumption data for reception and transmission are taken from [1], [14].

Uplink packet arrival rate was varied between 0.0009 and 0.0041 arrivals per node per unit slot; these values were chosen so that the maximum value of offered load is close to one. However, the value of 0.0041 packets per node per slot is not shown in all diagrams, for reasons to be explained below. Downlink traffic consists exclusively of sector POLL packets.

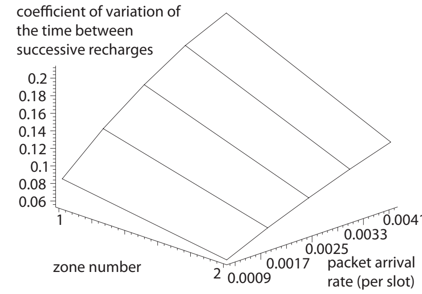
Our first set of diagrams depicts the performance of the recharging process. The corresponding results are shown in Fig. 2 where rows correspond to the network with 2, 3, 4, and 5 zones, respectively, while columns depict total offered load per zone, mean time between successive recharging pulses (in milliseconds), and coefficient of variation of that time, respectively. The two last parameters were calculated for each



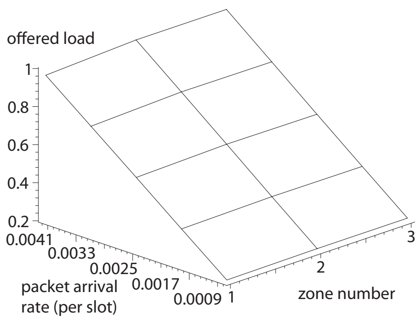
(a) Total offered load, $n_z = 2$ zones.



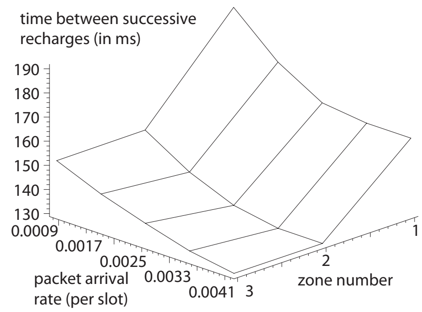
(b) Mean time between successive recharging pulses, $n_z = 2$ zones.



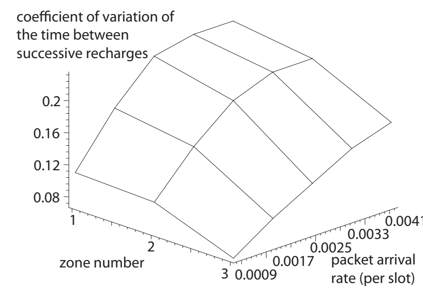
(c) Coefficient of variation of the time interval between successive recharging pulses, $n_z = 2$ zones.



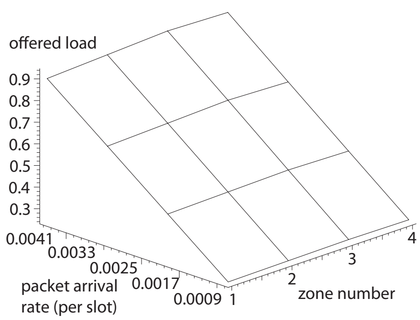
(d) Total offered load, $n_z = 3$ zones.



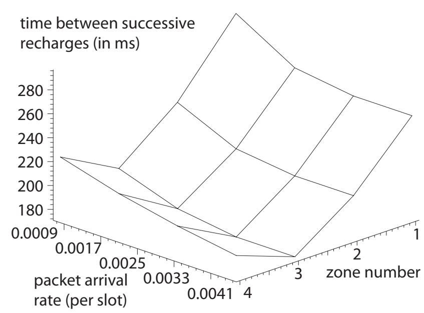
(e) Mean time between successive recharging pulses, $n_z = 3$ zones.



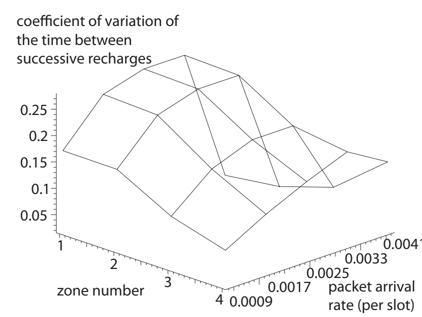
(f) Coefficient of variation of the time interval between successive recharging pulses, $n_z = 3$ zones.



