
Power-Aware Relay Selection and Routing Scheme for Multi-Interface Sensor Networks

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Abstract

We present a joint relay and radio interface selection algorithm with packet deadline under limited power usage in multi-interface sensor networks. We find route optimization techniques in multi-interface networks: 1) selecting the most conservatively lowest-power interface to guarantee timely transmission considering the remaining hops to destination, and 2) searching detouring paths when the power level of an involved relay node is too low to use the necessary interface that guarantees timely delivery. We aim to achieve data delivery with packet deadline requirement while minimizing energy consumption at each node, and further prolonging network lifetime by selecting cost-effective relay nodes and wireless interfaces.

We evaluate our proposed algorithm in terms of total power consumption and packet delivery performance, compared to homogeneous radio interface scenarios of only Wi-Fi interface and only 802.15.4 ZigBee interface. Simulation results show that the proposed algorithm exploits the given packet delivery time enough to conserve power consumption by selecting as low power interface as possible, and spreading out network traffic over the network. Our proposed algorithm demonstrates very reliable packet delivery performance without incurring delivery failures due to power outage and missed deadline.

Keywords: Relay Selection, Greedy Routing, Multi-Interface Sensor Networks, Energy Efficiency

1 Introduction

According to Gartner analyst firm, information technology (IT) accounts for 2% of the world's carbon emissions as of 2007 [3], and reducing network energy demands has been much more important than before. Devising energy-aware network services is regarded as one of the most critical design principles for making Green IT networks realizable.

As System-on-Chip (SoC) technology integrates a larger number of transistors in a given physical space with cheaper manufacturing cost, embedded networked systems are now installed with a variety of wireless network interfaces such as Wi-Fi, Bluetooth, 802.15.4 ZigBee, and even 3G, 4G LTE baseband. This implies that network devices can choose one of these network

interfaces to send and receive data packets depending on data rate, energy consumption, and delay.

Recently, network devices become connected each other by forming a multi-hop network. As wireless networks get broader thanks to the benefit of multi-hop transmission, the energy-efficiency issue becomes even more important since this affects a larger scale wireless network, and leads to tremendous energy consumption. Each wireless network interface consumes different amount of energy depending on the designed characteristics of physical, MAC, and network layer such as data rate and transmission range. For example, Wi-Fi interface can transmit data with a longer link compared to 802.15.4 ZigBee interface, but consumes more power in return.

Also, using a different wireless interface incurs different transmission delay, which influences the achieved data rate. If a network device uses a lower-power wireless interface to relay data packets to the next-hop relay node, it will consume less power, but will take longer to transmit. In embedded network systems, there exist real challenges and constraints of available remaining power to use (in battery-powered devices and sensor networked devices), and packet deadline for quality-of-service (QoS) requirement.

In this paper, we study the problem of relay selection and multi-hop routing using multiple wireless interfaces in sensor networks where each sensor node has limited power to use, and data packet should be delivered within a given packet deadline. We assume that all nodes in the network are stationary and have multiple radio interfaces for transmitting and receiving data. We consider all possible wireless interfaces that are expected to satisfy the packet deadline, and then choose the most energy-efficient interface among them. By selecting cost-effective relay nodes and wireless interfaces, we aim to achieve packet delivery within deadline while minimizing energy consumption and prolonging the overall network lifetime.

Prior work on relay selection in multi-interface ad-hoc networks [2, 9, 13, 14] have mainly focused on improving throughput or mitigating loss rate. However, they have not explicitly considered energy-awareness and packet deadline scenarios in multi-radio interface environments.

We propose a joint relay and radio interface selection algorithm with packet deadline under limited power availability in multi-interface sensor networks. To meet the packet deadline, each intermediate node en route picks up the lowest power radio interface among all possible interfaces that can guarantee timely delivery, expecting to use the same lowest interface over the remaining hops to the destination. In this way, intermediate relay nodes make their own distributed decision of relaying to the shortest next-hop node through the most energy-efficient interface while achieving packet delivery within the given deadline.

Further, we consider out-of-battery situations where a selected intermediate relay node runs out of power. To avoid the termination of packet transmission, we apply a local greedy forwarding technique that searches alternative paths (i.e., detouring paths) as long as the entire selected route can satisfy the packet deadline constraint. Although the high-level principle is similar to [11], we explicitly consider routing with packet deadline based on simple power cost calculation and consequent route decisions. Before the shortest route breaks, and the packet transmission is terminated, an intermediate node estimates that the next hop on the shortest-path would not have the necessary power for packet delivery within the allowed time limit, and then finds a detouring next-hop node that has enough power. Thus, the proposed algorithm diffuses network traffic by making more nodes involved with data routing, and balancing the network.

