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Distributed Sleep Management for Heterogeneous Wireless Machine-to-Machine Networks

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***Abstract*—Wireless machine-to-machine (M2M) communications are widely considered as part of the Internet of Things (IoT) infrastructure. Resource management is crucial for heterogeneous M2M networks. In this paper, we present new distributed sleep management techniques to prolong network lifetime for multi-hop heterogeneous wireless M2M networks, which consist of battery-powered nodes and mains-powered nodes. We also propose two novel battery energy aware routing metrics to efficiently select routes that satisfy performance guarantees. Finally, we present extensive performance evaluation of our sleep management techniques and routing metrics. Simulation results show that our schemes achieve high packet delivery rate, long network lifetime and low energy consumption even in very low percentage of mains-powered nodes.**

***Keywords*- Heterogeneous M2M, distributed sleep management, battery energy aware routing.**

I. Introduction

M2M communications are part of the Internet of Things (IoT) and connect resource-constrained smart objects through a lossy network. Smart objects are often heterogeneous in resources and capabilities and have to operate with resource constraints, such as power and memory. Hence, efficient resource management in M2M communications has attracted interest from the research community.

The challenges that we address in this paper are:

- How to save battery energy in an heterogeneous wireless M2M network, which consists of battery-powered nodes and mains-powered nodes.
- How to efficiently manage battery node sleep schedules in a distributed manner.
- How to route data packets when the majority of nodes is inactive and still satisfy performance guarantees.

In this paper, we propose new distributed sleep management techniques for heterogeneous wireless M2M networks to efficiently manage battery lifetime. Our network is heterogeneous in the sense that it consists of battery-powered nodes (BPNs) and a low percent of mains-powered nodes (MPNs). BPNs schedule variable length sleep intervals that start with an active period (AP) followed by a sleep period (SP). BPNs decide the length of sleep intervals in a distributed manner based on their local data traffic, which consists of buffered packets, self-generated packets, and prediction of incoming relay data traffic. For this purpose, we introduce a model to estimate the number of incoming relay packets, in which we take into account buffer overflow, channel uncertainty and probability of the BPN being active. In this way, each BPN can predict the amount of incoming traffic and configure its AP appropriately. In addition, we have proposed an AP extension scheme, which gives BPNs flexibility to transmit or receive more data packets. The decision of AP extension depends on the number of buffered packets and the amount of traffic relayed in the last AP or AP extension. Hence, a BPN extends its AP in the case it has plenty of packets to transmit or it is proved to be a reliable relay node.

We also introduce two novel battery energy aware metrics: *Battery Node Energy Waste* (EW) and *Battery Node Relay Cost* (RC). These two metrics are node related metrics and take into account sleep management and different causes of energy depletion. They aim to discover the best route that satisfies some battery related properties. The EW metric indicates the level of BPN's energy consumption due to idle listening and overhearing. Ideally, the routing protocol should reduce the amount of energy waste in order to increase network lifetime. Hence, selecting a route with minimum energy waste is preferred for energy savings. The RC metric exploits energy consumption of the BPN due to receiving and transmitting relay data packets. By using this routing metric, routing protocol intends to balance relay data traffic across the network in a way of prolonging network lifetime.

In addition, we propose some enhancements for the battery energy efficient routing protocol B-RPL [1]. We introduce a routing metric advertisement technique and a routing objective function that aims to find the routes to maximize network lifetime.

The rest of this paper is organized as follows. Section II presents related work. Section III specifies the distributed sleep management scheme. We describe our novel battery energy aware routing metrics in Section IV. Enhancements of B-RPL are presented in Section V. Section VI provides extensive evaluation and analysis of the proposed distributed sleep management and the newly introduced routing metrics based on simulations. We conclude our work in Section VII.

II. Related Work

In battery powered networks, efficient battery energy management is crucial for network operation. Several schemes have been proposed to enable sleep management and duty cycling for different type of networks. In [2], the authors propose the Estimated Duty Cycle (EDC) metric, which takes into account duty cycling in wireless sensor networks. They show that the EDC metric outperforms standard link metric Expected Transmission Count (ETX) [3] in terms of lifetime and end-to-end delay. We proposed a distributed sleep control

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framework in [1]. However, we did not provide method to realize distributed sleep control. In this work, we introduce new efficient sleep management techniques.

