PCOR: A Joint Power Control and Routing Scheme for Rechargeable Sensor Networks

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Abstract- **We propose PCOR, a power control and routing scheme for rechargeable wireless sensor networks (WSNs) that are characterized by spatial and temporal variations of energy resources. The proposed scheme is applied to asynchronous WSNs where overhearing plays a dominant role in the energy consumption. PCOR performs quality aware route selection while reducing the energy consumption in sensor nodes that have low remaining battery life through cooperative and network-wide adaptations of transmit power levels and parent selection. Performance evaluations are presented from extensive simulation studies as well as from an experimental testbed.**

Keywords: **Wireless sensor networks, power control, adaptive routing, distributed algorithms.**

I. Introduction

Powering wireless sensor nodes with energy harvested from the environment, such as solar, mechanical, thermal, and others, is an effective approach for achieving longterm maintenance-free operation of WSNs. A key challenge for achieving reliable and uninterrupted operation of WSNs powered by such renewable energy sources is to adequately address the variability of the energy resources in these devices. Renewable energy such as solar can have wide spatial and temporal variations due to natural (e.g. weather) and location specific factors (e.g. exposure to sunlight) that can be difficult to predict prior to deployment. An illustration of such spatio-temporal variations is shown in Fig 1, which depicts solar irradiance measurements obtained from an experimental testbed of MICAz motes equipped with pyranometers deployed at the UNC-Charlotte campus. The figure shows the irradiance values recorded at three nodes from three different days, illustrating high variations in solar irradiance over both time and space. Because of such variations of available solar irradiance, WSNs powered by solar energy can suffer from frequent and unpredictable node outages that can seriously affect the monitoring operations of the network. Similar problems also arise in WSNs that are powered by other forms of renewable energy resources. An effective approach for addressing this problem is to design network protocols and processing schemes that enable the nodes to dynamically adapt their energy consumption based on estimated energy resources [1], [2], [3], which is the main objective of this work.

We consider WSNs that are applied for environmental monitoring applications, typically using periodic transmissions of sensor observations to a centralized base station. For such data collection traffic, routing protocols such as the *Collection Tree Protocol (CTP)* [4] can be applied to achieve quality-aware routes from each node to the sink. Since network-wide time synchronization is difficult to achieve in resource-constrained sensor nodes, the traditional approach for conserving energy in such networks, especially when the network size is large (i.e. over 100 nodes), is application of asynchronous duty-cycling of sleep and wake states of the radio, such low-power listen [5]. While this is effective in reducing the energy consumption by reducing the radio active times, asynchronous duty cycling typically requires the use of extensively long preambles to be sent with each packet, which leads to energy wastage from overhearing [6], [7]. In our earlier work, we reported experimental assessment of the effect of overhearing in WSNs that apply asynchronous LPL under data collection traffic [2]. Results indicate that even with sleep cycles, overhearing is a dominating factor in the energy consumption in the nodes. Mechanisms such as interruption of reception of unnecessary packets based on information transmitted in the preamble [8], adaptive duty-cycling [9], [10] and others have been proposed to reduce the energy wasted from overhearing caused in such LPL and preamble sampling schemes.

In this work, we consider reducing overhearing by reducing the neighborhood size using transmission power control as well as through route adaptations. Although a significant amount of work has been reported on power control for WSNs, most of it has been directed towards reducing interference effects for improving the communication performance in the network [11], [12]. Here, our objective is to apply power control to achieve energy conservation by *reducing overhearing*. The main challenge for achieving this goal is that the degree of overhearing at a node depends on the transmit power levels and traffic of its *neighbors*. Consequently, effective overhearing control requires *network wide* adaptations of transmit power levels as well the distribution of data traffic in the nodes as opposed to independent adaptations at the nodes. To address these issues we implement a cooperative *joint Power COntrol and Routing (PCOR)* scheme for rechargeable sensor networks that derives benefits from two approaches. First, PCOR applies a prediction model at each node to determine the extent by which it can reduce its power while maintaining acceptable probability of success in data packet delivery to its parent. Secondly, PCOR incorporates a parameter into the routing metric that represents the level of overhearing caused by transmissions along candidate routes to nodes that have critically low energy resources.

