A Distributed Power Control and Routing Scheme for Rechargeable Sensor Networks

Amitangshu Pal, Bonee Soibam and Asis Nasipuri
Electrical & Computer Engineering, The University of North Carolina at Charlotte, Charlotte, NC 28223-0001
E-mail:{apal,bsoibam,anasipur}@uncc.edu

***Abstract-* We propose a joint power control and quality aware routing scheme for rechargeable wireless sensor networks (WSNs) that are characterized by a high degree of spatial and temporal variations of energy resources. The proposed scheme adapts the energy consumption in the nodes to meet their corresponding energy resources with the objective of attaining network wide reliability of operations. This is achieved by dynamically controlling the transmission powers and route selection. Some initial performance evaluations are presented from experimental studies to show the effectiveness of the proposed scheme.**

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

I. INTRODUCTION

Wireless sensor nodes are equipped with an integrated low power processor, memory and a radio that are dependent on its local energy supply. Since batteries are difficult to replace, the popular approach for achieving long term operations in wireless sensor networks (WSNs) is by utilizing harvested energy from renewable resources, such as solar. However, renewable energy 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. Consequently, rechargeable wireless sensor networks must have mechanisms to dynamically adapt their energy consumption based on estimated energy resources.

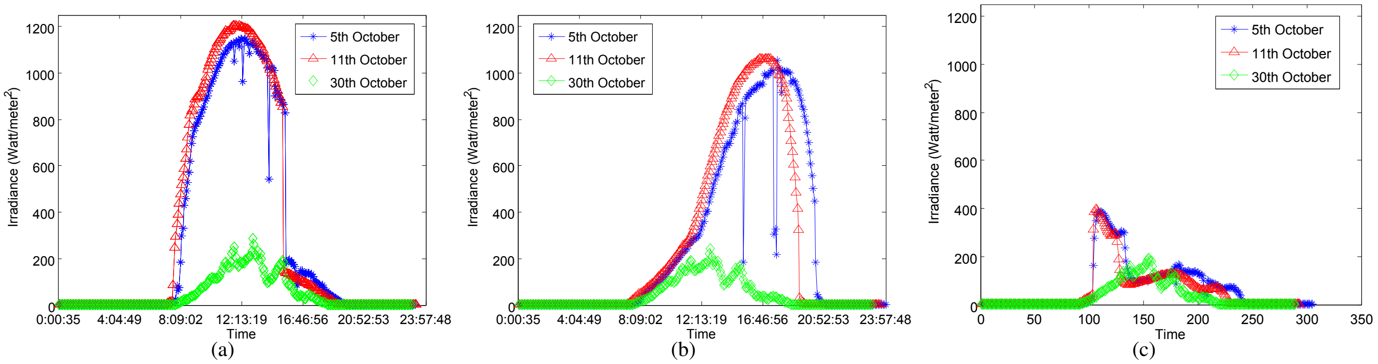
Transmission power control has been widely researched in the wireless community [1], [2]. The objectives of these schemes are mainly twofold: First, reducing transmit power reduces energy consumption on the sending node. Second, interference is reduced significantly by reducing transmit power. However, in low power wireless sensor nodes, the amount of energy consumed for transmissions is generally smaller than that consumed for receiving. In particular, in large scale WSNs that do not use transmission scheduling due to difficulties in achieving tight network-wide time synchronization, *overhearing* is the dominating factor that affects its energy consumption [3], [4]. Moreover, when the packet size and the packet transmission rates are small, interference is usually not a primary performance factor. The objective of the current work is apply transmit power control and route adaptations for controlling the energy consumed from overhearing. The main challenge 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 as opposed to independent adaptations at the nodes.

A significant amount of work has been reported on power control for WSNs. In [5], [6] the authors propose power control schemes that use feedback control to set the transmit power of a link to minimum level to achieve a required link quality. Unfortunately, these schemes do not address power control based on node specific requirements, which is a key objective of our work. Also, all these above schemes propose power control for a specific link. But power control is tied with routing as changing the link quality of a link results in changes in route selection. Thus the power control problem should be considered jointly with routing, which is one of the contributions of this work.