Extending network lifetime and also maintaining acceptable packet delivery rate is one of the major concerns in battery powered networks. The link metrics [4] involve the measurement of a particular quantity for the link between a pair of nodes. The link metrics aim to achieve high throughput but do not indicate energy level of a node. Hence, energy-related routing metrics have been proposed. In [5], authors use residual energy (RE) as a routing metric and design a new objective function for routing decision. They show that the RE metric outperforms link metric ETX in terms of network lifetime. To identify energy-bottleneck nodes and to prolong network lifetime, the expected lifetime (ELT) metric is introduced in [6], which outperforms standard RE metric in terms of network stability. In [7], authors propose a routing metric that aims at maximizing network lifetime and takes into account network congestion, energy level and node degree. Simulation results indicate that by using the Optimized Link State Routing Protocol (OLSR), the proposed metric outperforms standard metrics in different environmental conditions.

Finally, energy efficient routing algorithms have been recently proposed. In [8], authors introduce a central control algorithm that is based on cluster formation to extend network lifetime. An adaptive routing framework that satisfies certain transmission cost requirements is proposed in [9].

III. Distributed battery node sleep management

In this section, we introduce our distributed sleep management techniques to prolong network lifetime. To define network lifetime, we adopt the most widely used definition that is the time until the first BPN runs out of battery energy.

A. Network Model and Assumptions

A multi-hop wireless machine-to-machine (M2M) network can be modeled as a graph $G(V, E)$. For example, in standard RPL [10] authors model a network as the Destination Oriented Directed Acyclic Graph (DODAG). We consider a wireless M2M network that consists of N heterogeneous nodes such that power source is either *power grid* or *battery*. Nodes with *power grid* as power source are called mains-powered nodes (MPNs) and nodes with *battery* as power source are called battery-powered nodes (BPNs). MPNs have unlimited power supply and do not suffer from energy depletion. Hence, MPNs do not sleep. However, BPNs face significant energy depletion. There are several methodologies leading to energy saving from BPNs such as sleep control and energy aware routing metrics. Both of them are being exploited in our work. Suppose we have M MPNs and B BPNs, where $N = B + M$. Then, the percentage of MPNs in the network is defined as $p_m = M/N$.

We consider multi-point to point (MP2P) dominant traffic pattern with a sink node. The parent of a node is defined as an immediate successor of the node on a path towards the sink node. The child of a node is defined as an immediate predecessor of the node on a path towards the sink node. Suppose we have a H-hop network after topology formation and each layer may consist of router (relay) nodes or leaf nodes or both. Leaf nodes do not have any child node in the topology and only generate packets, but do not relay data packets. Router nodes generate packets and at the same time they relay data packets generated or relayed by their children.

B. Distributed Sleep Management

Using distributed sleep management, a BPN b sends a wakeup message upon waking up. Once receiving such wakeup message, neighbors can send packets to node b. To reduce packet collision and save energy, AP is divided into a reception (RX) period and a transmission (TX) period according to the traffic requirements and the relative position of node b in the topology graph. Node b dynamically determines RX period length and TX period length based on the number of buffered packets N_b^{BP}, number of self-generated packets N_b^{SP} and the number of incoming (relay) packets N_b^{RP}. Node b includes its RX period length and TX period length in wakeup message.

1) Model for incoming data packet arrival rate estimation: A BPN b knows its N_b^{BP} and can compute N_b^{SP} based on its packet generation rate R_b^S. To compute N_b^{RP}, the incoming data packet arrival rate, denoted by R_b^I, needs to be calculated. We therefore propose a model to calculate R_b^I.

To estimate R_b^I, we assume a h-hop node selects (h-1)-hop nodes for its parent set (hierarchical structure). $\mathcal{C}_j^h$, $\mathcal{BRC}_j^h$ and $\mathcal{MRC}_j^h$ denote a h-hop node j's child set, battery-powered router child set and mains-powered router child set, respectively, where $\mathcal{BRC}_j^h \subset \mathcal{C}_j^h$ and $\mathcal{MRC}_j^h \subset \mathcal{C}_j^h$. Moreover, $\mathcal{BP}_i^h$ and $\mathcal{MP}_i^h$ denote a h-hop node i's battery powered parent set and mains powered parent set, respectively.