II. Preliminaries

We consider a *data collecting* wireless sensor network where nodes follow a tree structure to forward data to the

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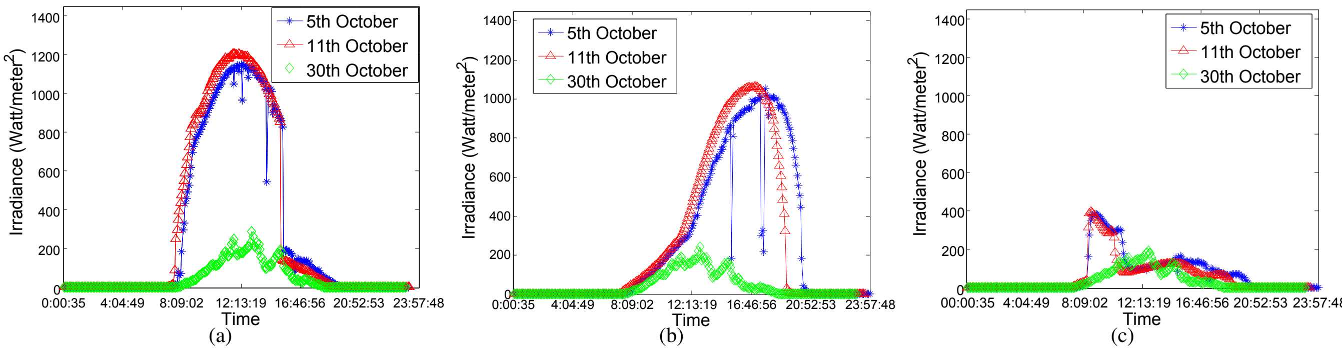

Fig. 1. Irradiance measurement of (a) node 153 (b) node 155 and (c) node 159 for two sunny days (5th and 11th October, 2012) and a cloudy day (30th October, 2012). Node 159 is kept in the shaded region, whereas 153 and 155 gets sunlight most of the time.

sink. There is no network wide time synchronization. It is assumed that the nodes apply asynchronous duty-cycling with uniform duty cycles to conserve energy. In such networks, a node overhears all transmissions within its receiving range, which causes wastage of energy. All nodes are powered by energy harvested from the environment such as solar, which results in random spatial and temporal variations of their energy resources. In PCOR, if a node has significantly lower energy resources compared to its neighbors (termed as an *energy-critical node*), its neighbors cooperatively reduce power to reduce overhearing on that node keeping the link quality within a reasonable range. This power control scheme is performed jointly with an adaptive routing scheme that helps in reducing the amount of overhearing to energy-critical nodes. The objective of the routing protocol is to divert traffic away from regions where energy-critical nodes are located, which in effect reduces overhearing on these nodes. PCOR achieves these objectives by applying a *statistical prediction model* to (i) measure the extent by which a node can reduce its transmit power while maintaining a reasonable link quality to its parent and (ii) the amount of overhearing caused to energy-critical nodes, which we discuss in section III. Before going into the details on the proposed scheme in section IV, we discuss some related terms and ideas first.

We define the *battery health-metric* H of a node to represent its remaining battery lifetime, i.e. the estimated time until its battery is depleted under its currently estimated energy usage. We assume $H \propto \frac{B}{\mathcal{I}}$, where B is the remaining capacity of the battery and $\mathcal{I}$ represents the estimated current drawn at the node. The current drawn in each node is represented as [13]:

$$\begin{aligned} \mathcal{I} &= \frac{I_{Bt}T_{Bt}}{T_B} + M.I_{Dt}T_{Dt} + N.\frac{I_{Br}T_{Br}}{T_B} + O.I_{Dr}T_{Dr} \\ &+ F.I_{Dt}T_{Dt} + \frac{I_sT_s}{T_D} + N_P.I_PT_P \end{aligned} \quad (1)$$

where I_x and T_x represent the current drawn and the duration, respectively, of the event x; and T_B represents the beacon interval. Transmission/reception of beacons is denoted by B_t/B_r, data transmit/receive is denoted by D_t/D_r and processing and sensing are denoted as P and S, respectively. O and F are the overhearing and forwarding rates, respectively, and N is the number of neighbors. M is the rate at which a node transmits its own packets. If there are no retransmissions, then $M = \frac{1}{T_D}$, where T_D is the data interval. N_P represents the number of times that a node wakes per second to check whether the channel is busy, and is set to 8 in our application. We assume that each node is able to estimate all the dynamic parameters that are used in equation (1), by periodic assessments of its overheard and forwarded traffic.