The rest of the paper is organized as follows. In section II, we summarize the motivations and objectives behind our work. Section III describes our proposed distributed power control scheme for WSNs. Some experimental results of our proposed scheme are discussed in section IV. We conclude our paper section V.

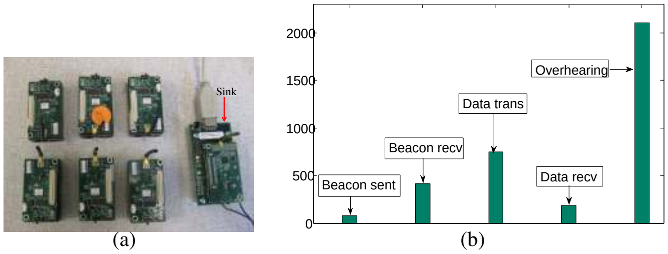
II. MOTIVATION AND OBJECTIVES

Development of effective solutions for energy harvesting from renewable resources is gaining increasing importance for achieving long term reliable operations of wireless sensor networks. This includes energy from sunlight, vibrations, heat, magnetic field, and others. All these sources produce spatial and temporal variations. In this paper we mainly focus on solar energy harvesting. A large scale WSN may comprise many sensor nodes placed somewhat randomly geographically, e.g. for environmental or structural monitoring applications. Random node placement may locate some nodes in shadows and others in extended sunlight. Nodes have different orientations, affecting the irradiance collected by the solar panels. Changes of weather and sun orientation also change solar power intake over time. This paper proposes a technique for adapting the transmit power levels as well as route selection to address these spatio-temporal characteristics in rechargeable wireless sensor networks. To study the nature of this spatio-temporal variations, we deploy an experimental testbed using a set if MICAz motes with irradiance sensors on the rooftop of our department building and collect irradiance data over a period of few months. Fig 1 shows the irradiance values of three



(a) (b) (c)

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.



(a) (b)

Fig. 2. Experimental setup (a) to assess the activities of the radio (b) of a wireless sensor node performing data collection.

motes in three different days, illustrating high variations in the amount of irradiance over both time and space.

Radio transmissions as well as receptions are the critical energy-consuming tasks in typical low-powered wireless sensor nodes. For instance, the MICAz nodes draw about $20mA$ of current while transmitting and receiving, whereas it draws about 20 μA in idle mode and $1\mu A$ in sleep mode. Hence, a key aspect of designing energy-efficient wireless sensor nodes is to minimize the radio active periods, allowing the node to sleep as long as possible. Popular energy efficient wireless sensor networking protocols such as $XMesh$ [7] employs low-power (LP) operation by letting nodes duty cycle in their sleep modes for brief periods of time to detect possible radio activity and wake up when needed. While this principle extends the battery life (lifetime) of the nodes considerably, a key factor that leads to energy wastage is *overhearing*, i.e. receiving packets that are intended for other nodes in the neighborhood. The traditional mechanism used for avoiding overhearing is transmission scheduling, which requires time synchronization that we assume is absent in the WSNs.

The effect of overhearing is illustrated in Figure 2, which depicts an experiment using six MICAz motes and a sink. The network is programmed with the *collection tree protocol (CTP)* [8] application where each node transmits periodic data packets comprising of sensor observations with an interval of 10 seconds and routing packets (beacons) with an interval that varies between 128 and 512000 milliseconds. The network uses the beacons to build link quality based least-cost routes from all nodes to the sink. All nodes use an extremely low transmit power of -28.5 dBm and apply the *LowPowerListening* scheme [9] with a wake-up interval of 125 milliseconds. We run this experiment for 10 minutes and record the total number of beacons and data packets sent/received throughout the network as well as the network wide overhearing. The results, shown in Figure 2(b), indicate that even with sleep cycles, overhearing is a dominating factor in the energy consumption in the nodes. In our previous works [10], [11] we developed a mechanism to distribute the network traffic over multiple channels which led to reduction in overhearing and significant improvement in the lifetime of the network. In this work we propose the scheme of cooperative power control to reduce overhearing on the nodes that are critical in terms of remaining battery capacities.