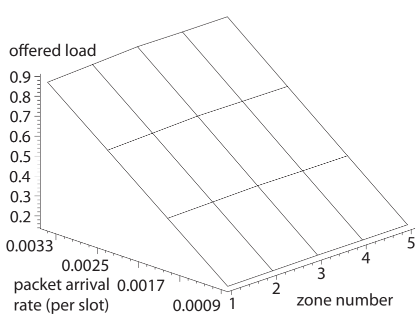
(g) Total offered load, $n_z = 4$ zones.



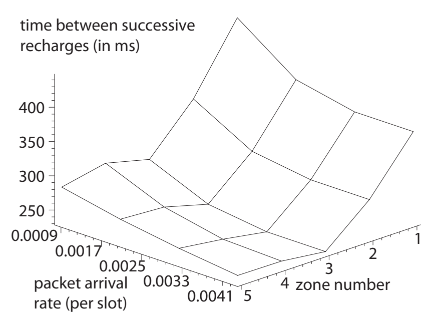
(h) Mean time between successive recharging pulses, $n_z = 4$ zones.



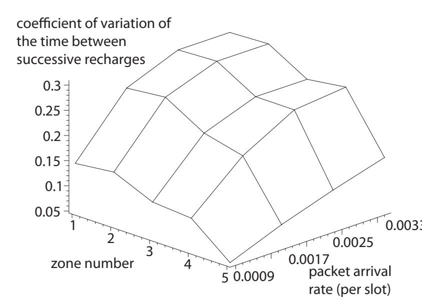
(i) Coefficient of variation of the time interval between successive recharging pulses, $n_z = 4$ zones.



(j) Total offered load, $n_z = 5$ zones.



(k) Mean time between successive recharging pulses, $n_z = 5$ zones.



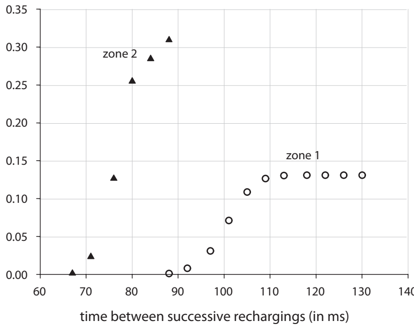
(l) Coefficient of variation of the time interval between successive recharging pulses, $n_z = 5$ zones.

Fig. 2. Performance descriptors of the recharging process.

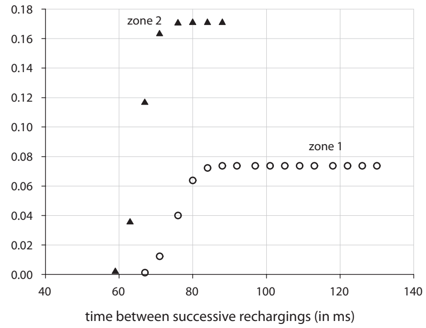
zone in isolation, in order to be able to accurately evaluate their behavior.

As each zone has equal number of nodes, the offered load is nearly constant for each zone. It increases in a nearly linear fashion with packet arrival rate, as can be expected.

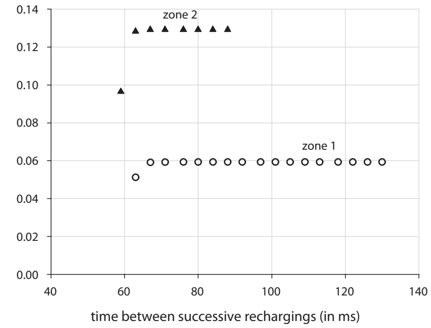
Mean recharging interval decreases with offered load, as



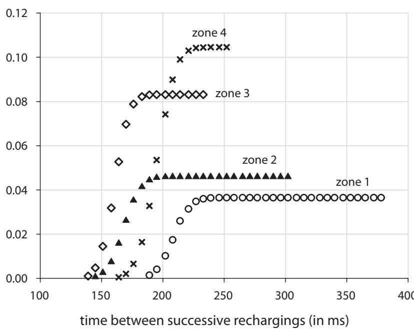
(a) Network with $n_z = 2$ zones, packet arrival rate $\lambda = 0.0009$ packets per node per slot.