The rest of this paper is organized as follows: In Sec. 2, we discuss related work, and Sec. 3 provides system model. In Sec. 4, we describe the proposed scheme, and evaluate the approach in Sec. 5. Finally, we conclude this paper Sec. 6.

2 Related Work

There is a large body of work on relay selection in wireless multi-hop networks. Our focus is on energy-aware routing schemes in multi-interface sensor networks. Recent work on this problem can be categorized in three areas: 1) relaying over multi-interface networks, 2) energy-aware relay scheme, and 3) relay selection algorithm.

Relay selection in multi-interface networks have mainly focused on achieving high throughput or mitigating loss rate by proposing a new routing metric [2, 9], or by exploiting the properties of multiplexing and diversity in the physical layer [13, 14]. These previously proposed relay schemes incorporate fundamental ideas from MIMO (multiple-input and multiple-out) into multi-interface networks. They aim to select better relay paths with multiple radios to improve the corresponding performance metrics (i.e., throughput, loss rate).

Regarding energy-aware relay scheme, previous works have been studied mostly in the context of sensor networks. Due to inevitable requirement of battery usage in sensor networks, a variety of energy-efficient routing techniques are proposed in [10, 12, 15, 18] to prolong network lifetime. They find efficient and low overhead relay nodes for data delivery to destination through data mining-based network optimization [10], network clustering [18], cooperative beamforming [12], or balancing between shorter high-quality links, and longer lossy links [15].

Previous works [6, 8, 16, 17, 19] have proposed relay selection schemes in cooperative networks that utilize game theory [8, 16, 19] or Markov modeling [6, 17]. The proposed schemes choose the optimal cooperative relay nodes that maximize their own utilities, while contributing to the entire network benefit.

Our proposed work is different from the previous works presented above, in that our proposed relay selection algorithm considers all of three design principles together, and thus presents an energy-aware relay scheme in multi-radio interface sensor networks.

3 System Model

This paper considers the problem of relay and interface selection in multi-radio interface sensor networks. The objective of our proposed method is to minimize power consumption at each sensor node and prolong network lifetime when delivering data packets from a source node to a destination node, while satisfying the packet deadline constraint. Each sensor node is stationary and is installed with multi-radio interfaces, e.g., Wi-Fi and 802.15.4. A sensor node can determine *where to relay* the received data packet using *which* radio interface. A high-power radio interface (e.g., Wi-Fi) will consume more power, but can transmit farther and faster in return compared to a lower-power radio interface – 802.15.4. We consider a sensor network application of data delivery with packet deadline requirement in a limited power consumption environment, which is the general situation in battery-powered sensor devices.

We aim to make more relay nodes involved with routing for prolonging the overall network life time. We find an alternative path for robust data delivery before the route path breaks due to energy depletion. We assume a fixed power transmission for each interface type, and do not consider adaptive power allocation. We also assume that data packet size is fixed, and focus on the single hop transmission delay since it is largely affected by data rate of that interface compared to queueing delay and MAC access time. We use the distance-vector algorithm as the underlying routing mechanism. We do not constrain ourselves with a specific one-to-one routing protocol; other advanced routing protocols can be used with our proposed algorithm. We assume that control beacon messages for maintaining up-to-date topology include the current power status of the originator. In this way, a sensor node knows information of power availability

of neighboring nodes and can use it for its route decision of selecting the next relay node and the radio interface.

4 Relay Selection Scheme

In our network setup, a packet is transmitted from a source node to a destination node. Upon packet generation at the source node, the packet is assigned a delivery deadline. Each node along the routing path updates the remaining time before deadline in the packet header before relaying it further. Each relay node makes a local decision for interface type and next hop when transmitting the packet, while carefully considering the remaining time before deadline. Various factors such as transmission time and power consumption as well as power availability influence the success of packet delivery. We design three route selection algorithms that take these factors into account. We now describe our routing schemes in turn.