Thus the objective of designing the power control and routing scheme is to adapt the energy consumption in the nodes by *controlling the corresponding overhearing traffic* as determined by network traffic in their neighborhoods. In the absence of such adaption, nodes that are in the shadowed region will deplete all their energy faster, which can result in unbalanced lifetimes of the nodes. This paper addresses a distributed collection tree based power control and routing scheme where each node controls its transmit power based on amount of energy-intakes, battery remaining capacities and usages of its own as well as in its neighborhood.

III. POWER-CONTROLLED ROUTING IN WSNS

We consider a *data collecting* wireless sensor network where nodes follow a tree structure to forward data to the sink. In these kind of networks, a node overhears all nodes that are in the receiving range of that node. Also based on different forwarding and overhearing rates, the rate of battery drainings are also different. In this paper we assume that the amount of harvesting energy intake is reflected in the nodes battery voltages, which we use to calculate the battery health condition as explained later. In our power control scheme, if a node has lesser battery health compared to its neighbors, the neighbors cooperatively reduce power to reduce overhearing on that node keeping the link quality within a reasonable range. This power controlling scheme may result a node to change its route that helps its neighbor that is of lesser battery health.

A. Preliminaries

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. Based on the experimentally validated model [12], the current drawn in each node is calculated as follows:

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

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 assessment of its overheard and forwarded traffic.

The battery capacity B (energy resource) depends on a number of factors that include the solar irradiance, the efficiency of the solar panel, the efficiency of the converter circuit, as well as physical and environmental factors such as temperature and state of health of the battery or storage element. An appropriate model for estimating the battery state of charge is currently being developed by the researchers, and will be included in future work. For the development and evaluation of the power control and routing scheme for adapting the energy consumpiton at the nodes to their battery health, we assume that the battery capacity is obtanied from battery voltage. To further simplify the task of estimating B, we apply a linear relationship between the battery voltage and B, which is explained later.[1]

To estimate the quality of a route, we use the *expected number of transmissions (ETX)* that is used in *Collection Tree Protocol (CTP)* which is discussed later. An ETX is the expected number of transmission attempts required to deliver a packet successfully to the receiver. Hence, a low ETX value indicates a good end to end quality of a route, and vice versa. In our scheme, ETX is calculated similar to [8].

B. Collection Tree Protocol (CTP)

CTP is a tree based collection protocol whose main objective is to provide best effort anycast datagram communication to one of the collection root nodes in the network. At the start of the network some of the nodes advertise themselves as the root nodes or sink nodes. The rest of the nodes use the root advertisements to connect to the collection tree. When a node collects any physical parameter, it is sent up the tree. As there can be multiple root nodes in the network, the data is delivered to one with the minimum cost. CTP is an *address free protocol*, so a node does not send the packet to a particular node but chooses its next hop based on a routing gradient. CTP uses ETX as its routing gradient as mentioned earlier. 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. This measure assumes that nodes use link-level acknowledgements and retransmissions. 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.

C. The Proposed Cooperative Power Control Scheme

We now present the proposed power control and routing scheme for WSNs that mainly tries to reduce overhearing on *critical nodes*, which are nodes that have battery health lower than average. This will extend the overall lifetime of the network. 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, ETX value and a field named *critical node (CN)* which is 1 if a node is critical and 0 otherwise. Also the beacon message carries another field named *probability of control (POC)* which is explained later.