We first model the successful packet delivery probability p_{ij}^s from node i to node j. This probability takes into account possible packet drops due to queue overflow and wireless channel condition. We denote packet drop probability due to queue overflow for node i as p_i^q. This probability is estimated by using the number of packets deleted due to full queue, and the number of packets being pushed into queue measured in previous sleep interval. Queue overflow can lead to significant performance decrease. Let p_{ij}^c be the packet drop rate due to link condition from i to j, which can be approximated using ETX as $p_{ij}^c = 1 - \frac{1}{ETX}$.

Combining the two probabilities, we can estimate the probability for a packet to be successfully delivered from node i to node j as

$$p_{ij}^s = \frac{(1 - p_i^q)}{ETX} \tag{1}$$

The probability of a MPN m being active is equal to 1 since MPNs do not sleep. For a BPN b, we denote its AP length as T_b^a and SP length T_b^s in a sleep interval. Therefore, the probability of node b being active can be estimated by

$$p_b^a = \frac{T_b^a}{T_b^a + T_b^s} \tag{2}$$

Combing equations (1) and (2), the probability a h-hop node i successfully sending a packet to a battery powered parent b is given by

$$P2B_{ib}^h = \frac{p_b^a * p_{ib}^s}{\sum_{k \in \mathcal{BP}_i^h} p_k^a * p_{ik}^s + \sum_{k \in \mathcal{MP}_i^h} p_{ik}^s} \tag{3}$$

and the probability a h-hop node i successfully sending a packet to a mains powered parent m is given by

$$P2M_{im}^h = \frac{p_{im}^s}{\sum_{k \in \mathcal{BP}_i^h} p_k^a * p_{ik}^s + \sum_{k \in \mathcal{MP}_i^h} p_{ik}^s} \tag{4}$$

The estimation of incoming data packet arrival rate is conducted using the recursion approach. Let R_i^S be the data packet generation rate of node i. In a H-hop network, H-hop nodes are leaf nodes and therefore, do not relay packets. For a (H-1)-hop BPN b, R_b^I is given by

$$R_b^I = \sum_{i \in \mathcal{C}_b^{H-1}} R_i^S * P2B_{ib}^H \tag{5}$$

and for a (H-1)-hop MPN m, R_m^I is given by

$$R_m^I = \sum_{i \in \mathcal{C}_m^{H-1}} R_i^S * P2M_{im}^H \tag{6}$$

For h-hop BPN b and h-hop MPN m ($h = 1, 2, ..., H-2$), R_b^I and R_m^I can be estimated recursively by

$$\begin{aligned} R_b^I = & \sum_{i \in \mathcal{C}_b^h} R_i^S * P2B_{ib}^{h+1} + \sum_{i \in \mathcal{BRC}_b^h} R_i^I * R_i^S * P2B_{ib}^{h+1} \\ & + \sum_{i \in \mathcal{MRC}_b^h} R_i^I * R_i^S * P2B_{ib}^{h+1} \end{aligned} \tag{7}$$

$$\begin{aligned} R_m^I = & \sum_{i \in \mathcal{C}_m^h} R_i^S * P2M_{im}^{h+1} + \sum_{i \in \mathcal{BRC}_m^h} R_i^I * R_i^S * P2M_{im}^{h+1} \\ & + \sum_{i \in \mathcal{MRC}_m^h} R_i^I * R_i^S * P2M_{im}^{h+1} \end{aligned} \tag{8}$$

2) Active Period Length Estimation: For a BPN b, AP length T_b^a equals the sum of RX period length T_b^{RX} and TX period length T_b^{TX}. To efficiently estimate node b's T_b^a, our distributed algorithms consider the sleep state of the parent nodes as well as the current and future traffic amount. N_b^{BP} represents the current traffic amount, N_b^{SP} and N_b^{RP} indicate future traffic amount. Node b has a large TX period if it has more packets to transmit and a large RX period if it needs to relay more packets.

