

Joint Radio Selection and Relay Scheme through Optimization Model in Multi-Radio Sensor Networks

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*Received December 27, 2013; revised August 28, 2014; accepted November 20, 2014;
published December 31, 2014*

Abstract

We present joint radio selection and relay scheme that delivers data from a source to a sink in heterogeneous stationary sensor networks consisting of various radio interfaces. The proposed scheme finds the optimal relay nodes and their corresponding radio interfaces that minimize energy consumption throughout the network while satisfying the end-to-end packet deadline requirement. We formulate the problem of routing through radio interface selection into binary integer programs, and obtain the optimal solution by solving with an optimization solver.

We examine a trade-off relationship between energy consumption and packet delay based on network level simulations. We show that given the end-to-end deadline requirement, our routing algorithm finds the most energy-efficient routing path and radio interface across mesh hops. We demonstrate that the proposed routing scheme exploits the given packet delivery time to turn into network benefit of reducing energy consumption compared to routing based on single radio interface.

Keywords: Energy-Efficient Routing, Adaptive Radio Interface Selection, Heterogeneous Sensor Networks, Network Optimization

1. Introduction

With the advent of ubiquitous wireless networks triggered by very cheap supply of System-on-Chip (SoC) communication processors, consumer electronic devices are becoming more equipped with multiple wireless radios such as 802.11 Wi-Fi, Bluetooth, 802.15.4 ZigBee, UWB, and WiMAX on one single device. In order to leverage wireless networks more efficiently, wireless ad-hoc routing concept has widely been adopted in military networks as well as in commercial router market. For example, Google WiFi in Mountain View, USA and Meraki networks in San Francisco, USA form ad-hoc networks for data delivery among users and Internet sharing.

Efficient data delivery in wireless ad-hoc networks has actively been studied in the last two decades [1–6]. Since the routing path in ad-hoc networks consists of multi-hops, additional energy cost of retransmissions due to packet loss over hops would be incurred. Especially in large scale ad-hoc networks, routing algorithm design needs to consider energy efficiency and load balancing so that routing cost in terms of energy can be reduced, and network load can be balanced throughout the network, while guaranteeing data delivery reliability.

Although wireless devices supporting multiple radio interfaces have rapidly been distributed, the problem of energy-aware ad-hoc routing under multiple radio interfaces in sensor networks has not been well studied. The routing problem and radio interface problem have separately been considered. Further, data to deliver are not necessarily timely critical in sensor networks, but rather have some allowable end-to-end deadline constraint depending on application. Thus, an efficient routing algorithm can be devised through intelligence, i.e., by finding a routing path that causes minimum energy consumption through suitable radio interface selection, while also meeting the end-to-end deadline QoS requirement.

In this paper, we study the problem of routing data from a stationary source to a stationary sink in heterogeneous sensor networks supporting various radio interfaces. Depending on the energy consumption cost for respective radio interface selection of each sensor node, and the end-to-end packet deadline, we aim to find an energy-efficient routing path and selected radio interfaces for ad-hoc hops through network optimization.

To solve this problem, we formulate the problem of routing using multiple radio interfaces into binary integer programs with constraints of route discovery and deadline requirement. We calculate the optimal routing path and radio interface by solving optimization problems. We analyze an interesting trade-off property between energy consumption and delay in the networking protocol layer, and examine how the deadline constraint affects joint routing decision and radio interface selection.

To the best of our knowledge, this paper is the first to formulate the problem of joint radio selection and multi-hop routing in multi-radio networks into binary integer programs, and find the optimal solution to minimize energy consumption over the entire route path.

Our main contributions can be summarized as:

- We propose a novel delivery scheme that extends a static one-to-one routing algorithm by adding one more design space of *selecting* an energy-efficient radio interface that optimizes routing paths and radio interfaces for sensor nodes to select for minimizing energy consumption throughout the network.
- We formulate the routing problem under various radio interfaces into binary integer problems, considering constraints of routing path existence and deadline requirement.

