Impact of Power Control in Wireless Sensor Networks Powered by Ambient Energy Harvesting (WSN-HEAP) for Railroad Health Monitoring

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Abstract

The use of wireless sensor networks (WSNs) for structural health monitoring is gaining popularity since it allows for a low-cost, rapid and robust assessment of structural integrity. Meanwhile, recent advances in ambient energy harvesting technology have made it a viable alternative source of energy for powering WSNs. WSNs powered by ambient energy harvesting (WSN-HEAP) are potentially more useful and economical in the long term than traditional battery-powered WSNs as they can operate for very long periods of time without the need for human involvement, thus paving the way towards alleviating energy constraints that continue to challenge WSNs.

In this paper, we evaluate the impact of transmit power control on the usefulness of a multi-sink WSN-HEAP, deployed in uniform string topology for railway track monitoring. Based on current achievable energy harvesting rates from track deflections, and commercially available sensor mote parameters, our analysis reveals that availability can be maximised while maintaining good data delivery ratio and throughput-fairness by appropriate setting of the transmit power over a wide range of deployment density, Signal-to-Noise Ratio requirements and energy harvesting characteristics.

1. Introduction

Railway systems form a critical infrastructure in many countries. Although transportation by rail is currently very safe for passengers, train collisions, derailments, and collapse of bridges and/or tunnels do still occur. Recently, battery-powered wireless sensor networks (WSNs) for railway track [1] and bridge [2] monitoring have been proposed. In [1], the proposed model consists of multiple mutually-wired control centres, and many wireless sensor nodes across a railway track. It exploits multi-homing, multi-path routing and a fuzzy aggregation system to reduce the occurrence rate of accidents and improve the efficiency of railroad maintenance activities. A set of experiments were conducted to verify the system's ability to predict inclinations in tracks.

In [2], the authors presented BriMon, an easily-deployable long-term railways bridge monitoring system that requires minimal maintenance. The novelties of the BriMon system lie in (i) the use of high gain external antennae at designated nodes on the bridge that can detect an arriving beaconing train way in advance, and (ii) the transfer of collected vibration data to passing trains. Various system components have been prototyped and tested on road bridges, and were shown to successfully measure vibrations on the bridge induced by passing trains.

The need to change batteries, and remoteness of location and low frequency of maintenance of the above systems can limit their practical deployment. However, recent advances in ambient energy harvesting technology have made it a viable potential alternative source of energy for powering wireless sensor networks. In particular, piezoelectric devices are emerging, both as energy harvesters as well as sensors in the transportation industry [3], as they can withstand harsh environmental conditions. Numerical simulations based on theoretical models of these devices as well as an analytical model of rail track deflection were validated in [4] by laboratory and field tests, and hold promise for scavenging power (near 1mW) to power WSNs.

In WSNs <u>p</u>owered *solely* by <u>a</u>mbient <u>e</u>nergy <u>h</u>arvesting (referred to as WSN-HEAP in this paper), each device has a *perpetual* lifetime, alternating between *charging* (harvesting ambient energy and storing) and *discharging* (energy dissipation through microprocessor and/or transceiver) phases (see Fig. 2(b)). Consequently, WSN-HEAP are potentially more useful and economical in the long-term as they can operate for very long periods of time until hardware failure, while delineating the need for human involvement. However, the unpredictable nature of energy harvesting poses a challenge to the design and evaluation of WSN-HEAP.

In this paper, we show, via analysis and simulation, that transmit power control is important for WSN-HEAP to achieve good overall performance in railroad health monitoring. We describe related work in this area in Section

2, and define our system model in Section 3. We analyse the impact of transmit power control on the availability as well as the reliability of data delivery of WSN-HEAP in Section 4, and present some numerical results in Section 5. Finally, we provide some concluding remarks and directions for future work in Section 6.

2. Related Work

Most research efforts on power management and control in WSNs with energy harvesting devices have proposed using harvested energy to *supplement* the battery power. In such networks, the main focus of power management is to estimate the amount of energy that can be harvested in the future [5], [6], [7], so as to optimise duty cycles and the scheduling of tasks [8], [9], [10] to maximise system performance, such as latency [11]. However, the concept of duty cycle optimisation is not applicable to WSN-HEAP, since the energy harvesting process depends on the environment, and is hence unpredictable.