We define a node to be energy-critical if its $H < \alpha.\mu_H$, where μ_H is the mean of its neighbors health metrics. Energy-critical are indicated by a variable called *critical node (CN)* that is set to 1. It then makes the POC = $\frac{\mu_H - H}{\mu_H}$. Otherwise, the node is considered as a good node and POC = 0 for all good nodes. The parameter POC is mainly used by an energy-critical node to inform its neighbors how much cooperation is required from them in conserving its energy. If a node's condition is very critical, it broadcasts a high POC, prompting its neighbors to reduce their transmit powers with high probability. The reverse happens when a node is less critical.

In addition to energy considerations, PCOR also tries to achieve a minimum quality of established routes. To estimate the quality of a route, we use a path metric that is obtained as the sum of the *expected number of transmissions (ETX)* on each of its links, which is the same principle applied in CTP. An ETX for a link is the expected number of transmission attempts required to deliver a packet successfully over the link. In CTP, path selection is performed based on maximizing a path quality metric, which implies minimizing the path-ETX, which is the sum of link ETXs along the path. This is achieved as follows. The sink always broadcasts an ETX = 0. Each node calculates its ETX as the ETX of its parent plus the ETX of its link to the parent. A node i chooses node j as its parent among all its neighbors if ETX$_{ij}$ + ETX of $j <$ ETX$_{ik}$ + ETX of k $\forall k \neq j$, where ETX$_{ij}$ and ETX$_{ik}$ are the ETX of link $i \rightarrow j$ and $i \rightarrow k$ respectively. In this process a node chooses the route with the lowest ETX value to the sink. We define forward-ETX of a link as the ETX in the forward direction, i.e. from sender to the receiver. We also define min-ETX of a node as the path-ETX of the best quality route towards the sink.

III. Prediction Model for Power Control

We now develop a power control model that represents the relationship between a node's transmission power level and its forward link quality with a minimum number of parameters. The model can also be applied to determine the level of overhearing caused by a node to a specific neighbor. The objective is to develop a mechanism for nodes to estimate

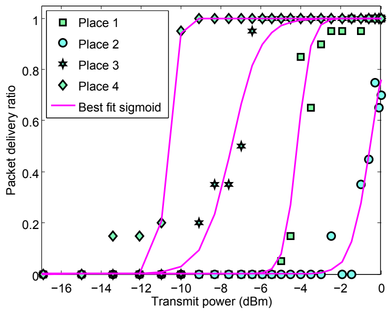

Fig. 2. Sigmoid best fit curve of delivery ratio vs transmit power.

the range of transmit power levels that can be used for cooperative overhearing control and quality-aware route selection. Note that overhearing is really a physical layer phenomenon; however, the amount of overhearing can be estimated from the number of received packets as observed at the network layer.

We observe that the packet delivery ratio (PDR) of a link under *log-normal shadowing* can be represented as follows.

$$\begin{aligned} PDR &= Prob\left[P_r(d) > \gamma\right] = Prob\left[P_t - P_l(d) > \gamma\right] \\ &= Prob\left[P_t - \overline{P_l(d)} + X_\sigma > \gamma\right] = Q\left(\tfrac{\gamma - P_t + \overline{P_l(d)}}{\sigma}\right) \end{aligned}$$

where P_t is the transmit power, $P_r(d)$ and $P_l(d)$ are the power received and path loss at distance d, γ is the threshold for minimum received signal level at the received. X_σ is a Gaussian random variable, used to model the shadowing effects that has a zero-mean and a standard deviation of σ.