Each of our route selection algorithms takes as an input the packet delivery deadline R , as well as the time D and transmission power P through each interface $j \in \{1, \dots, M\}$ (where M is the number of radio interfaces to take). D and P are vectors of size M , and are initialized in increasing order of transmission power (i.e., $D_1 > D_2 > \dots > D_j > \dots > D_M$ and $P_1 < P_2 < \dots < P_j < \dots < P_M$). Each sensor node has topology information for each interface type j (*Topology*) and can calculate the shortest path between source and destination. To do this, a sensor node utilizes Dijkstra's algorithm, where each edge between nodes in the topology is weighted with the expected transmission count ETX [1] as per-hop cost through the corresponding link. Considering this information, each node along the path makes a local routing decision to select interface and next hop in order to meet the packet delivery deadline while minimizing the overall power consumption in the system. Informally, our route selection algorithms take advantage of the provided packet delivery deadline and prolong the packet transmission time in order to conserve energy by selecting low power transmissions. We now describe in more detail our proposed route selection schemes.

4.1 Naive Method

We first describe a *Naive* counterpart inspired by Longest-Job-First scheduling algorithm [5] such that the longest-time-spending interface is assigned first due to the least power consumption. This algorithm only considers the remaining time before packet deadline in the scope of the local neighborhood in a *myopic* view. As detailed in Algorithm 1, each decision-making node (i.e. *currentNode*) finds the lowest power interface that takes less time than the remaining time before deadline, $R_{currentNode}$ and selects this interface. Naturally, this algorithm favors low power interfaces, and fails shortly as en-route delivery is getting behind schedule.

Algorithm 1 Naive

```
1: Input:src, dst, D, P, Topology
2: Output:Route from src to dst
3: currentNode=src
4: while currentNode  $\neq$  dst do
5:   for all interfaces  $j \in \{1, \dots, M\}$  do
6:      $[path_j, cost_j] = Dijkstra(currentNode, dst, Topology_j)$ 
7:   end for
8:   Select  $\arg \min_{j \in \{1, \dots, M\}} P_j$ , s.t.  $D_j \leq R_{currentNode}$ 
9:    $currentNode = path_j[indexOf(currentNode) + 1]$ 
10:   Transmit packet (update remaining time)
11: end while
```

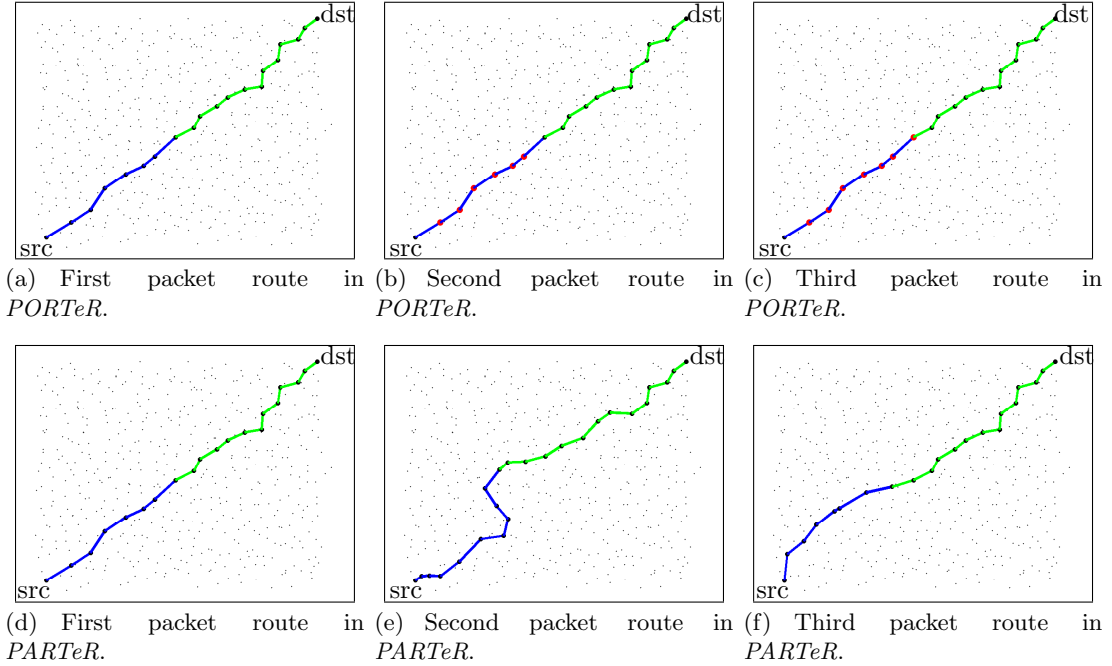


Figure 1: **Route selection.** Figures (a), (b) and (c) present routes selected by the *PORTeR* algorithm, whereas (d), (e) and (f) are routes taken by the *PARTeR* algorithm. Green links present 802.15.4 links, and blue links correspond to Wi-Fi links. Red dots denote the nodes that reach the maximum power limit. *PARTeR* successfully finds a detouring route path before the route path is broken due to energy depletion.