Let Q_b^C be queue capacity of node b. Estimation of RX period length $T_{b,e}^{RX}$ is given in Alg. 1, which considers buffered packets, self-generated packets and incoming relay packets. Ideally, node b receives until its queue is full and then starts transmitting. However, it may take a long time to fill up the queue if both R_b^S and R_b^I are small. Therefore, a threshold T_{TH}^{RX} is defined.

Algorithm 1 **RX Period Length Estimation**

1: **if** $N_b^{BP} = Q_b^C$, i.e., queue is full **then**
2: $\quad T_{b,e}^{RX} = 0$, i.e., no RX period
3: **else**
4: $\quad T_{b,e}^{RX} = \frac{Q_b^C - N_b^{BP}}{R_b^S + R_b^I}$, i.e., time to fill up queue
5: $\quad$ **if** $T_{b,e}^{RX} > T_{TH}^{RX}$ **then**
6: $\quad\quad T_{b,e}^{RX} = T_{TH}^{RX}$
7: $\quad$ **end if**
8: **end if**

Estimation of TX period length $T_{b,e}^{TX}$ is given in Alg. 2. In TX period, node b does not expect incoming relay packets and only considers buffered packets and self-generated packets. We assume R_b^S is less than the packet transmission rate R_b^T. Otherwise, node b can't sleep. Ideally, node b transmits until its queue is empty. However, it may take a long time to empty queue if no parent is active. Hence, a threshold T_{TH}^{TX} is defined.

Algorithm 2 **TX Period Length Estimation**

1: $T_{b,e}^{TX} = \frac{N_b^{BP}}{R_b^T - R_b^S}$, i.e., time to empty queue
2: **if** $T_{b,e}^{TX} > T_{TH}^{TX}$ **then**
3: $\quad T_{b,e}^{TX} = T_{TH}^{TX}$
4: **end if**

We use both estimated lengths ($T_{b,e}^{RX}, T_{b,e}^{TX}$) and measured lengths ($T_{b,p}^{RX}, T_{b,p}^{TX}$) in previous sleep interval to configure AP length using the exponential weighted moving average (EWMA) with a weight parameter $0 \leq \alpha \leq 1$ as

$$T_b^a = \alpha * T_{b,p}^{RX} + (1-\alpha) * T_{b,e}^{RX} + \alpha * T_{b,p}^{TX} + (1-\alpha) * T_{b,e}^{TX} \tag{9}$$

3) Sleep Period Length Estimation: In sleep mode, a BPN b does not receive any packets and does not transmit any packets. Only self-generated data packets are pushed into queue. Ideally, node b can sleep until its queue is full. However, it may take a long time to fill up queue if R_b^S is small. Therefore, a threshold T_{TH}^S is defined. The SP length T_b^S computation is provided in Alg. 3.

Algorithm 3 **Sleep Period Length Estimation**

1: $T_b^S = \frac{Q_b^C - N_b^{BP}}{R_b^S}$, i.e., time to fill up queue
2: **if** $T_b^S > T_{TH}^S$ **then**
3: $\quad T_b^S = T_{TH}^S$
4: **end if**

4) Active Period Extension: AP extension is a crucial part of the distributed sleep management. It is necessary in cases BPNs need to transmit or receive more packets. At the end of the AP or AP extension, a BPN b determines if it extends AP. We define two modes in which the AP is extended. The first mode is the transmission mode, which represents the case node b has plenty of buffered packets, i.e., N_b^{BP} is greater than a queue threshold Q_{TH}. The second mode is the reception mode that indicates node b is either a reliable relay, i.e., it has received packets and has forwarded all of them, or has not received packets for a long period of time and therefore has more battery energy. In Alg. 4, T_b^{RE} is the latest RX period ending time among all active parents, T_b^{EQ} is time needed for node b to transmit all buffered packets, T_b^{TE} is the latest TX period ending time among all active parents, T_b^{MT} is time needed for node b to transmit the maximum number of allowed packets in parent's TX period (N_{PT}^{MA}), N_b^R is the number of packets received, and E_{TH} is the energy threshold.