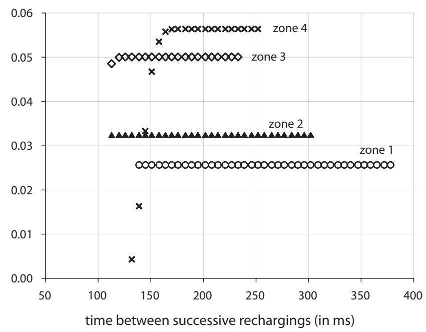
(b) Network with $n_z = 2$ zones, packet arrival rate $\lambda = 0.0025$ packets per node per slot.



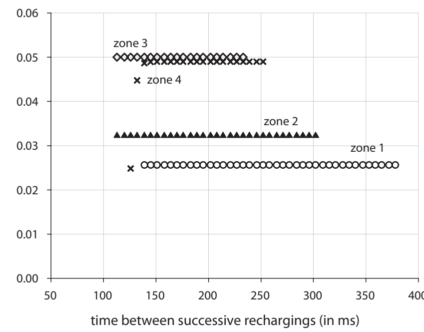
(c) Network with $n_z = 2$ zones, packet arrival rate $\lambda = 0.0041$ packets per node per slot.



(d) Network with $n_z = 4$ zones, packet arrival rate $\lambda = 0.0009$ packets per node per slot.



(e) Network with $n_z = 4$ zones, packet arrival rate $\lambda = 0.0025$ packets per node per slot.



(f) Network with $n_z = 4$ zones, packet arrival rate $\lambda = 0.0033$ packets per node per slot.

Fig. 3. Probability distribution of time interval between successive recharging pulses.

more packets mean more energy consumption and require more frequent recharging. Mean recharging interval also depends on the actual zone as well as on the total number of zones. In general, nodes in the zone closest to the master (zone 1) enjoy the longest operational time due to the fact that they receive the highest amount of energy during recharge; by the same token, nodes located farthest from the master experience the shortest operational time.

However, relaying changes the picture since nodes in all zones but the highest-numbered one use energy for relaying as well, and nodes in closer zones have to relay more packets. As the result, shortest mean time between successive recharging pulses can be found in zone 2 in the network with two zones, but in zones 2 and 3 in the network with three zones, and in zone 3 in the network with four or five zones.

Coefficient of variation of the recharging interval ranges up to 0.2 to 0.3, depending on the number of zones. Due to the random character of node traffic, the first node to request recharge in a given polling cycle can be in (almost) any zone. To verify this observation, we have plotted the probability distribution of recharge interval in Fig. 3 for two different number of zones and three different values of packet arrival rate. In the network with two zones (top row), the two probability distributions are virtually disjoint at low arrival rates, Fig. 3(a). As the distribution for zone 2 occurs at lower values of the recharging interval than the one for zone 1, virtually all requests for recharging will come from zone 2. However, as the packet arrival rate increase, Figs. 3(b) and 3(c), the two distributions begin to show more and more overlap, which means there is increasing probability that a recharge request may originate from a node in zone 1 as well.

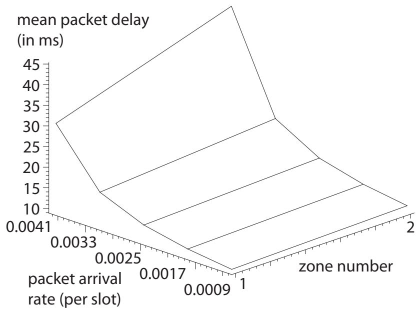
In the network with four zones (bottom row), probability distributions overlap in a large portion of the observed range of packet arrival rates. In this case, a recharge request may come from nodes in different zones, although the corresponding probabilities will differ, with nodes in the most distant zone most likely to send such a request.