4.2 Power-Oblivious Routing with Strict Time Requirements

Our second routing scheme, called Power-Oblivious Routing with strict Time Requirements (*PORTeR*), enhances *Naive* by incorporating knowledge about the number of future hops N_j to the destination through each interface type $j \in \{1, \dots, M\}$ in a *far-sighted* view. Particularly, *PORTeR* checks if the number of remaining hops N_j through interface j multiplied by the transmission time D_j through interface j is lower or equal to the remaining time before packet deadline $R_{currentNode}$ (line 8 from Algorithm 2). By doing so, this scheme enforces in-time packet delivery in all feasible cases.¹ This scheme, however, does not consider power availability in nodes in the process of route selection.

¹We call a case feasible if transmission through the highest power interface M throughout the whole route guarantees timely delivery, i.e. $N_M * D_M \leq R$.

Algorithm 2 *PORTeR*

```

1: Input:src, dst,  $D, P, Topology$ 
2: Output:Route from src to dst
3: currentNode=src
4: while currentNode  $\neq$  dst do
5:   for all interfaces  $j \in \{1, \dots, M\}$  do
6:      $[path_j, cost_j] = Dijkstra(currentNode, dst, Topology_j)$ 
7:   end for
8:   Select  $\arg \min_{j \in \{1, \dots, M\}} P_j$ , s.t.  $N_j * D_j \leq R_{currentNode}$ 
9:   currentNode =  $path_j[indexOf(currentNode) + 1]$ 
10:   Transmit packet (update remaining time)
11: end while

```

Algorithm 3 PARTeR

```

1: Input:src, dst,  $D, P, Topology, PowerMap$ 
2: Output:Route from src to dst
3: currentNode=src
4: while currentNode  $\neq$  dst do
5:   for all interfaces  $j \in \{1, \dots, M\}$  do
6:      $[path_j, cost_j] = Dijkstra(currentNode, dst, Topology_j)$ 
7:   end for
8:   Select  $\arg \min_{j \in \{1, \dots, M\}} P_j$ , s.t.  $N_j * D_j \leq R_{currentNode}$ 
9:    $P_{txCurNode} = P_j$ ;  $P_{rxNextNode} = P_j$ 
10:   $nextNode = path_j[indexOf(currentNode) + 1]$ 
11:  Find  $\arg \min_{j \in \{1, \dots, M\}} P_j$ , s.t.  $N_j * D_j \leq R_{nextNode}$ 
12:   $P_{txNextNode} = P_j$ 
13:  if  $PowerMap[nextNode] < P_{rxNextNode} + P_{txNextNode}$  then
14:    altNextHop( $cost_j, currentNode, dst, Topology_j$ )
15:  end if
16:  Transmit packet (update remaining time)
17: end while

```

Algorithm 4 altNextHop

```

1: Input: $cost_j, currentNode, dst, D, P, Topology, PowerMap$ 
2: Output:Alternative next hop
3:  $ImNeigh = FindImmediateNeighbors(currentNode, j)$ 
4: for all nodes  $n$  in  $ImNeigh$  do
5:   for all interfaces  $j \in \{1, \dots, M\}$  do
6:      $[pathNxt_j, costNxt_j] =$   

        $Dijkstra(nextNode, dst, Topology_j)$ 
7:     Select  $\arg \min_{j \in \{1, \dots, M\}} P_j$ , s.t.  $N_j * D_j \leq R_{nextNode}$ 
8:      $P_{txNextNode} = P_j$ ;  $P_{rxNextNode} = P_j$  {Next statement guarantees a loop-free route}
9:     if  $costNxt_j < cost_j$  and  $PowerMap[nextNode] < P_{rxNextNode} + P_{txNextNode}$  then
10:       $neighbors = neighbors.Append(n)$ 
11:     end if
12:   end for
13: end for
    {Select a random alternative next hop from  $neighbors$ }
14:  $altNextHop = SelectRandom(neighbors)$ 
15: return  $altNextHop$ 

```

4.3 Power-Aware Routing with Strict Time Requirements

Finally, we propose a route selection scheme that considers power availability in nodes when making route decisions. We call this scheme as Power-Aware Routing with strict Time Requirements (*PARTeR*). Similarly to *PORTeR*, *PARTeR* also takes into account the number of future hops N_j and the transmission time D_j to enforce timely packet delivery. However, it takes one additional step to check if the selected next hop has enough power to receive and transmit the packet (lines 13-15 from Algorithm 3). If not, *PARTeR* selects an alternative next hop from its neighborhood.