Our AP extension is a combination of deterministic and probabilistic approaches. In transmission mode, if node b has any parent in RX period it attempts to transmit all buffered packets, and if node b has any parent in TX period it attempts to transmit N_{PT}^{MA} packets. Probabilistic extension depends on probabilities p_1, p_2 and p_3. The p_1 is related to queue utilization and it needs to be greater for bigger queue utilization. The p_2 and p_3 are related to hop count of node b and are greater as node b approaches the sink node. Nodes having large hop count should not extend their AP with high probability if they are in reception mode. We choose appropriately constants C_1, C_2 and C_3 according to our objective. We want to extend AP with relatively high probability if node b is in transmission mode

Algorithm 4 Active Period (AP) Extension

// Transmission Mode ($N_b^{BP} > Q_{TH}$)
if ∃Parent in RX period **then**
  Extend AP by $\min\{T_b^{RE}, T_b^{EQ}\}$
else if ∃Parent in TX period **then**
  Extend AP by $\min\{T_b^{TE}, T_b^{MT}\}$
else if ∄Parent active **then**
  Pick probability $p_1 = C_1 * N_b^{BP}/Q_b^C$
  Extend AP by N_b^{BP}/Q_b^C second with probability p_1
  if Energy of node b is greater than E_{TH} **then**
    Send AP extension notification message
  end if
  // Reception Mode ($N_b^{BP} \leq Q_{TH}$)
else if Node b has received and forwarded data packets during last AP or AP extension **then**
  Pick probability $p_2 = C_2/hop\_count$ with $C_1 >> C_2$
  if Node b is in this mode for several consecutive times (e.g., 5) **then**
    if Energy of node b is greater than E_{TH} **then**
      Extend AP by N_b^R/Q_b^C second with probability p_2
      Send AP extension notification message
    end if
  end if
else if Node b has not received data packets during last AP or AP extension **then**
  Pick probability $p_3 = C_3/hop\_count$ with $C_2 > C_3$
  if Node b is in this mode for several consecutive times (e.g., 20) **then**
    if Energy of node b is greater than E_{TH} **then**
      Extend AP by T^a_{min} (e.g., 0.1s) with probability p_3
      Send AP extension notification message
    end if
  end if
end if

and therefore C_1 has a large value. On the other hand, a node should extend its AP in reception mode only if it is proved to be a reliable relay, or if it has not received packets for several consecutive active periods or AP extensions. Hence, C_2 and C_3 are chosen to have smaller values than C_1. In simulation, we set $C_1 = 0.8$, $C_2 = 0.2$ and $C_3 = 0.1$.

Alg. 4 shows that node b only announces reception AP extension but not transmission AP extension. The number of times a BPN can extend its AP depends on different objectives. For high packet delivery rate, a BPN can extend its AP as many times as needed. This process is called *PDR-oriented* extension. On the other hand, for long network lifetime, a BPN can extend up to a threshold of consecutive times (5 in simulation). This process is called *Lifetime-oriented* extension.

5) Transmission (TX) Control in Active Period: Using distributed sleep management, all nodes must monitor and maintain parent's RX and TX schedules. MPNs are considered to be in RX period all the time. BPNs announce their RX and TX schedules in wakeup messages and AP extension messages. A node (BPN or MPN) should send packets to parents that are in RX periods. It should select the best parent to send packets. A node sends packets to a parent in that parent's TX period only if its queue overflows and no parent is in RX period. Due to distributed sleep schedules, a node may miss parent's wakeup message or AP extension message. In case of queue overflow, even a node does not receive RX and TX schedules from a parent it can still send a packet to that parent if (i) the node overhears transmission from that parent or (ii) the node overhears a neighbor's transmission to that parent.

IV. Battery energy aware routing metrics for heterogeneous networks

Different metrics exploit different characteristics of the network. Residual energy (RE) is a widely used metric for battery powered networks. RE, however, does not indicate how energy has been consumed, i.e., wasted or used for packet transmission and/or packet relay. We propose two novel routing metrics *Battery Node Energy Waste* (EW) and *Battery Node Relay Cost* (RC) to exploit how energy has been used. We compare EW and RC metrics with the RE metric.