Our proposed model comprises of a relationship between the packet delivery ratio p and the transmit power t that is represented by only two parameters that can easily be estimated from a sequence of transmission measurements between a transmitter and a receiver using a linear regression curve-fitting approach. The model is essentially a sigmoid function that effectively approximates the distribution of delivery ratio at different transmission power levels. By using extensive experimental results, we model this relationship as

$$p = \tfrac{1}{1+e^{-(a.t+b)}} \qquad \Rightarrow a.t + b = \ln\left(\tfrac{p}{1-p}\right) = P \text{ (say)}$$

A set of sigmoid curves that represent this model for different transmitter receiver pairs are shown in Fig 3. We formulate this predictive model in the following way, which uses two vectors $\mathbb{T}$ and $\mathbb{P}$. $\mathbb{T}$ contains all transmission power levels, thus $\mathbb{T} = \{t_1, t_2, ..., t_N\}$. The vector $\mathbb{P}$ contains all the $\ln\left(\frac{p}{1-p}\right)$ terms, i.e. $\mathbb{P} = \{P_1, P_2, ..., P_N\}$. Thus, expressing equation (2) in matrix form we get

$$\begin{bmatrix} t_1 & 1 \\ \vdots & \vdots \\ t_N & 1 \end{bmatrix} \begin{bmatrix} a \\ b \end{bmatrix} = \begin{bmatrix} P_1 \\ \vdots \\ P_N \end{bmatrix} \Rightarrow \begin{cases} a = \frac{\sum P_i . \sum t_i - m . \sum t_i . P_i}{\sum t_i . \sum t_i - m . \sum t_i^2} \\ \text{and} \\ b = \frac{\sum P_i - a . \sum t_i}{m} \end{cases}$$

Note that a and b can change with time, depending on link characteristics. The idea is for each node to estimate these values and broadcast them using beacon messages. Beacon messages are sent with the highest power so that all neighboring nodes can receive them.

Here we need to mention three points which are important corresponding to this prediction model. First, the accuracy of this prediction model increases with the number of data samples. Thus the prediction model is used only when a node gets enough confidence over a link, i.e. if it receives enough data packets covering a significant range of PDR values. Second, this prediction model is receiver-oriented, i.e. the receiving node is able to estimate the coefficients (a, b) of a link when it receives or overhears packets transmitted by a sender in different power levels The coefficients a and b are then broadcasted along with the sender ID with the beacon messages. If the receiver does not have enough confidence from its data samples, it simply broadcasts a and b with their default values. The transmitter uses these coefficients to predict the link quality to that receiver for any power level. Third, beacons are transmitted periodically with the highest transmit power. Note that in this scheme a node appends the coefficients and the neighbor ID corresponding to each neighbor in its beacon message. If a node has a large number of neighbors, this scheme increases the packet size. To restrict the beacon message size, in our scheme a node appends n (we assume n to 3) neighbor's ID and coefficients in each beacon. Thus the neighbor IDs as well as their coefficients are appended in a round-robin fashion, each time for n neighbors.

IV. The Proposed Cooperative Joint Power Control and Route Adaptation (PCOR) Scheme

We now present the proposed joint power control and routing scheme PCOR for WSNs that mainly tries to fulfill two objectives. First, it reduces overhearing on *energy-critical nodes*. This will extend the overall lifetime of the network. Second, routes are adapted dynamically and in a distributed fashion to avoid regions that have energy-critical nodes, which reduces forwarding and overhearing rates on the nodes that have critically low energy resources. All nodes periodically determine their parents as well as transmit powers based on their neighboring link qualities and their neighbors health metrics. We assume that all nodes broadcast periodic beacon messages, which include their node ID, its ETX value, CN (which is 1 if a node is critical and 0 otherwise), and the POC. Besides that a beacon message includes n neighbor IDs, their corresponding coefficients and the current forward-ETX (ETX$_F$) of the link from its neighbor to itself, as well as its current transmit power level. For the sake of simplicity, we explain the power control and parent selection separately as follows. Although power control and parent selection are described separately, these are done jointly as explained later.

Power control: If there are no energy-critical nodes in the network, then it works the same as CTP. The parent is selected as the neighbor with lowest ETX and is done periodically. The power adaptation does not take place in this case. When a node becomes critical, it broadcasts its beacon message with CN = 1. Any node that receives a beacon with CN = 1 adapts its transmit power level to its parent as follows:

Reduce transmit power in steps: If it only knows the default values of the coefficients a, b for the forward link to its parent, it reduces its transmission power in steps, i.e. by β, with probability = POC of its critical neighbor, if its link-ETX is less than some threshold ETX$_m$ and its current transmit power is more than a minimum level. If it receives beacon messages from multiple critical nodes, the power is reduced with probability equal to the maximum of all POCs