Algorithm 4 provides details for the selection of alternative next hop. First, we identify all immediate neighbors of *currentNode* reachable through interface type j . We then calculate the path and cost to destination through each of the alternative next hop candidates. We select a random next hop candidate whose path cost ($costNxt_j$) is lower than the path cost of the current node ($cost_j$) (i.e., selecting a next-hop node closer to destination than the current node). The latter guarantees a loop-free route.

5 Evaluation

We validate our route selection schemes. We start with a description of our simulation environment and continue with analysis of route selection, and then evaluate network performance. We compare the routing schemes described in Sec. 4 with two basic counterparts that use only Wi-Fi and only 802.15.4 ZigBee (Sensor) interfaces; we call these counterparts as *WiFi* and *Sensor*, respectively.

5.1 Simulation environment

We evaluate our routing algorithms in a MATLAB simulated network, which consists of 518 nodes in a $500 \times 500\text{m}^2$ grid. Each node has two interfaces: one 802.11 (Wi-Fi) and one 802.15.4 (Sensor). For our simulations, we use a realistic propagation model, which is based on a combined path-loss and shadowing model [4]. We use a path-loss exponent of 3, a reference loss of 46.67 dB and additive white Gaussian noise of $\mathcal{N}(0, 5^2)$ dB. We transmit packets of 10 KBytes at data rate of 11Mbps and 250 Kbps for Wi-Fi and Sensor, respectively. With these packet size and transmission rates, the transmission delays are $D_w = 0.89\text{ms}$ through Wi-Fi and $D_s = 40\text{ms}$ through Sensor. We assume that power consumption for transmission is equal to that for reception and is $C_w = 100\text{mW}$ for Wi-Fi and $C_s = 1\text{mW}$ for Sensor [7].

For each experimentation, we transmit K packets in the network (specified below). As we evaluate power and time-related aspects of the system, we carefully select the initial power charge in nodes as well as the tolerated packet delivery deadline to demonstrate the benefits of our proposed algorithms. We stress out system performance when the mesh network operates at power or packet delivery deadline extremes. Particularly, we assign initial power of $K \cdot C_w$ at each node, which is enough for the transmission or reception of K packets through Wi-Fi, and vary the transmission delivery deadline between 0.2s and 1.6s to force only Wi-Fi and only Sensor transmission, respectively. We present our evaluation results below.

5.2 Route selection

We start our evaluation by presenting two examples of route selection by our *PORTeR* and *PARTeR* algorithms. Figure 1 presents the selected routes for a toy-example in which three consecutive packets are transmitted from node 1 to node 518. Each node in the mesh topology has 300 mW of power charge and nodes' battery levels are updated after each packet transmission and reception. As can be seen in Figure 1(a), 1(b), 1(c), *PORTeR* always selects the same route regardless of the power level of nodes along the path. This results in nodes running out of power as early as the second packet transmission. At the same time, *PARTeR* modifies the transmission route based on the prior knowledge of power change of the neighboring nodes as in Figure 1(d), 1(e), 1(f). As a result, *PARTeR* is capable of finding alternative routes without exhausting any of the nodes in the network.

5.3 Effects of packet delivery deadline

Next we explore the effects of packet delivery deadline on network performance. We present results for a single packet transmission from node 1 to node 518. For each run, we double the packet deadline, starting at 0.2s.

Figure 2(a) presents our results for path length with increasing delivery deadline. As expected, *WiFi* and *Sensor* maintain the same path length irrespective of packet deadline. At the same time, all of *Naive*, *PORTeR* and *PARTeR* take advantage of the increasing delivery deadline by increasing the number of hops to the destination. This, as indicated in Figure 2(b),