A. Battery Node Energy Waste (EW)

The EW measures the energy consumed by operations not related with packet transmission and reception. Main causes of energy waste are idle listening and overhearing. Idle listening indicates efficiency of the sleep management scheme. Ideally, BPNs should consume as little energy on idle listening as possible and be active only for packet reception and transmission. EW is a sleep aware metric and is used to forward traffic through more sleep effective intermediate nodes, which have consumed less energy on idle listening and overhearing. EW is an additive metric. For MPNs, we define $EW = 0$. For a BPN b, computation of EW metric involves energy consumption on packet transmission (E_{TX}) and energy consumption on packet reception (E_{RX}), which are given by

$$E_{TX} = N_T * ETX * P_T * \frac{L_p}{D_R} \quad (10)$$

$$E_{RX} = N_R * P_R * \frac{L_p}{D_R} \quad (11)$$

where N_T is the number of packets transmitted by b, N_R is the number of packets received by b, P_T is transmission power, P_R is the reception power, L_P is average packet length and D_R is PHY data rate. Let E_0 be the initial energy and RE_t be the residual energy at time t. The total energy consumption is given by $E_c = E_0 - RE_t$. Hence, EW at time t is computed as

$$EW = E_c - (E_{TX} + E_{RX}) \quad (12)$$

B. Battery Node Relay Cost (RC))

The RC measures the energy consumption on reception and transmission of relay packets. RC is also an additive metric. RC metric balances relay packets across intermediate nodes with objective function of selecting paths with small RC. For MPNs, we define $RC = 0$. For a BPN b, computation of the RC metric involves energy consumption on relay packet transmission (ER_{TX}) and energy consumption on relay packet reception (ER_{RX}), which are given by

$$ER_{TX} = NR_T * ETX * P_T * \frac{L_p}{D_R} \quad (13)$$

$$ER_{Rx} = NR_R * P_R * \frac{L_p}{D_R} \quad (14)$$

where NR_T is number of relay packets transmitted by b and NR_R is number of relay packets received by b. At time t, RC metric is computed as

$$RC = ER_{TX} + ER_{RX} \quad (15)$$

C. Distributed ETX Measurement

In this section, we briefly describe the distributed ETX measurement process. We take into account only upward traffic for MP2P traffic pattern. A child node maintains a sequence number for each parent. A parent node uses the sequence number to determine the upward ETX for each child. In order to send updated ETX to children, parents use different approaches depending on whether they are battery-powered or mains-powered. Battery-powered parents include a (Child, ETX) list in wakeup messages so that once a child receives the wakeup message, it also obtains updated ETX metric. On the other hand, mains-powered nodes broadcast (Child, ETX) lists periodically so that mains-powered children can receive ETX update and unicast the ETX update to a battery-powered child once they receive a wakeup message from the child. By using the above described approach, every child obtains updated ETX for each parent and can use it to compute routing metrics, such as EW and RC, or select routes based on ETX.

V. Battery metric aware B-RPL routing protocol

Distributed sleep management and battery energy aware metrics are used to enhance the B-RPL protocol [1]. The B-RPL protocol is an enhanced version of standard RPL [10] to support distributed sleep control in networks consisting of heterogeneous nodes. In this section, we present enhancements we have proposed for B-RPL.

A. Metric Advertisement

Metric advertisement and updates are crucial in order to select the best route among all the candidate routes. In our protocol, routing metrics, e.g., EW, RC, RE and ETX, are not only included in the DODAG Information Object (DIO) messages but also in wakeup messages. In this way, all children have updated metrics regarding the candidate routes every time they receive a wakeup message from a parent. This approach is lightweight and does not significantly increase overhead since BPNs have to transmit wakeup messages.

B. Objective Function (OF) for Route Selection

OF specifies how routing protocols select routes based on specific metrics. For example, for hop count metric and the shortest path OF, a node will select routes with minimum hop count to the sink node. For each metric, different OFs can be defined.