In WSN-HEAP, transmit power control determines the level of connectivity (topology) of the network as well as the achievable throughput of the network. In [12], the minimum number of sinks required to keep the network connected is analyzed. Another approach [13] is to tradeoff energy consumption with packet error to maximize performance. In our earlier work in [14], we studied the performance of various MAC schemes for a single-sink WSN-HEAP architecture, where WSN-HEAP nodes transmit at *maximum* transmit power. Building on this work, as well as [4], our focus in this paper is to study the impact of *transmit power control* on the performance of a *multi-sink* WSN-HEAP for railway track monitoring.

We restrict ourselves to vibrational energy harvested from track displacement since (i) solar panels are expensive, cumbersome to use, prone to theft and solar energy is not always available (e.g., in a tunnel or at night); (ii) tunnels are inaccessible to a mobile host such as an unmanned aerial vehicle that can fly to the sensors of interest and transmit energy via radio frequency [15].

3. System Model

Let us assume that perpetually-powered sinks/gateways (e.g., using AC power supply) are placed at fixed intervals (x) along a railway track as shown in Fig. 1. These sinks form the interface between the WSN-HEAP and the outside world. The inter-sink separation, x, depends on the availability of AC power supply, which may be higher in urban areas but lower in rural areas. In addition, for low-cost monitoring, the inter-sink separation, x, should be kept as large as possible.

Over the interval between each pair of sinks, we deploy k-1, $k \geq 2$, WSN-HEAP nodes, whose components are given in Fig. 2(a). The energy harvesting device (either an inductive coil or piezoelectric device) converts vibrational energy generated by track deflections into electrical energy. Since the rate of energy harvesting ($\approx$ 1mW) is significantly lower than the rate of energy consumption (typically of the order of tens of mW), the harvested energy is continually stored in a supercapacitor (or supercapacitors) with (virtually) unlimited recharge cycles. Once the stored energy reaches a useful level, the energy consumers (sensor, microprocessor and wireless transceiver) draw power to carry out their operations.

We assume that each WSN-HEAP node is configured to communicate *directly* with the sinks, and define a simple energy model as given in Fig. 2(b). Each charging cycle m comprises a charging phase, characterised by the charging rate, G_m, and the full energy level, E_f, and the discharging phase characterised by the power dissipation levels and duration of each consuming component.

The charging time in cycle m, $t_{c,m}$, depends on E_f as well as the characteristics of G_m. We assume that the microprocessor and transceiver constitute the main power consumption components in each WSN-HEAP node [16]. While the microprocessor power consumption is fixed and denoted by P_μ, the transceiver power consumption, $P_{\delta,t}$, depends on the actual transmission power, P_{tx}.

4. Performance Analysis

For monitoring applications using WSN-HEAP, it is desirable to maximize the *availability* and *data delivery ratio* of the monitoring system while maintaining *throughput-fairness* for a given deployment. In this study, we quantify the availability in terms of the *throughput density*, which is given by the number of *new* (i.e., newly-sensed) packets received per second over each interval x. Since the WSN-HEAP node has no buffering capacity, the data delivery ratio is given by the proportion of new packet transmissions that are successfully received at the sink(s). Throughput-fairness is important as it ensures that all WSN-HEAP nodes will get an "equal" share of the network throughput in the case of a homogeneous system, i.e., no node(s) will be favoured while other nodes starve. In this study, we quantify throughput-fairness in terms of the Jain's index [17].

Given transmission data rate of α bps, data packet size of s_d bits and power consumption P_d during packet transmission, the energy expended during transmission of a data packet of duration $t_d = \frac{s_d}{\alpha}$ is $P_d t_d$. Assuming E_m is the residual energy at the end of charging cycle m, we have:

$$E_m = E_{m-1} + G_m t_{c,m} - P_d t_d + G_m t_d.$$

Taking expectations, and assuming E[E_m] = E[E_{m-1}] under steady state, we have the following:

$$t_{c,m} = \frac{P_d - G_m}{G_m} t_d.$$

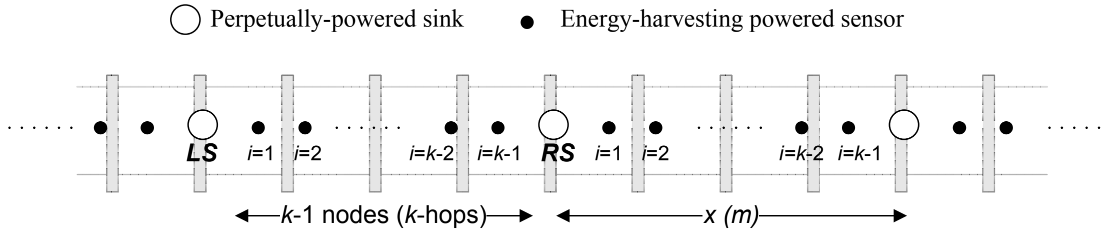

Figure 1. String topology that comprises k-1 WSN-HEAP nodes uniformly deployed between uniformly spaced perpetually-powered sink nodes along a railroad track.

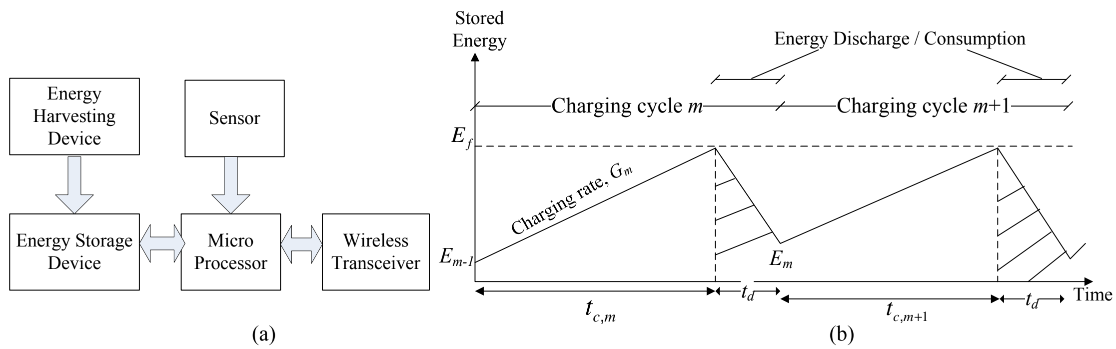

Figure 2. (a) Components and (b) energy model of a WSN-HEAP device.

Hence, the *expected* duration between successive packet transmission attempts, T_{tx}, is given as follows:

$$\begin{aligned} T_{tx} &= E[t_c] + t_d \\ &= \frac{P_d}{E[G]} t_d. \end{aligned}$$

Referring to Fig. 1, let us consider node i, which is i hops away from the left sink (denoted by LS) and k-i hops away from the right sink (denoted by RS). Assuming a simple path-loss model, the corresponding receive power levels at LS and RS are given as follows:

$$\begin{aligned} P_{i,LS} &= \frac{KP_{tx}}{x^{\gamma}}(\frac{k}{i})^{\gamma} \\ P_{i,RS} &= \frac{KP_{tx}}{x^{\gamma}}(\frac{k}{k-i})^{\gamma}, \end{aligned}$$

where γ is the path-loss exponent ($2 \leq \gamma \leq 4$ typically), and the propagation factor, K, depends on the antenna gain and carrier frequency.

Any node n's transmission will interfere with node i's transmission in charging cycle m as long as their transmission intervals overlap, and this occurs with probability:

$$\begin{aligned} q_n &= \frac{2t_d}{t_{c,m} + t_d} \\ &= \frac{2G_m}{P_{\delta,t} + P_{\mu}}. \end{aligned} \tag{1}$$

Hence, the Signal-to-Interference Noise Ratio (SINR) at each sink is given as follows:

$$\begin{aligned} SINR_{i,LS} &= \frac{P_{i,LS}}{I_{i,LS} + N_0} \\ SINR_{i,RS} &= \frac{P_{i,RS}}{I_{i,RS} + N_0}, \end{aligned}$$

where N_0 is the receiver noise floor, $I_{i,S} = \sum_{j \in I_S \setminus i} P_{j,S} q_j$ is the total interference power to node i's transmission at sink S and I_S is the set of nodes whose transmission can be detected at sink S under interference-free conditions.