Note that our model gives complete probability distribution of the time between successive recharge pulses, hence the actual probability that a node in zone n is more likely to request recharge than a node in zone j may be calculated as

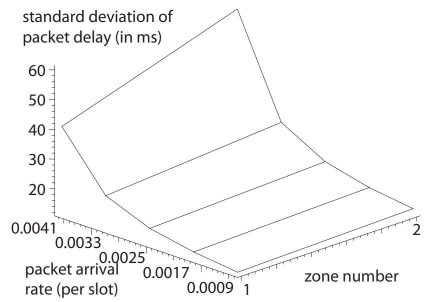
$$P(T_{rec,n} < T_{rec,j}) = \sum_{k=miny_j}^{maxy_j} P_{t(j,k)} \cdot \sum_{l=miny_n}^{k-1} P_{t(n,l)} \quad (31)$$

The final set of diagrams, Fig. 4, shows the mean, standard deviation, and coefficient of variation of packet delay. As before, rows correspond to the network with 2, 3, 4, and 5 zones. Delay is affected by the number of hops a packet has to pass before it reaches the master, which increases with the number of zones. However, packet delay is also extended by cycle and recharging vacations. As these last considerably longer than individual packet transmissions, mean packet delay does not differ much from one zone to the next, as can be seen from the diagrams in the leftmost column of Fig. 4.

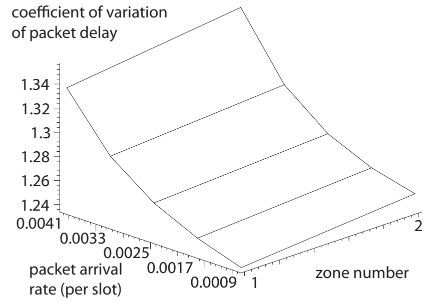
An unwanted consequence of the zoning approach is the



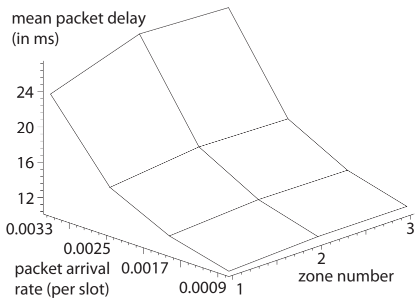
(a) Mean packet delay, $n_z = 2$ zones.



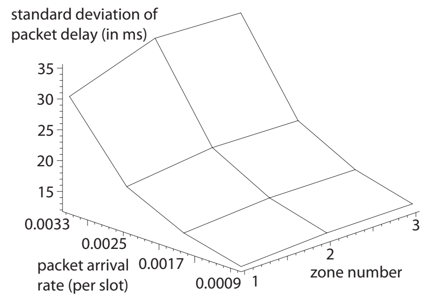
(b) Standard deviation of packet delay, $n_z = 2$ zones.



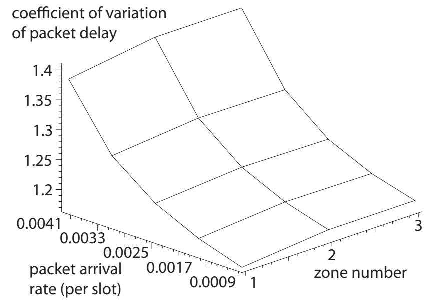
(c) Coefficient of variation of packet delay, $n_z = 2$ zones.



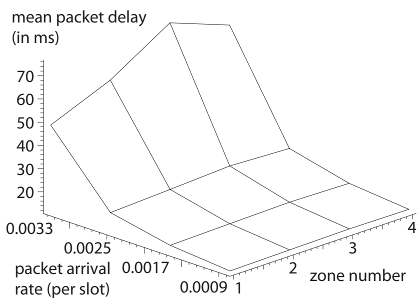
(d) Mean packet delay, $n_z = 3$ zones.



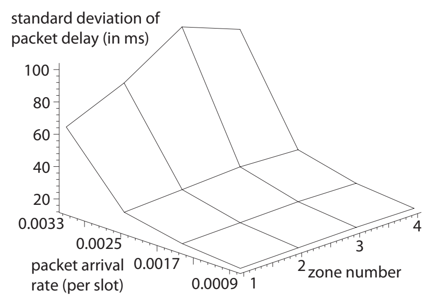
(e) Standard deviation of packet delay, $n_z = 3$ zones.



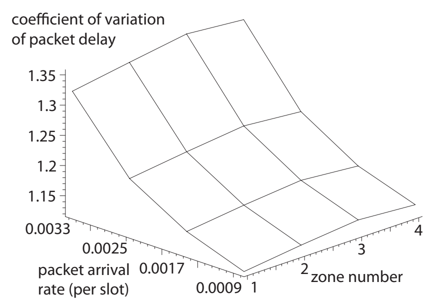
(f) Coefficient of variation of packet delay, $n_z = 3$ zones.