We define a node as critical node if its $H < \alpha.\mu_H$, where μ_H is the mean of its neighbors health metrics. It then makes the POC = $\frac{\mu_H - H}{\mu_H}$. Otherwise, the node is considered as good node and POC = 0 for all good nodes. The parameter POC is mainly used by a critical node to inform its neighbors how critical the node is. If a node's condition is very critical, it broadcasts a high POC. So its neighbors reduce their transmit power with high probability. The reverse happens when a node is less critical.

If a node is not in a critical stage, it broadcasts beacons with CN = 1 and everything works 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. Nodes that receive a beacon with CN = 1 reduce their power by β with probability POC that is sent by the critical node, if its link-ETX is less than some threshold ETX$_m$ and its current transmit power is more than a minimum level. Link-ETX of a node is defined as the ETX of the link between that node and its parent. If it receives beacon messages from multiple critical nodes, the power is reduced with probability equal to the maximum of all POCs

---

[1] Note that the battery voltage does not accurately reflect its state of charge, however, it is a simple way to obtain an approximate measure of the level of charge in a battery.

of the critical nodes. This results in reduced overhearing on the critical nodes. Also if the link-ETX of any node goes beyond a threshold ETX_M, nodes start increasing power in steps of β. In this scheme the change in transmit power affects ETX which results in change in routes. Thus the joint power control and routing is achieved that tries to avoid overhearing traffics on critical nodes. The pseudocode for our power control scheme is depicted in Algorithm 1.

Algorithm 1 Power control scheme for any node i

```
CN_i = 1, if $i$ is a critical node and 0 otherwise
$X_i$ = 1, if $i$ is a neighbor of a critical node and 0 otherwise
power_i = current transmit power of node $i$
linkETX_i = ETX of the link between node $i$ and its parent
$P_m$, $P_M$ = Minimum and maximum transmit power
if linkETX_i $> \text{ETX}_M$ && power_i $\leq P_M - \beta$ then
    power_i = power_i + $\beta$
else
    if $X_i$ == 1 && CN_i $\neq$ 1 && linkETX_i $< \text{ETX}_m$ && power_i $\geq P_m + \beta$ then
        power_i = power_i - $\beta$ with probability = maximum POCs of all critical nodes
    end if
end if
```

D. Discussion

Our proposed power controlled routing scheme takes into account a number of factors that are explained as follows:

Battery state of individual nodes: The battery state of any node is taken into account by using the term B. If the battery condition of any node is bad, its health metric decreases. When it becomes a critical node, its neighbors reduce power with some probability which tries to reduce overhearing on that critical node.

Reduced load and overhearing on critical nodes: The term $\mathcal{I}$ calculates the average current consumption of a node. Thus, if a node becomes a critical node due to over-usage, its health metric decreases. So that nodes in its neighborhood reduces power with some probability.

Route quality: Also the ETX quantifies how good a route is. The route quality is important as bad routes result in more retransmissions which reduce the network lifetime.

The proposed scheme does not incur any additional control overhead other than periodic beacon updates. Also to avoid *idle listening*, nodes use low-power listening [9] where they sleep most of the time and wakes up in a periodic interval. If they sense the channel to be busy, they remain on. Otherwise, they go back to sleep to conserve energy. Problems such as routing loop detection and repairing are tackled similar to CTP.

IV. PERFORMANCE EVALUATION

This section presents evaluation results of our power control scheme from experiments on a real testbed. We first demonstrate that our proposed power control scheme effectively reduces overhearing on critical nodes using an experimental testbed comprising of 13 MICAz motes consists of a sink in an area of 12×9 meters^2. The transmit power can be varied in between -13 dBm (corresponds to the power level of 9 for MICAZ motes) and -28.5 dBm (corresponding power level is 2). Also ETX_M and ETX_m are assumed to be 3 and 2.5 respectively, α and β are assumed to be 0.5 and 1 respectively. The beacon and DATA transmission interval are 10 and 15 seconds respectively. Parents are selected in every 1 minute. The power adaptation interval is assumed to be 5 minutes. In our experiment, all nodes send their transmit power, ETX and the number of packets overheard in the last 1 minute in their DATA packets to the sink. These parameters are recorded and monitored in a laptop that is connected to the sink to be analyzed later. Parameters used for experiments are listed in Table I.