- We provide an explicit way to fully exploit the given packet delivery time to turn into network benefit of reducing energy consumption. We analyze a trade-off property between energy consumption and packet delay based on network level simulations.

The rest of this paper is organized as follows: after we discuss related work in Section 2, we formally define the problem that we aim to solve in Section 3. Section 4 provides our proposed routing approach, and then we evaluate the performance of our algorithm in Section 5. Finally, we conclude this paper in Section 6.

2. Related Work

Recent research efforts on data delivery in multi-radio networks have been done in the following areas: 1) efficient network selection between 3G and Wi-Fi networks through offloading, 2) routing algorithm through an efficient channel selection in wireless mesh networks, and 3) heterogeneous packet routing in Wi-Fi and WiMax networks.

Some researchers in [7,8] have studied how using Wi-Fi interface along with 3G interface can help to improve system performance and load balancing. In overload scenarios, concurrent call attempts from a number of UEs in a local area can cause serious call access failure issue and call drop problem. Wi-Fi networks when available can be used to offload the intensive data traffic, and contribute to reducing energy consumption and mitigating the overload in macrocell. Wi-Fi data offload up to 65% can reduce energy consumption with up to 55% [8].

Regarding routing research in multi-channel mesh networks, many routing algorithms are proposed by selecting one channel out of multiple radio channels such as 802.11a, 802.11b, 802.11g, depending on channel status [9-11]. ETX (Expected Transmission Time) reflecting channel quality is calculated as hop-by-hop routing cost, and then the optimal routing path is determined by minimizing the accumulated ETX. To assign a non-overlapped channel among multi-channels, an approach of using multi-graph for multi-channels based on list coloring algorithm is proposed in [12]. Also, a routing protocol in multi-radio ad-hoc networks is proposed considering load balancing [13] and QoS [14]. Although many research works based on heuristic approaches demonstrate their network performance by experiments, the underlying routing principle and the optimal way to route using multiple channels have not been well investigated.

More closely related works to this paper have been studied to propose an intertwined packet routing and link scheduling scheme by solving an optimization problem in heterogeneous networks of Wi-Fi and WiMAX in [15]. Its formulation aims to maximize link utilization across multi-hop routing path using dual radio interfaces of Wi-Fi and WiMAX. Our paper is different from this work in two aspects: 1) our work aims to minimize energy consumption across multi-hop routing path by selecting joint optimal radio interface and route that should satisfy the end-to-end deadline, and 2) we generalize the routing problem considering a variety of radio interfaces such as Wi-Fi, 802.15.4, Bluetooth, and UWB so that our work can provide a flexible and practical routing solution for multi-radio wireless networks.