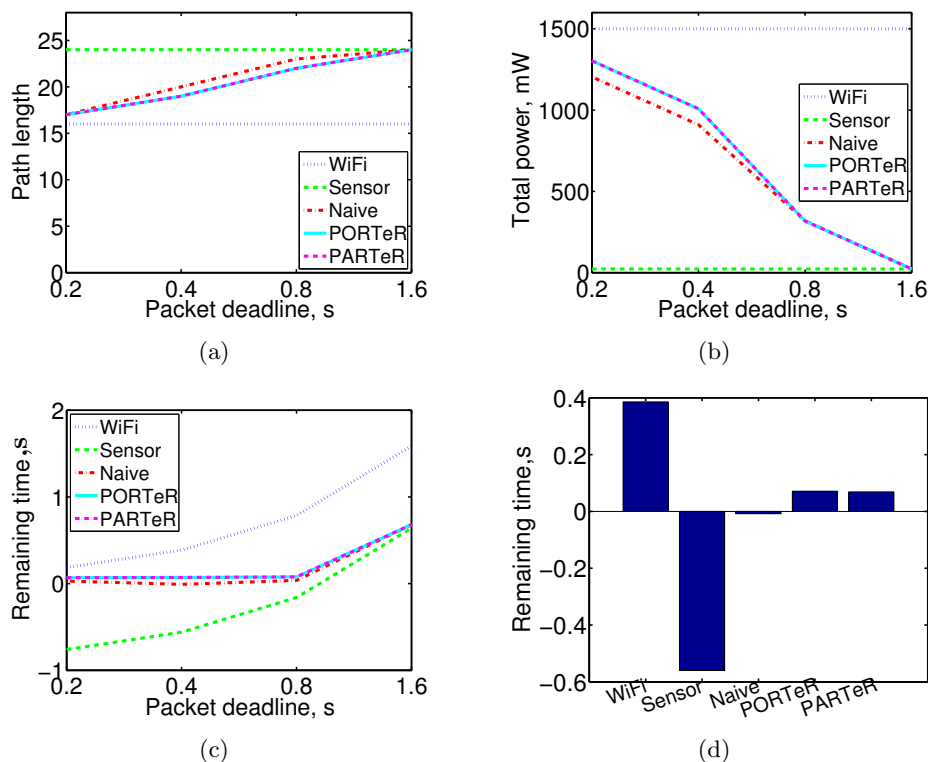


Figure 2: **Performance over increasing packet delivery deadline:** (a) Path length; (b) Total TX power; (c) Remaining time; (d) Remaining time for permitted delivery deadline of 0.4s.

can explain how total consumed power for packet transmission is drastically dropped, as nodes favor lower power transmissions where time allows.

Finally, in Figure 2(c), we measure the remaining time till the deadline each algorithm incurs as the permitted delivery deadline increases. For low delivery deadline values, *Sensor* and *Naive* always miss the deadline, whereas *WiFi*, *PORTeR* and *PARTeR* are well within deadline requirements. As we will see in subsection 5.4, *WiFi* and *PORTeR* do so at the cost of exhausting power resources in nodes, which results in packets being lost due to nodes along the route running out of power.

5.4 Network behavior over consecutive packet transmissions

We extend our evaluation by exploring performance trends when multiple consecutive packets are transmitted in the network. Particularly, we transmit 30 packets ($K = 30$) in a network where each node has 3 W of power to start with. The power level at each node is updated as the transmission of packets progresses. For each of the five routing schemes, we evaluate the number of nodes along a route that ran out of power, the path length taken, and the total consumed power. We also report the number of lost packets in two categories: (i) due to nodes running out of power and (ii) due to transmission taking longer than the permitted delivery deadline.

We start with evaluation of the number of nodes that ran out of power for each algorithm. As Figure 3(a) shows, *Sensor* and *PARTeR* do not cause nodes to run out of power. As detailed in subsection 5.3, however, *Sensor* does this at the cost of missed packet delivery deadlines. *WiFi*, *Naive*, and *PORTeR* exhaust 15, 9 and 8 nodes respectively after the transmission of the