TABLE I

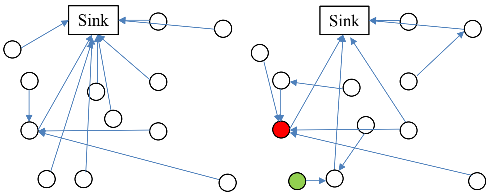
PARAMETERS USED

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	8 mA	T_P	3 ms	I_S	7.5 mA	T_S	112 ms

For the purpose of this work, we estimate battery capacity B from the battery voltage. MICAz motes operates in a voltage range of 2.7V to 3.3V. The actual battery voltage is related to the ADC reading as follows: $V_{bat} = \frac{1.223 \times 1024}{\text{ADC reading}}$ [13]. Assuming that the battery capacity changes linearly from 0% at 2.6V (battery sensor = 482 ADC units) to 100% at 3V (battery sensor = 417 ADC units), we can estimate the capacity for any given ADC reading x to be $\frac{482-x}{0.65}$. Since batteries can actually have voltages exceeding its peak rating, we set all voltages above 3V to reflect a capacity of 100%. Hence, we model battery capacity $B = \min\left(100, \frac{482-x}{0.65}\right)$. Note that estimation of battery capacity from the voltage is not accurate; however it provides a computationally simple method for evaluating the performance of our power control and routing scheme experimentally.

In our experimental setup we place the sensor nodes in a layout similar to Fig 3. All nodes are initially at 100% capacity. After 25 minutes the capacity of a node is manually changed to 50% by reducing its battery voltage (using a variable power source) so that it becomes a critical node. Fig 3 shows one instance of the data gathering tree of our network before and after changing the capacity of the critical node. This figure shows that when all nodes are in good state of battery, all of them directly send their traffics to the sink as all of them are in their highest power level. Later on when a critical node comes in picture, nodes started reducing their transmit power and start multi-hopping to forward packets to the sink.

Fig 4 shows the variation of overhearing with time for the critical node which clearly shows the reduction in overhearing on the critical node after 25 minutes. This is because of the fact that other neighboring nodes started reducing their transmit power to avoid overhear the critical node. Fig 5 shows the transmit power and ETX of a neighboring node of the critical node. This figure shows that the transmit power started reducing after 25 minutes and also the change in ETX is clear with the change in transmit power. Due to the restriction of the maximum ETX threshold, the transmit power starts oscillating when it reaches below this maximum threshold. This short



(a) (b)

Fig. 3. An instance of our network topology (a) before and (b) after changing the battery capacity of the critical node. The red node is made to be a critical node after 25 minutes.

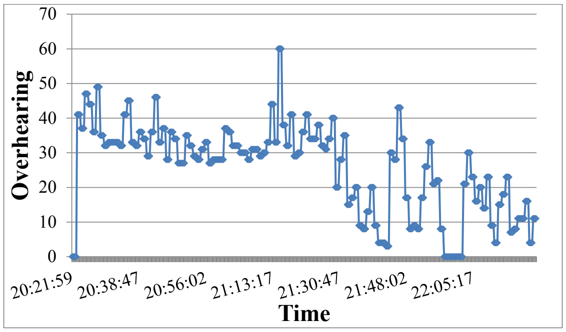


Fig. 4. Overhearing of the critical node (shown in green in Fig 3). The x-axis is showing the number of packets overheard in the last 1 minute.