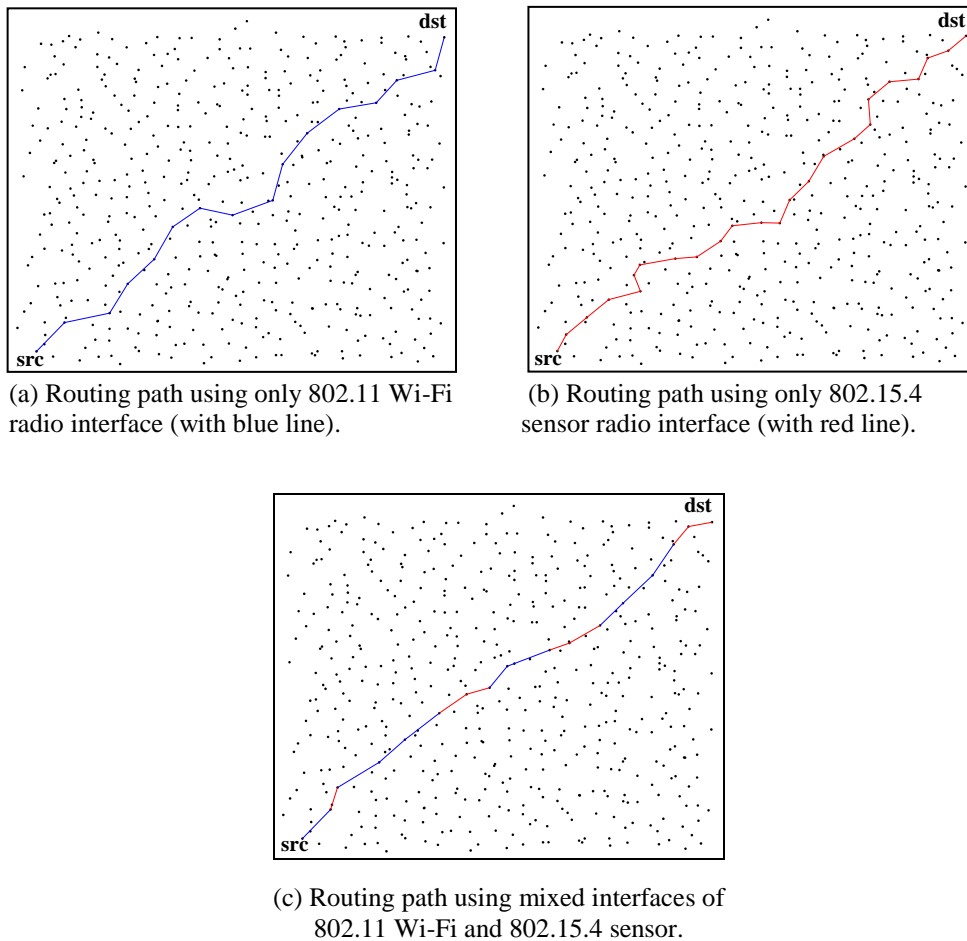


Fig. 1. Routing path from data source in left bottom to data sink in right top, depending on radio interface. Given a packet deadline, different route path and radio interfaces are selected to minimize energy consumption.

3. Problem Formulation

This paper considers the problem of multi-hop routing in heterogeneous stationary wireless networks where multiple radio interfaces such as 802.11 Wi-Fi and 802.15.4 are supported in ad-hoc sensor nodes. Our goal is to minimize energy consumption for routing data from a source to a destination, while meeting a given packet deadline requirement, by selecting a suitable radio interface per hop. Energy consumption for wireless transmission is different for each different radio interface. For example, energy consumption of Wi-Fi transmission is significantly larger than that of 802.15.4's. In heterogeneous wireless networks, a hop-by-hop delay is largely affected by transmission time due to the specific wireless interface selected because a wireless interface has a different data rate, compared to MAC access time and queueing delay common for general wireless networks. Thus, we focus on the hop-by-hop delay due to data rate according to each selected wireless interface, eventually contributing to the overall end-to-end packet delay without loss of generality.

We assume that all of sensor nodes are static, and are configured with heterogeneous wireless interfaces. Since different radio interface results in different network topology, each sensor node has a different neighboring node list for a respective radio interface type. A sensor node can choose any radio interface according to its own decision or a centralized network decision (by source) for either transmitting or receiving packets from the network. For instance, a sensor node can receive packets from 802.15.4 radio interface, and relay them to a neighboring sensor node using 802.11 Wi-Fi radio interface, and vice versa. We also assume that a packet that traverses the network from a source to a destination should be delivered within a given packet deadline, and packet deadline is determined by application and elasticity type.

In this paper, we aim to solve the multi-hop routing problem under heterogeneous wireless radio interfaces that can be described as jointly finding a series of sensor nodes and selected radio interfaces of them on a hop-by-hop basis, to minimize energy consumption throughout the network and also satisfy the end-to-end deadline requirement.