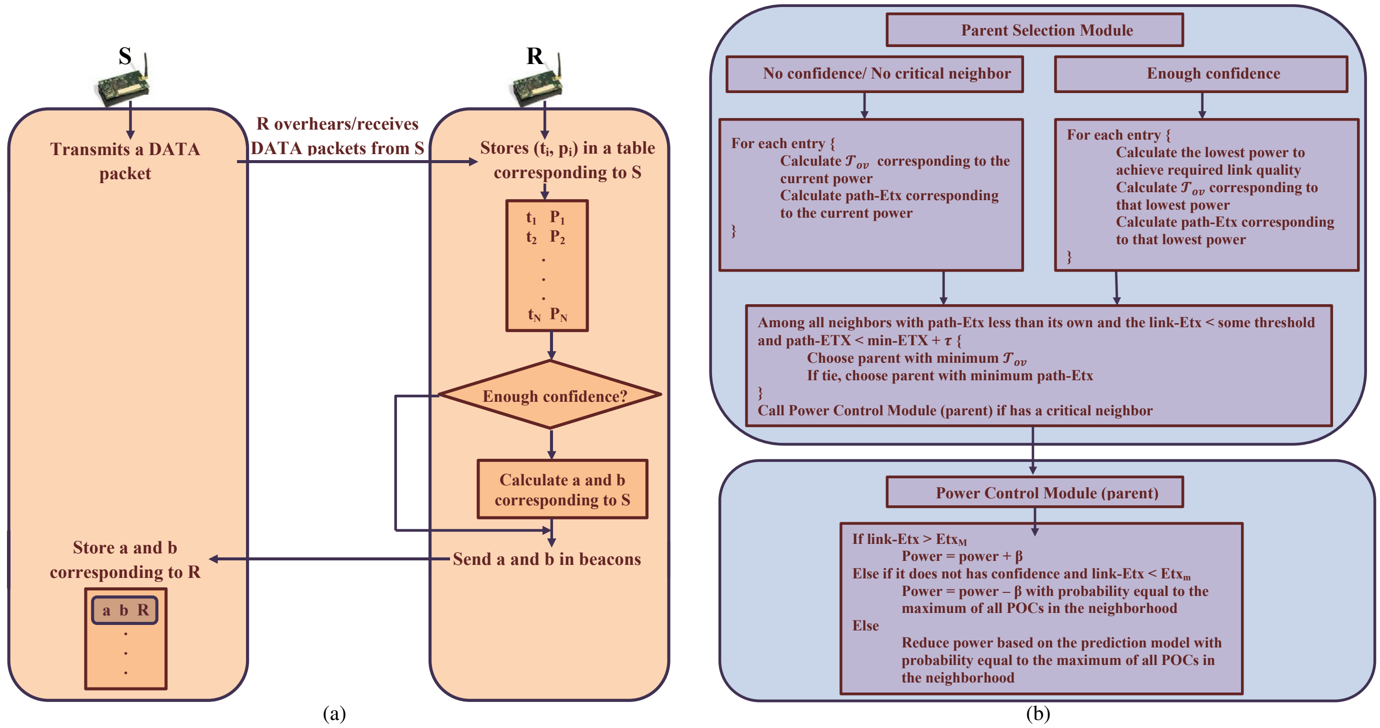

Fig. 3. (a) Receiver-oriented prediction model. (b) Proposed joint power control and route adaptation scheme.

of the critical nodes. This results in reduced overhearing on the critical nodes.

Reduce transmit power using the prediction model: If the node is aware of the estimated (non-default) values of the parameters (a, b) for the link with its parent, it uses the prediction model to reduce its power. In that case the node uses transmit power t such that t is the minimum transmit power to achieve a delivery ratio greater than some threshold required to maintain a minimum link quality.

Increase power: A node starts increasing power in steps of β if (i) the link-ETX to its parent goes beyond a threshold ETX_M, or (ii) its $\mathbb{R}$ consecutive transmissions to its parent fail. For our performance evaluations, we assume $\mathbb{R}$ to be 10.