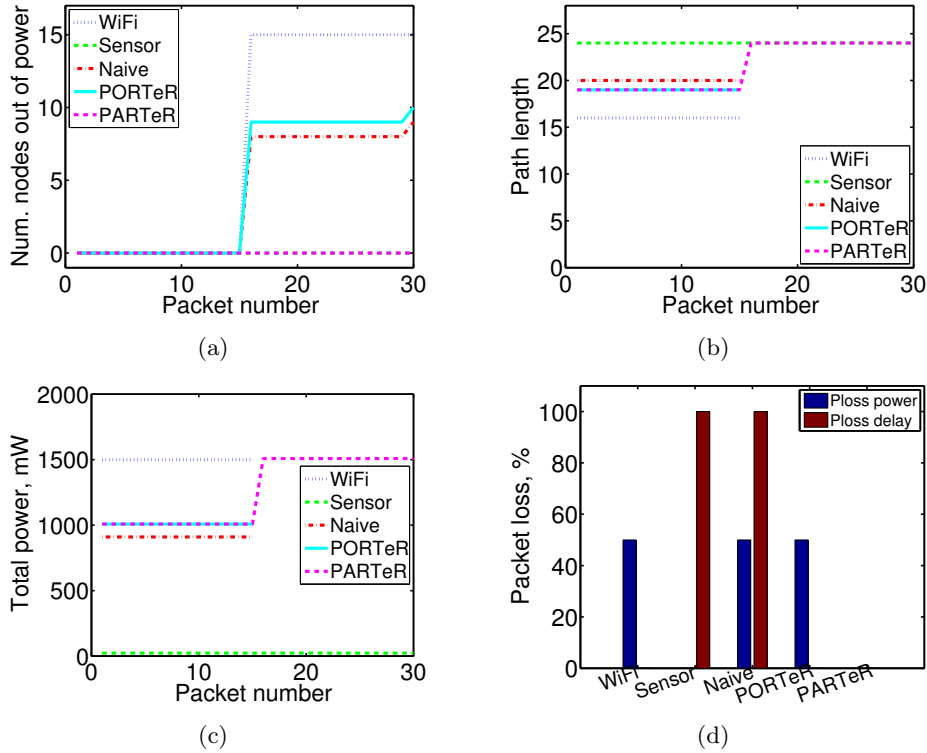


Figure 3: **Performance over consecutive packet transmissions:** (a) Number of nodes out of power; (b) Path length; (c) Total TX power; (d) Packet loss.

15th packet. In our simulations, we let the nodes out of power continue with packet transmission while counting the number of nodes with negative power, just to effectively show power consumption dynamics of other nodes. This trend persists or increases as packet count progresses, because these three counterpart schemes do not search for alternative routes, and keep using the same route while exhausting the remaining power of the nodes en route. On the other hand, our proposed *PARTeR* scheme does not cause any nodes with negative power because it finds detouring paths dynamically as consecutive packet transmissions continue. This means that in real battery-powered scenarios, packet transmission for *WiFi*, *Naive*, and *PORTeR* will be terminated as soon as one of the nodes en route runs out of power, whereas our proposed *PARTeR* scheme will continue packet transmissions without any node failures due to energy depletion.

Next, in Figure 3(b), we evaluate the path length for each of the algorithms when transmitting consecutive packets. All algorithms but *PARTeR* maintain the same path length over different packet transmissions, because they always select nodes from the shortest path. *WiFi*, *Naive* and *PORTeR* cause nodes to run out of power by the 15th packet transmission, at which point packet transmission is terminated. *Sensor* maintains an uninterrupted path of 24 relay nodes over continuous packet transmissions, but it sacrifices packet deadline requirements. *PARTeR*, however, manages to select an alternative route after nodes on the shortest path run out of power. This results in increase of 5 nodes of the route length. It also translates in increase of transmission power consumption, as indicated by Figure 3(c). At the cost of more power, however, *PARTeR* is capable to successfully transmit longer packet sequences.

Finally, we summarize results for packet losses incurred by each algorithm. We differentiate between two types of losses: (i) such that were caused by nodes along the route running out of power and (ii) such that were caused by a missed deadline. Figure 3(d) presents for each algorithm packet loss rate for 30 consecutive packet transmissions. *WiFi* and *PORTeR* both

have 0% loss due to missed deadline, but they both lose 50% of the packets due to nodes running out of power along the route. *Sensor* is most power conserving, and accordingly incurs 0% packet loss due to power outage. However, it causes 100% packet loss due to missed deadline. *Naive* causes 50% packet loss due to power outage and 100% packet loss due to missed packet deadline. In contrast, *PARTeR* successfully transmits all 30 packets.

6 Conclusion

Design of energy-efficient technologies is crucial both for reducing the footprint of technology on the environment as well as for successful adoption of technology in areas with limited availability of electricity. In line with this need, we design an energy-efficient route selection scheme for heterogeneous sensor networks that leverages knowledge for permitted packet delivery delay and finds routes with minimal power consumption. Each node in these networks is equipped with multiple interfaces that take different amount of time and power for a single packet transmission.

In this paper, we outline three schemes for route selection in such heterogeneous networks and provide evaluation that brings out important trade-offs that need to be considered in the design of such routing schemes. One crucial design principle to guarantee timely packet delivery (i.e., no packet loss due to missed deadline), the most conservatively lowest-power interface needs to be selected by taking into account the expected remaining hops to destination in a long-term view. Also, it is important that a routing algorithm considers the power availability of nodes along the routing path to ensure no packet loss due to power outages by adaptively taking alternative (detouring) paths. Such power-aware algorithm performs more computationally-intensive search for alternative routes, but returns back with increased network lifetime in comparison to shortest path-based counterparts.