4. Routing through Radio Interface Selection

In heterogeneous sensor networks where sensor nodes are equipped with multiple radio interfaces such as 802.11 Wi-Fi, 802.15.4, Bluetooth, and UWB, we leverage various radio interfaces for each sensor node to choose for relaying packets to destination while reducing energy consumption. Depending on whether data to deliver is timely critical or not, the required route from the source to the destination would be differently established. For example, if data to transmit is delay-sensitive and does not permit considerable delay, a route that uses a radio interface with the highest data rate and the largest transmission range would rather be selected. However, it would consume a significantly larger amount of transmission energy across the route, than using other lower-power radio interfaces. On the other hand, if data to transmit has some relaxed deadline and is not timely critical, a multi-hop route would be allowed to use lower-power radio interfaces for certain parts of sensor nodes on route for reducing energy consumption.

As an overview example with the network equipped with 802.11 Wi-Fi and 802.15.4 in **Fig. 1**, for delay-sensitive data delivery, a route using the interface with the highest data rate and the largest transmission range (i.e., Wi-Fi instead of 802.15.4 in this example) has been selected (even though it would consume large transmission energy), and traverses across 15 hops (**Fig. 1(a)**). On the other hand, in the case of data delivery with a large packet deadline, the most efficient route using only 802.15.4 is chosen to minimize energy consumption across multi-hop transmission of 23 hops (**Fig. 1(b)**). For the deadline requirement in between these two extremes, a mixed combination of Wi-Fi and 802.15.4 is used as long as total incurred delay is less than the end-to-end deadline (**Fig. 1(c)**).

In the next two sections, we describe the overall necessary steps in the protocol level (Section 4.1), and then we formulate the problem of heterogeneous ad-hoc routing with multiple radio interfaces as binary integer programs (Section 4.2).

4.1 Protocol

We consider the following scenario: in heterogeneous static sensor networks, a data source wants to deliver data to a data sink with packet deadlines. The source node as well as other sensor nodes know the entire static network topology, meaning that any sensor node has global knowledge of the network [16] and can find one (or several) route to any data sink in the

network along shortest routes for a given radio interface. We provide a necessary protocol to take in the proposed system as follows:

1. Sensor node and radio interface selection.

A data source tries to delivery a packet to a destination node. Depending on applications, the packet may have a different deadline requirement. Given the packet deadline constraint and topological distance between the source and the sink, the data source finds the most energy-efficient route by selecting sensor relays as well as their radio interfaces to use. For the route selection, it solves an optimization problem to achieve the optimal route and interface selection for the entire routing that also satisfies the deadline requirement (as in Section 4.2), it appends all of the calculated route and radio interface information till the final destination on top of data payload, and transmits the packet to the selected next sensor relay with the selected radio interface.

2. Packet relay of en-route sensor nodes.

If an intermediate sensor relay node receives data from a neighboring node, it checks out the embedded route information to see *whom* it should relay to using *which* radio interface that has already been determined at the source node. Based on the embedded instruction, it turns on the selected radio interface for transmission and transmits the data to the selected next relay node.

3. Delivery completion of a packet at sink.

The data sink receives the packet and checks if the destination ID is the same as its own ID. To this end, the data packet is finally routed to a data sink by referring to the route record that the data source computed and appended in the packet.

Refer to [Algorithm 1](#) for more detailed data relay and reception procedure.

<p>Data: 1) Data on reception, 2) Computed route table of (relay node ID, radio interface type)</p> <p>Result: Relaying the data to the selected next relay node using the selected radio interface</p> <pre> // for retrieving the received route table; routeTable = data->header->routeTable; dstID = data->header->dstID; if dstID == myID then Reception of data from the source is done; end else // for finding the index (in routeTable) for the selected next relay selectedNextIndex = searchIndex(routeTable, myID) + 1; selectedNextRelay = routeTable[selectedNextIndex].nodeId; selectedRadioInterface = routeTable[selectedNextIndex].radioType; Relay the received data to the <i>selectedNextRelay</i> node with <i>selectedRadioInterface</i>; end </pre>
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Algorithm 1. Data relay procedure with joint relay and radio interface selection.