Parent selection: As the change in transmit power affects the ETX, adapting transmit power may result a node to adapt its route, i.e. parent selection as well. Hence, our scheme effectively ties routing with power control. If a node is not a direct neighbor of a critical node, it does not adapt its transmit power; but it may still select a parent such that the chosen route avoids the neighboring regions of the critical nodes. This is implemented by a route metric $\mathcal{T}_{ov}$, which represents the total overhearing caused by all transmissions along the route to energy-critical nodes. $\mathcal{T}_{ov}$ is computed as follows. Let $\mathcal{N}_{ov}$ of a node represent the rate of its packets that are overheard by its worst critical neighbor, i.e. $\mathcal{N}_{ov} = F.p_{ov}$, where p_{ov} is the probability that packets transmitted by the node are overheard by its most energy-critical neighbor. p_{ov} is basically the packet delivery ratio which can be measured (i) from the prediction model corresponding to any power level, if estimated (non-default) values of the coefficients are known or (ii) from ETX_F if the coefficients are their default values.

The sink broadcasts beacons with $\mathcal{T}_{ov} = 0$. The value of the routing metric from node i to the sink is represented as $\mathcal{T}_{ov}^{i}$, and the value of the routing metric for node j if it selects node i as its parent is $\mathcal{T}_{ov}^{ij}$, which is given as the $\mathcal{T}_{ov}^{i}$ broadcasted by i plus its own $\mathcal{N}_{ov}$. For each entry i in its neighbor table, a node j calculates the minimum transmit power t_{ij} required to achieve a minimum link quality from the prediction model if the non-default coefficients are known. Otherwise it considers its current transmit power level t_c. It also calculates its $\mathcal{N}_{ov}^{ij}$, which is its $\mathcal{N}_{ov}$ corresponding to the transmit power (t_{ij} or t_c) and record the metric $\mathcal{T}_{ov}^{ij}$ which is the sum of that $\mathcal{N}_{ov}^{ij}$ and the $\mathcal{T}_{ov}^{i}$ sent by neighbor i. Also it calculates the link-ETX and path-ETX based on that transmit power. It then chooses the entry corresponding to the minimum $\mathcal{T}_{ov}^{ij}$ $\forall$ i among the neighbors that has (i) an ETX less than its own (to avoid routing loop) and (ii) has a reasonable link-ETX (to avoid links with very poor quality) and (iii) the path-ETX $< \tau$ + min-ETX (to avoid routes that have very low quality than the best quality route), as its parent. For our performance evaluations we assume τ to be 0.5. The $\mathcal{T}_{ov}^{ik}$ corresponding to its parent entry k is then broadcasted using the beacon messages. In case of a tie, it chooses the parent that gives least path-ETX. Thus a route with minimum $\mathcal{T}_{ov}$ is the route that overhears the critical nodes with least probability and the route with minimum path-ETX gives the route with minimum cost. While choosing its parent k in this process, the node j determines its transmit power (t_{kj} or t_c) as well, which fulfills our objective of *joint* power control and route adaptation to avoid overhearing on the critical nodes. This transmit power and parent selection go on periodically.

The design for our joint power control and route adaptation scheme is depicted in Fig 3(b). The proposed scheme does

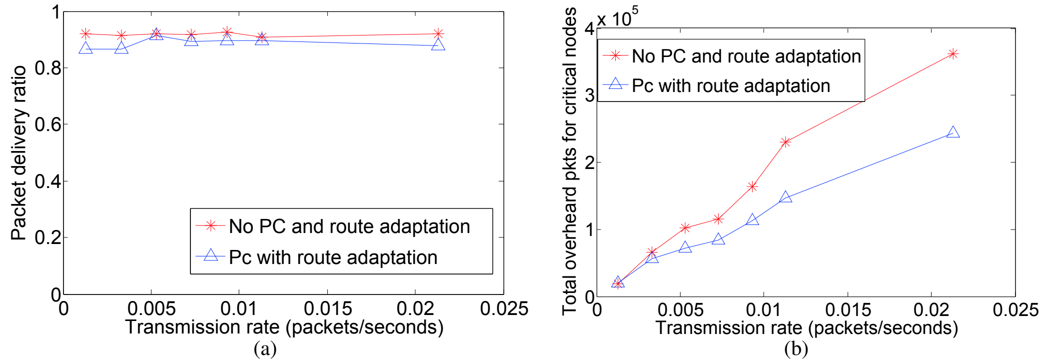

Fig. 4. Comparison of (a) packet delivery ratio and (b) packets overheard by the critical nodes with different rates.