For each packet to be correctly received at the sink, the SINR has to exceed a given threshold, θ. Each packet from node i is successfully delivered as long as it arrives at *at least* one sink, and this occurs with probability, $p_{succ,i}$, given by:

$$\begin{aligned} p_{succ,i} &= p_{i,LS}\overline{p}_{i,RS} + p_{i,RS}\overline{p}_{i,LS} + p_{i,LS}p_{i,RS} \\ &= p_{i,LS} + p_{i,RS} - p_{i,LS}p_{i,RS}, \end{aligned}$$

where $\overline{p}_{i,y}$ = 1-$p_{i,y}$ and $p_{i,y}$ = P($SINR_{i,y} \geq \theta$) can be numerically computed given E[G] and θ.

Hence, the average data delivery ratio, DR, is given as follows:

$$DR = \frac{\sum_{i=1}^{k-1} p_{succ,i}}{k-1}. \tag{2}$$

Since each node i transmits at every T_{tx} seconds on average, its throughput, R_i, is given by:

$$R_i = \frac{p_{succ,i}}{T_{tx}}. \quad (3)$$

Therefore, the throughput density, S, is given by:

$$S = \frac{\sum_{i=1}^{k-1} R_i}{x}. \quad (4)$$

In this study, given (k,x,θ) and the energy harvesting characteristics, our objective is to investigate the impact of transmit power assignment to WSN-HEAP nodes on the availability, data delivery ratio and fairness of the monitoring system, subject to the maximum transmission power, P_{max}.

5. Numerical Results

We evaluate the performance of WSN-HEAP for railroad health monitoring based on the specifications of commercially available MICAz sensor motes [18], with an operating voltage of 3V. Based on the data sheet of the CC2420 radio, we perform a polynomial fit to obtain the approximate relationship between transceiver power dissipation during packet transmission, $P_{\delta,t}$ and the corresponding transmission power, P_t as shown in Fig. 3. The parameters used are

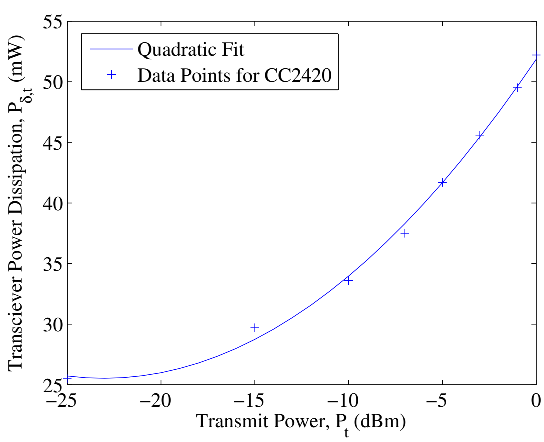

Figure 3. Transceiver power dissipation during packet transmission, $P_{\delta,t}$ (mW) vs transmit power, P_t (dBm) obtained with polynomial fit of CC2420 radio data.

summarised in Table 1. We also set the inter-sink placement distance to the maximum communication range to allow multi-sink redundancy to be exploited.

We consider a range of SINR threshold, $\theta \in \{3, 5, 7, 9\}$ dB to correspond to BER requirements of different types of applications and/or different modulation and coding schemes employed in the transceiver. We set the mean charging rate, E[G] = 1.5mW according to the power scavenging capabilities of piezoelectric devices from track displacement.

Parameter	Value
x (m)	100
k	[2:20]
θ(dB)	[3,5,7,9]
P_μ(mW)	24
α(kbps)	250
s_d(bytes)	100
$E[G]$ (mW)	1.5
γ	2
N_0(dBm)	0
P_{max} (dBm)	0
K	3.1623 X 10^{-6}

Table 1. Parameters for numerical results.

5.1. Performance Sensitivity to Transmit Power and Energy Harvesting Characteristics

In this section, we first investigate the choice of P_{tx} to achieve maximal performance. Due to space constraints, we only plot each performance metric as a function of P_{tx} for k=5, θ = 5 and 7 dB in Fig. 4.