4.2 Route Optimization

Instead of taking traditional approaches based on heuristic radio interface selection by each relay node's *local* route optimization, we try to formulate the problem of data delivery in

multiple radio sensor networks into a *global* optimization problem. We find the optimal routing path and radio interface to use at each sensor node as output, and construct a route table at a source node for the use of relay nodes.

In order to formulate an optimization problem, we first introduce indicator functions $I_{r, i \rightarrow j}$ denoting whether the direct wireless link from node i to node j through radio interface r is selected as a part of the routing path (where $r \in R = \{w, s, b, u, \dots\}$, w standing for Wi-Fi 802.11 radio, s for 802.15.4 sensor radio, b for Bluetooth radio, and u for UWB radio).

We define C_r as energy cost consumed when transmitting data using the radio interface r , and D_r as total incurred delay on a direct link using the radio interface r . We assume that the data rate is a dominant factor for determining the hop-by-hop delay, and thus, D_r is inversely proportional to data rate of the radio interface r in simulation results in Section 5. T_{\max} is the end-to-end deadline required by an application that generates packets.

First, we formulate the problem of multi-hop routing where sensor nodes support Wi-Fi 802.11 and 802.15.4 sensor, and then extend it to general multi-radio networks.

4.2.1 Networks with Wi-Fi 802.11 and 802.15.4

We consider heterogeneous networks where sensor nodes are equipped with Wi-Fi 802.11 and 802.15.4 sensor radios. We write the objective function to minimize energy consumption for a complete routing path from the data source to the destination, which can be expressed as $f = C_w \cdot \sum_{i,j} I_{w, i \rightarrow j} + C_s \cdot \sum_{i,j} I_{s, i \rightarrow j}$. Therefore, the routing problem can be formulated as a binary integer program as follows:

$$\text{minimize} \quad C_w \cdot \sum_{i,j} I_{w, i \rightarrow j} + C_s \cdot \sum_{i,j} I_{s, i \rightarrow j} \quad (1)$$

$$\text{subject to} \quad \sum_j [I_{w, src \rightarrow j} + I_{s, src \rightarrow j}] = 1 \quad (2)$$

$$\sum_i [I_{w, i \rightarrow dst} + I_{s, i \rightarrow dst}] = 1 \quad (3)$$

$$\sum_i [I_{w, i \rightarrow src} + I_{s, i \rightarrow src}] = 0 \quad (4)$$

$$\sum_j [I_{w, dst \rightarrow j} + I_{s, dst \rightarrow j}] = 0 \quad (5)$$

$$\sum_i [I_{w, i \rightarrow j} + I_{s, i \rightarrow j}] = \quad (6)$$

$$\sum_k [I_{w, j \rightarrow k} + I_{s, j \rightarrow k}] \leq 1$$

$$D_w \cdot \sum_{i,j} I_{w, i \rightarrow j} + D_s \cdot \sum_{i,j} I_{s, i \rightarrow j} \leq T_{\max} \quad (7)$$

The objective function (1) minimizes routing cost in terms of energy consumption in involved sensor nodes. The indicator functions $I_{w, i \rightarrow j}$ and $I_{s, i \rightarrow j}$ are variables, which will be computed as the output of this optimization problem. Constraint (2) ensures that the source node should send data out to one of next sensor relays, while constraint (3) enforces that the

data should be delivered from any sensor relay eventually to the destination node. Constraints (4) – (5) exclude all possible routing loop cases at source and destination. Constraint (6) forces a conservation law for packet ingress and egress at each sensor node. Lastly, constraint (7) makes sure to satisfy the end-to-end delay requirement.

Given the end-to-end packet deadline T_{\max} , using these definitions and constraints, the problem is to find a set of indicator functions ending up with 1 that minimizes the total routing cost from a data source node to a data sink node. From this set of indicator functions equal to 1, we obtain the selected routing path consisting of 802.11 Wi-Fi and 802.15.4.