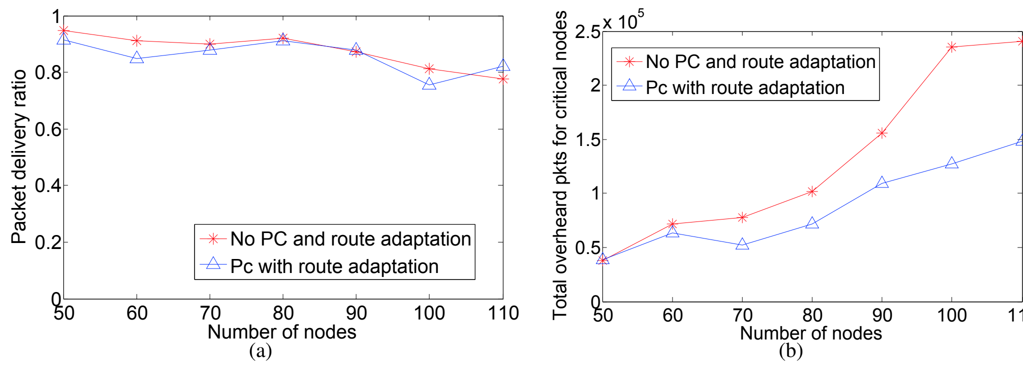

Fig. 5. Comparison of (a) packet delivery ratio and (b) packets overheard by the critical nodes with different node density.

not incur any additional control overhead other than periodic beacon updates. Problems such as routing loop detection and repairing are tackled similar to CTP.

V. Performance Evaluation

This section presents evaluation results of PCOR from experiments on a real testbed as well as from simulations. We implement the proposed scheme in the Castalia simulator [14] to demonstrate its effects on a large network. We also demonstrate that our proposed multi-channel scheme effectively reduces overhearing on the critical nodes using an experimental testbed comprising of 25 MICAz motes.

A. Simulations

We simulate our joint power control and routine scheme in the *Castalia* simulator where nodes are placed in grid structure in an area of 100×100 meters. We have chosen 10% nodes to be critical nodes that has less capacities as well as receive less amount of sunlight compared to others. In this way we try to imitate an actual spatial nature of an outdoor environment. The beacon interval varies between 5 seconds to 50 seconds similar to *Trickle* algorithm used in CTP. The maximum retransmission count is set to 3. Routes are updated in every 8 seconds. At first transmit power is controlled periodically in every 5 minutes. When a node receives confidence for using the sigmoid model, the transmit power is updated along with the route updates. Each simulation is run for around four hours. Parameters used for experiments are listed in Table I.

TABLE I. Parameters Used

Var	Values	Var	Values	Var	Values	Var	Values
I_{Bt}	20 mA	T_{Bt}	140 ms	I_{Br}	20 mA	T_{Br}	140 ms
I_{Dt}	20 mA	T_{Dt}	140 ms	I_{Dr}	20 mA	T_{Dr}	140 ms
I_P	20 mA	T_P	3 ms	I_S	7.5 mA	T_S	112 ms

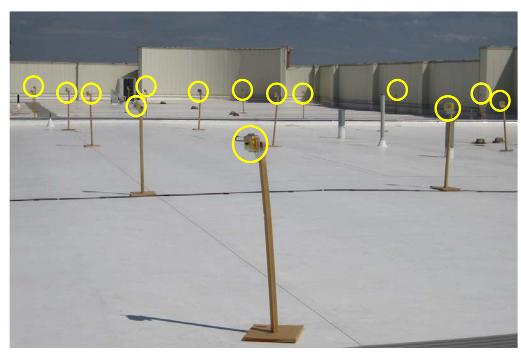

Fig. 6. A 25-node wireless sensor network testbed.

Comparison with different rates: Fig 4 shows the variation of the packet delivery ratios, as well as the overhearing counts for the critical nodes with different transmission rates, where 80 nodes are placed in a grid. It is observed that the packet delivery ratio is above 90% for all cases. However, overhearing is reduced by nearly 20-25% for the critical nodes when the transmit power is controlled with route adaptation. This clearly shows the effectiveness of our proposed scheme in reducing overhearing on the critical node without significantly affecting the overall packet delivery ratio.