We identify some limitations of our proposed schemes. While they are efficient in providing timely packet delivery at minimal power cost, as packet transmission progresses, they become unfair. The reason for this is that our proposed schemes favor high power transmissions in the beginning of the routes, in order to assure timely delivery, while consistently allowing nodes later in the path to use low power transmissions. With increasing number of packets between the same source and destination, the power charge of part of the nodes is exhausted, which ultimately results in network disconnection. To address this problem, as future work, we plan to design a more advanced route selection scheme that diversifies interface selection along the path with fairness, while still meeting the packet delivery deadline.

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References

- [1] D. S. J. De Couto, D. Aguayo, J. Bicket, and R. Morris. A high-throughput path metric for multi-hop wireless routing. In *ACM MobiCom*, 2003.
- [2] R. Draves, J. Padhye, and B. Zill. Routing in multi-radio, multi-hop wireless mesh networks. In *ACM MobiCom*, pages 114–128, 2004.
- [3] Gartner Inc. *Gartner Symposium/ITxpo*, April 2007.

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- [4] A. Goldsmith. *Wireless Communications*. Cambridge University Press, New York, NY, USA, 2005.
- [5] R. L. Graham. Bounds on multiprocessing timing anomalies. *SIAM Journal on Applied Mathematics*, 17(2):416–429, 1969.
- [6] H. Halabian, I. Lambadaris, C.-H. Lung, and A. Srinivasan. Throughput-optimal relay selection in multiuser cooperative relaying networks. In *MILCOM*, pages 507–512. IEEE, 2010.
- [7] S. Han, T. Li, C. Qian, D. Leith, A. K. Mok, and S. S. Lam. HartFi: an energy-efficient localization system. In *GreenNets, ACM SIGCOMM workshop on Green networking*, 2011.
- [8] H. Kwon, H. Lee, and J. M. Cioffi. Cooperative strategy by stackelberg games under energy constraint in multi-hop relay networks. In *IEEE GLOBECOM*, pages 1–6, 2009.
- [9] P. Kyasanur and N. H. Vaidya. Routing and link-layer protocols for multi-channel multi-interface ad hoc wireless networks. *ACM SIGMOBILE Mobile Computing and Communications Review*, 10(1):31–43, 2006.
- [10] H. Lee, M. Wicke, B. Kusy, O. Gnawali, and L. Guibas. Data stashing: Energy-efficient information delivery to mobile sinks through trajectory prediction. In *ACM/IEEE IPSN*, 2010.
- [11] H. Lin, M. Lu, N. Milosavljevic, J. Gao, and L. J. Guibas. Composable information gradients in wireless sensor networks. In *ACM/IEEE IPSN*, pages 121–132, 2008.
- [12] R. Madan, N. Mehta, A. Molisch, and J. Zhang. Energy-efficient cooperative relaying over fading channels with simple relay selection. *Wireless Communications, IEEE Transactions on*, 7(8):3013–3025, 2008.
- [13] A. Miu, H. Balakrishnan, and C. E. Koksal. Improving loss resilience with multi-radio diversity in wireless networks. In *ACM MobiCom*, pages 16–30, 2005.
- [14] M.-G. Peng, J. Zhang, W.-B. Wang, and H.-H. Chen. Heterogeneous cooperative relay selection with maximal-ratio combining for multi-radio access networks. *International Journal of Communication Systems*, 23(6-7):732–750, 2009.
- [15] K. Seada, M. Zuniga, A. Helmy, and B. Krishnamachari. Energy-efficient forwarding strategies for geographic routing in lossy wireless sensor networks. In *ACM SenSys*, pages 108–121, 2004.
- [16] B. Wang, Z. Han, and K. R. Liu. Distributed relay selection and power control for multiuser cooperative communication networks using buyer/seller game. In *IEEE INFOCOM*, pages 544–552, 2007.
- [17] Y. Wei, F. Yu, and M. Song. Distributed optimal relay selection in wireless cooperative networks with finite-state markov channels. *Vehicular Technology, IEEE Transactions on*, 59(5):2149–2158, 2010.
- [18] M. Younis, M. Youssef, and K. Arisha. Energy-aware routing in cluster-based sensor networks. In *IEEE MASCOTS*, pages 129–136, 2002.
- [19] J. Zhang and Q. Zhang. Stackelberg game for utility-based cooperative cognitive radio networks. In *ACM MobiHoc*, pages 23–32, 2009.