In this paper, our objective is to maximize network lifetime and maintain acceptable packet delivery rate. Hence, we identify OF candidates that satisfy our goal. To maximize the network lifetime, we focus on reducing the maximum energy consumption among BPNs and not the total energy consumption. Therefore, we choose an OF that selects path p from a set of candidate paths P as

$$p \in argmin_{p \in P}[max_{i \in p}(RoutingMetric(i))] \tag{16}$$

where i is a node on path p and $RoutingMetric(i)$ is the value of routing metric at node i. In case of EW, this OF tries to find a path that wastes the least battery energy and in case of RC, this OF tries to find a path that relays the least packets. Thus, in both cases, this OF tries to minimize the maximum energy consumption of a node in the network and maximize lifetime.

In the case of standard RE metric, we are trying to find the path that has maximum residual energy. Therefore, we use OF described as

$$p \in argmax_{p \in P}[min_{i \in p}(RE(i))] \tag{17}$$

VI. Performance Evaluation and Analysis

In this section, we present extensive performance evaluation of our distributed sleep management scheme and battery energy aware routing metrics using the NS2 simulator. The IEEE 802.15.4 MAC and PHY are modified to support sleep operation. We simulated a heterogeneous wireless M2M network containing 500 nodes deployed in a 23×23 grid. Each unit in the grid represents a 10×10 square meter real-world field and contains a single node. Each node is randomly placed in its corresponding square field. A data sink is placed at the center of the grid. Our M2M network consists of BPNs and MPNs. All BPNs have 100% of battery level at the beginning of the simulation. We examine low percentage of MPNs that varies from 1% to 20%, but due to space limit we present results only for 5% of MPNs.

In periodic sleep (PS) scenario, each BPN has a fixed sleep interval with fixed AP length and SP length and wakes up in a periodic pattern. In this case, there is no AP and SP configurations and no AP extension as described in Section III. In simulation, the sleep interval for all BPNs is 60 seconds with 0.05 seconds of AP and 99.95 seconds of SP. We use PS scheme as benchmark to compare performance of our distributed sleep (DS) scheme.

In our simulation, we have also introduced the structured mains-powered node placement (SMNP) and we compare its performance with random mains-powered node placement (RMNP). In SMNP case, we place selected MPNs in specific grid units. For example, selected MPNs are placed in horizontal, vertical or diagonal lines from the center of the grid that the sink node is placed.

The enhanced B-RPL is used as routing protocol. EW, RC and RE metrics are used in simulation. We simulated the data collection scenario in which each node (BPN or MPN) generates 1 packet per minute. The queue capacity of each node is 15 and our simulation runs for 15000 seconds. We use several performance metrics for our evaluation but the main ones are packet delivery rate (PDR), network lifetime and idle time percentage of BPNs.

A. Distributed Sleep Management and Structured Mains-powered Node Placement Performance Evaluation

In this section, we present the performance evaluation of the DS scheme and the SMNP using newly introduced routing metrics. We compare the performance of the DS scheme with the performance of the PS scheme under different scenarios. Following figures show simulation results for 5% of MPNs.

Fig. 1 compares the PDR for different scenarios with EW metric. The PS with RMNP has only 10% of PDR. However, the DS with RMNP obtains 33% of PDR. Therefore, the DS improves PDR by 23%. The PS with SMNP obtains 46% of PDR. On the other hand, the DS with SMNP achieves 78% of PDR. In this case, the DS improves PDR by 32%. With the PS, SMNP improves PDR by 36% and with the DS, SMNP improves PDR by 45%. These results indicate the importance of the MPN placement and they also show that the DS utilizes MPNs better than the PS does. Fig. 2 shows the minimum battery node energy level, which indicates the network lifetime. The PS provides longer network lifetime in expense of the PDR, but the DS still maintains comparable network lifetime.

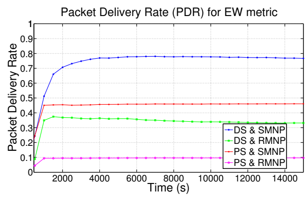

Fig. 1: PDR Per Sleep Scheme

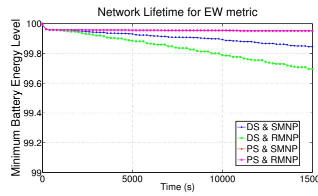

Fig. 2: Lifetime Per Sleep Scheme

Fig. 3 and Fig. 4 show results using the RC metric. It can be seen that the DS and SMNP achieves similar results as those using EW metric. The DS achieves much higher PDR and comparable network lifetime compared with the PS.