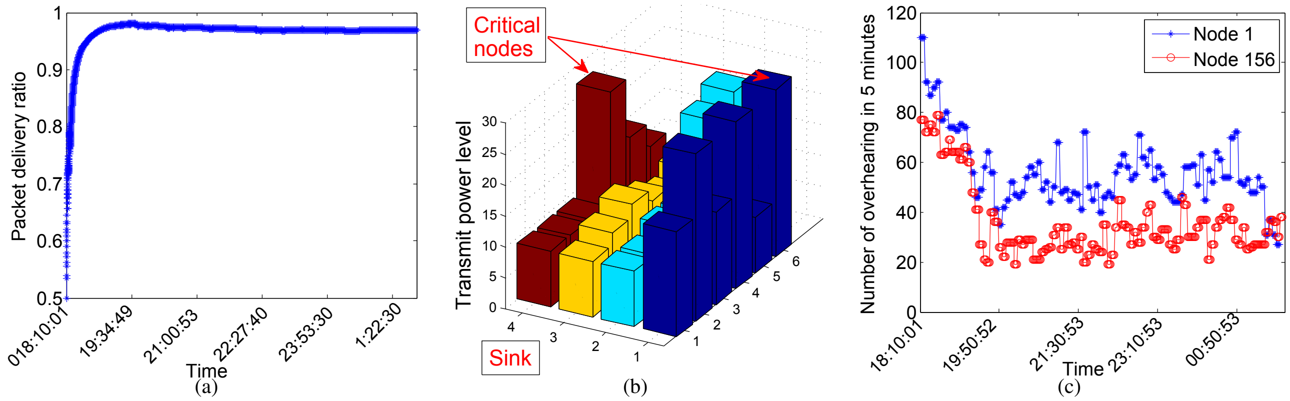

Fig. 7. (a) Overall packet delivery ratio to the sink over time. (b) Transmit power levels of different nodes, power level 27 corresponds to -1 dBm and power level 9 corresponds to -13.4 dBm. (c) Number of packets overheard by the two critical nodes over time.

Comparison with different node density: Fig 5 shows the variation of the packet delivery ratios and overhearing counts for the critical nodes, where the number of nodes are varied from 50 to 110. From this figure also we can observe that with different node densities, the overhearing on the critical nodes are reduced by a significant amount, which validates the effectiveness of our proposed transmit power control and route adaptation scheme.

B. Experimental Tests:

We implement our proposed scheme PCOR in TinyOS in an experimental testbed comprising of 25 MICAz sensor nodes as shown in Fig 6. The motes periodically sense and forward sensor data to the sink using our proposed power control and route adaptation scheme. The beacon interval is adaptively varied between 525 milliseconds and 1 minute. The DATA interval is chosen to be 1 minute. The transmit power is varied between -1 dBm to -13.4 dBm. We place two critical nodes whose energy availability is assumed to be significantly lower compared to others. The maximum number of retransmissions is set to 5. ETX_m and ETX_M are set to be 1.5 and 2, respectively.

The results obtained over a duration of six hours are shown in Fig 7(a)-(c). All nodes start with the maximum power level of -1 dBm and then gradually reduce power and adapt routes to avoid overhearing caused to the energy-critical nodes. Fig 7(b) shows the transmit power levels of different nodes after six hours, which shows that most of the nodes significantly reduce their transmit power. At the same time we can see some variations in transmit power levels, which comes from the spatial variations of the route and channel qualities. Fig 7(c) shows the variation of overhearing with time for the critical nodes which clearly shows the reduction in overhearing on the critical node due to power control and route adaptation done by the other nodes. These results demonstrate that PCOR signficantly reduces energy wastage due to overhearing on the energy-critical nodes without affecting the packet delivery ratio significantly (Fig 7(a)).

VI. Conclusions

In this paper, we propose a distributed scheme for controlling transmit power and adapting routes dynamically in a data gathering rechargeable wireless sensor networks for maximizing the network lifetime. Through simulations, we demonstrate that our proposed scheme significantly reduces overhearing on the critical nodes. The proposed scheme has no additional overhead other than periodic beacon updates, which makes it suitable for implementations in real-life applications to prolong the network lifetime.

Acknowledgement

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