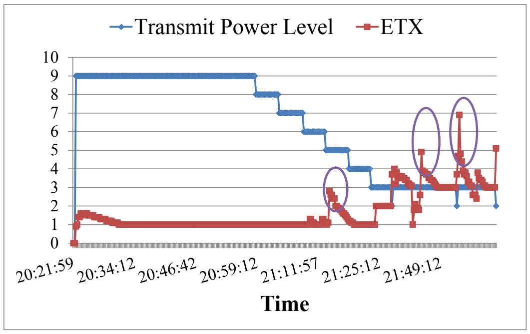


Fig. 5. Transmit power and ETX of a neighbor (shown in green in Fig 3) of the critical node.

experiment clearly shows the effectiveness of our proposed scheme in reducing overhearing on the critical node.

V. CONCLUSIONS AND FUTURE WORK

In this paper, we propose a distributed scheme for controlling transmit power in a data gathering rechargeable wireless sensor networks for maximizing the network lifetime. Through experiments, 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.

In future we plan to extend our proposed power control scheme in several directions. First, we will implement an accurate model for estimating the battery state of charge. This is being developed from extensive experimentation and modeling of different battery technologies. In addition, we are researching models for solar irradiance predictions to obtain more realistic assessment of energy variations. Third, currently our scheme controls power when it finds a critical node. Even if there are no critical node, sometimes transmit power can be controlled without sacrificing the network quality which is one of our future considerations. Fourth, as shown in Fig 5, for some nodes the transmit power as well as ETX oscillates which can result in packet drops and retransmissions. Thus an approach to dampen these oscillations will improve the network performance. Also simulating and experimenting our scheme in larger network scenarios will give more insights about the performances and tradeoffs which is one of our future considerations. These extensions can make our scheme more suitable for large and dense WSNs in practice.

ACKNOWLEDGEMENT

This work was supported by NSF grant CNS-1117790.

REFERENCES

[1] T. A. ElBatt, S. V. Krishnamurthy, D. Connors, and S. K. Dao, “Power management for throughput enhancement in wireless ad-hoc networks,” in *ICC (3)*, 2000, pp. 1506–1513.

[2] G. J. Foschini and Z. Miljanic, “A simple distributed autonomous power control algorithm and its convergence,” *IEEE Transactions on Vehicular Technology*, vol. 42, no. 4, pp. 641–646, 1993.

[3] P. Basu and J. Redi, “Effect of overhearing transmissions on energy efficiency in dense sensor networks,” in *IPSN*, 2004, pp. 196–204.

[4] W. Ye, J. S. Heidemann, and D. Estrin, “An energy-efficient mac protocol for wireless sensor networks,” in *INFOCOM*, 2002.

[5] S. Lin, J. Zhang, G. Zhou, L. Gu, J. A. Stankovic, and T. He, “ATPC: adaptive transmission power control for wireless sensor networks,” in *SenSys*, 2006, pp. 223–236.

[6] Y. Fu, M. Sha, G. Hackmann, and C. Lu, “Practical control of transmission power for wireless sensor networks,” in *ICNP*, 2012.

[7] “Xmesh user manual, Crossbow technology,” `http://www.xbow.com/Products`, 2007.

[8] O. Gnawali, R. Fonseca, K. Jamieson, D. Moss, and P. Levis, “Collection tree protocol,” in *SenSys*, 2009, pp. 1–14.

[9] D. Moss, J. Hui, and K. Klues, “Low Power Listening, Core Working Group, TEP 105.”

[10] A. Pal and A. Nasipuri, “A distributed channel selection scheme for multi-channel wireless sensor networks,” in *MobiHoc*, 2012, pp. 263–264.

[11] ——, “DRCS: A distributed routing and channel selection scheme for multi-channel wireless sensor networks,” in *IEEE PerSeNS*, 2013, pp. 602–608.

[12] A. Nasipuri, R. Cox, J. Conrad, L. V. der Zel, B. Rodriguez, and R. McKosky, “Design considerations for a large-scale wireless sensor network for substation monitoring,” in *LCN*, 2010, pp. 866–873.

[13] “MIB/MPR user manual,” `http://www.xbow.com`.