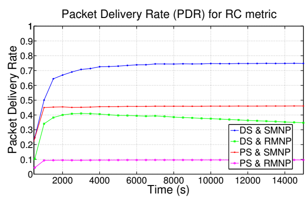

Fig. 3: PDR Per Sleep Scheme

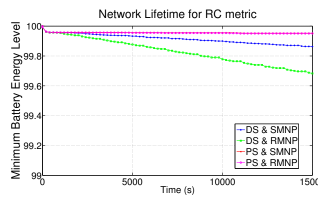

Fig. 4: Lifetime Per Sleep Scheme

B. Routing Metrics Performance Comparison

In this section, we present performance comparison for our newly introduced battery energy aware routing metrics EW and RC described in Section IV. We use standard RE metric as a comparison benchmark. The combined DS and SMNP scenario is used since it is the optimized case. Following figures show simulation results for 5% of MPNs.

Fig. 5 compares PDR across all routing metrics in the optimized scenario. The EW and RC metrics have improved PDR by almost 10% compared with the standard RE metric. The EW achieves the highest PDR. Fig. 6 shows that the EW and RC metrics also perform better in terms of network lifetime than RE metric does. However, the RC metric achieves the best performance in terms of network lifetime. Fig. 5 and Fig. 6 indicate the efficiency of the proposed battery energy aware routing metrics.

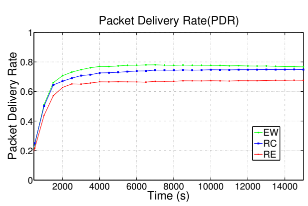

Fig. 5: PDR Per Routing Metric

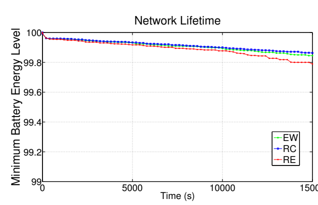

Fig. 6: Lifetime Per Routing Metric

Fig. 7 shows the idle time percentage of the BPNs. Across all routing metrics the idle time percentage is low for all BPNs, which indicates that the proposed distributed sleep management scheme is very efficient so that BPNs are active only if they need to ensure reliability.

Finally, we also have results showing that the total energy consumption for all BPNs is lower with EW and RC metrics in comparison with standard RE metric.

VII. Conclusion

We propose new distributed sleep management techniques for battery powered nodes in heterogeneous wireless machine-to-machine networks. The proposed distributed sleep management techniques enable each battery-powered node to self-determine the optimal times to sleep or wake up and process data based on traffic measurements and predictions. We

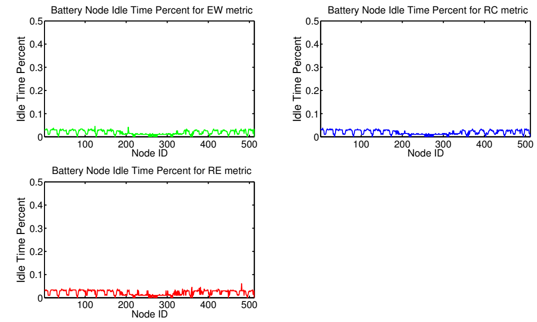

Fig. 7: Battery Node Idle Time Percentage Per Routing Metric

also propose two novel battery energy aware routing metrics, battery node energy waste (EW) and battery node relay cost (RC), that take into account the main causes of energy depletion. We illustrate the effectiveness of our techniques by conducting extensive simulations. The results show significant improvement in comparison with benchmark cases. Our distributed sleep management can improve packet delivery rate (PDR) by 32% compared with periodic sleep scenario while maintaining comparable network lifetime. Our EW and RC metrics outperform the standard residual energy (RE) metric in terms of PDR, network lifetime and idle time percentage. As part of future work, we plan to investigate the combination of energy aware routing metrics according to the routing objective and a formal optimization approach for defining the placement of mains powered nodes in the network.

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