We observe that the network throughput density increases as P_{tx} is reduced from 0dBm to -5dBm, but decreases significantly with further reduction in P_{tx}. On the other hand, the data delivery ratio and throughput-fairness are marginally reduced as P_{tx} is reduced from 0dBm to -5dBm, and significantly reduced with further reduction in P_{tx}.

Next, we investigate the performance sensitivity to the statistical characteristics of the charging process. Since the performance metrics derived from the analysis are based only on the first order statistics of the energy harvesting (charging) process, i.e., E[G], we compute the corresponding metrics obtained for different charging time distributions from simulations obtained with the Qualnet [19] simulator.

We simulate a linear network that comprises 7 intervals of k-1 WSN-HEAP nodes each, as shown in Fig. 1, where the interval of interest (bound by LS and RS) forms the central interval. The charging time of each WSN-HEAP node is drawn from an (i) *exponential* or (ii) *uniform* distribution according to E[G] = 1.5 mW. Performance metrics, evaluated for the interval of interest over a simulation duration of 200 secs, are plotted alongside the analysis results in Fig. 4.

We observe that the performance metrics are almost invariant with the distribution of the charging time. Furthermore, the corresponding performance obtained with mean-value analysis matches the simulation results closely, indicating that our analysis may be able to provide insight into the actual performance achievable when the characteristics of energy harvesting is unknown.

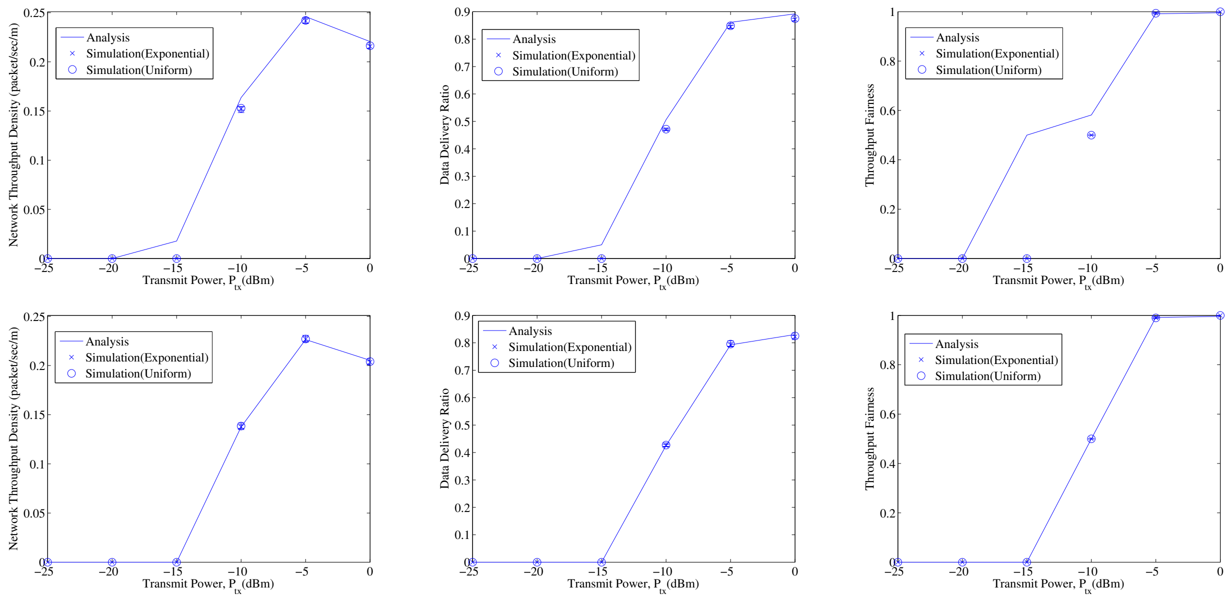

Figure 4. Network throughput density (left), data delivery ratio (centre) and fairness (right) vs transmit power for a 5-hop WSN-HEAP for railroad track monitoring with θ = 5dB (top) and 7dB (bottom).

5.2. Impact of θ and k

Next, we investigate the impact of varying the SINR threshold and node density on each performance metric based on our analysis. We plot each performance metric vs transmit power for $\theta = \{3,5,7,9\}$ dB and k=5 and 10 in Fig. 5. At each (θ, k), we observe similar performance trends as in Section 5.1.