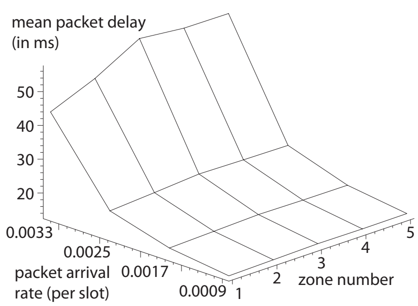
(g) Mean packet delay, $n_z = 4$ zones.



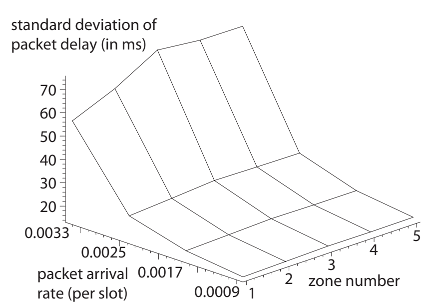
(h) Standard deviation of packet delay, $n_z = 4$ zones.



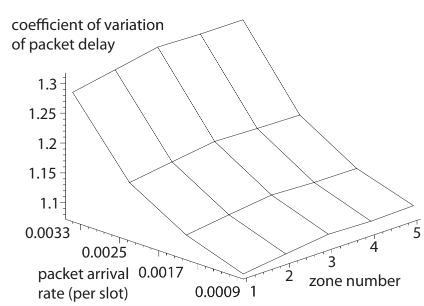
(i) Coefficient of variation of packet delay, $n_z = 4$ zones.



(j) Mean packet delay, $n_z = 5$ zones.



(k) Standard deviation of packet delay, $n_z = 5$ zones.



(l) Coefficient of variation of packet delay, $n_z = 5$ zones.

Fig. 4. Performance of packet transmission.

reduced bandwidth due to the need that packets from all zones except zone 1 (the closest one) undergo several hops. In networks with more than two zones, the highest value of packet arrival rate (0.0041 packets per node per slot) leads to saturation and a drastic increase of packet delays, which is why the corresponding data points are not shown.

Standard deviation of packet delay is shown in the diagrams in the middle column of Fig. 4. It is close to the mean packet delay, but increases to higher values at high packet arrival rates. This increase is due to the fact that some packets are damaged and have to be retransmitted, as is the case with any packets that have arrived since the initial transmission of the damaged packet. As all packets must wait for the entire duration of the vacation period, even a small number of retransmissions increase both mean delay and its standard deviation.

This observation is further corroborated by the diagrams of the coefficient of variation of packet delay, shown in the rightmost column of Fig. 4. In all cases, the coefficient of variation is well above one, which means that the actual distribution of packet delay values exhibits hyperexponential behavior.

VI. Conclusion and future work

In this paper we have described the concept of zoning with relaying in wireless sensor networks with wireless recharging of node batteries, The network is partitioned into zones and sectors so that packets are forwarded within the sector to nodes that are closer to the master which acts as the network sink. We have described and evaluated a MAC protocol based on polling which supports the operation of such a network, and developed a probabilistic model of the energy depletion process and a queueing model of the sensor node. Our analysis leads to the following conclusions:

- The zoning approach augmented with relaying is indeed capable of extending the recharging interval, as was the initial objective.
- At low traffic volume, recharging will be mainly determined by the nodes which are farthest away from the master (i.e., those in the highest numbered zone). As the traffic volume increases, variability of the recharging interval increases and nodes in closer zones may also generate recharging requests.
- At the same time, zoning tends to reduce the available bandwidth. In a network with more zones, high packet arrival rates are more likely to lead to saturation in which case packet delays increase and available bandwidth is drastically reduced.
- Therefore, the number of zones should be determined on the basis of desired throughput of sensed data (event sensing reliability), guided by the results of the analysis above.

Our future work will focus on optimization of the number of zones, in particular in cases where the spatial distribution of nodes is non-uniform, and further refinements of the MAC protocol.

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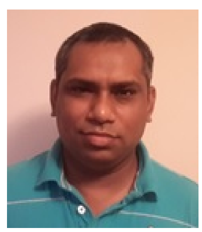

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