For a given k, as θ increases, the tolerance towards interference is reduced, and hence performance is degraded as expected. Similarly, for a given θ, performance is degraded as k increases since the level of interference is correspondingly increased.

6. Conclusions and Future Work

In this paper, we evaluate the impact of transmit power control on the usefulness of wireless sensor networks powered by ambient energy harvesting (WSN-HEAP) for railway track monitoring. We consider the placement of perpetually-powered data sinks at fixed intervals (corresponding to the maximum communication range) along the track, and deploy WSN-HEAP devices in a linear topology uniformly between each pair of sinks, forming a multi-sink WSN-HEAP.

Based on current achievable energy harvesting rates from track deflections, and commercially available MICAz sensor mote parameters, we analyse the achievable availability, data delivery ratio and throughput-fairness at different transmit power levels, deployment densities and Signal-to-Interference Noise Ratio (SINR) requirements. Our analysis is validated by extensive simulations using Qualnet, and reveals that availability can be maximised while maintaining good data delivery ratio and throughput-fairness by appropriate setting of the transmit power (below the maximum transmit power), over a wide range of deployment density, SINR requirements and energy harvesting characteristics.

We plan to validate the current analysis further by accurately characterising the energy harvesting behavior using commercial energy harvesting devices. We also plan to extend the current analysis to spatially-variant power control schemes that adapts to the deployment density of WSN-HEAP.

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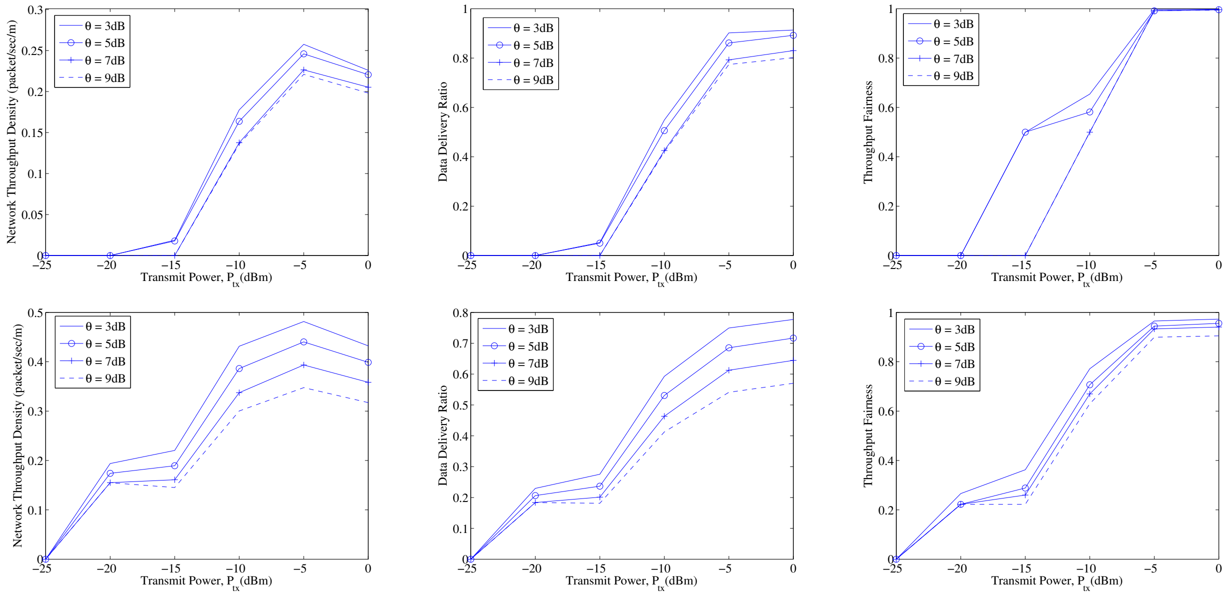

Figure 5. Comparison of network throughput density (left), data delivery ratio (centre) and fairness (right) with various transmit power assignments for a 5-hop (top) and 10-hop (bottom) WSN-HEAP for railroad track monitoring.

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