4.2.2 General networks with all possible radio interfaces

We generalize our formulation for heterogeneous networks with all possible radio interfaces equipped in sensor nodes. Each sensor node can choose one of radio interfaces in R , i.e., 802.11 Wi-Fi, 802.15.4 sensor, Bluetooth, or UWB. The generalized binary integer program is formulated as follows:

$$\text{minimize} \quad \sum_{r \in R} [C_r \cdot \sum_{i,j} I_{r,i \rightarrow j}] \quad (8)$$

$$\text{subject to} \quad \sum_j \sum_{r \in R} I_{r,src \rightarrow j} = 1 \quad (9)$$

$$\sum_i \sum_{r \in R} I_{r,i \rightarrow dst} = 1 \quad (10)$$

$$\sum_i \sum_{r \in R} I_{r,i \rightarrow src} = 0 \quad (11)$$

$$\sum_j \sum_{r \in R} I_{r,dst \rightarrow j} = 0 \quad (12)$$

$$\sum_i \sum_{r \in R} I_{r,i \rightarrow j} = \sum_k \sum_{r \in R} I_{r,j \rightarrow k} \leq 1 \quad (13)$$

$$\sum_{r \in R} [D_w \cdot \sum_{i,j} I_{r,i \rightarrow j}] \leq T_{\max}. \quad (14)$$

Note that our formulation does not exclude general cases such that sensor nodes are configured with respectively different radio interfaces: e.g., sensor node 1 supports Wi-Fi 802.11 and Bluetooth, whereas sensor node 2 supports 802.15.4 and Bluetooth. If both node i and j do not support the same radio interface r , we do not include $I_{r,i \rightarrow j}$ in the formulation. To this end, our formulation can cover the general case of a variety of radio combinations per sensor node, and provides the optimal path as well as the optimal radio interface on each sensor node basis.

Given the end-to-end packet deadline T_{\max} , using these definitions and constraints, the problem is to find a set of indicator functions ending up with 1 that minimizes the total routing cost from a data source node to a data sink node. From this set of indicator functions equal to 1, we obtain the selected routing path consisting of a variety of radio interfaces.

4.2.3 Considering interface switching delay

We take into account the switching delay from one interface to another in heterogeneous

networks equipped with Wi-Fi 802.11 and 802.15.4 sensor radios. To penalize the interface switching decision, we apply the *regularization* technique [17] by a factor of α . Using a form of regularization is to minimize the weighted sum of the objectives: 1) routing cost in terms of energy consumption and 2) the number of interface switching.

$$\text{minimize} \quad C_w \cdot \sum_{i,j} I_{w,i \rightarrow j} + C_s \cdot \sum_{i,j} I_{s,i \rightarrow j} + \alpha \cdot \left(\sum_{i,j,k} \lambda_{i,j,k,w \rightarrow s} + \sum_{i,j,k} \lambda_{i,j,k,s \rightarrow w} \right) \quad (15)$$

$$\text{subject to} \quad \sum_j [I_{w,src \rightarrow j} + I_{s,src \rightarrow j}] = 1 \quad (16)$$

$$\sum_i [I_{w,i \rightarrow dst} + I_{s,i \rightarrow dst}] = 1 \quad (17)$$

$$\sum_i [I_{w,i \rightarrow src} + I_{s,i \rightarrow src}] = 0 \quad (18)$$

$$\sum_j [I_{w,dst \rightarrow j} + I_{s,dst \rightarrow j}] = 0 \quad (19)$$

$$\sum_i [I_{w,i \rightarrow j} + I_{s,i \rightarrow j}] = \sum_k [I_{w,j \rightarrow k} + I_{s,j \rightarrow k}] \leq 1 \quad (20)$$

$$D_w \cdot \sum_{i,j} I_{w,i \rightarrow j} + D_s \cdot \sum_{i,j} I_{s,i \rightarrow j} + \delta \cdot \left(\sum_{i,j,k} \lambda_{i,j,k,w \rightarrow s} + \sum_{i,j,k} \lambda_{i,j,k,s \rightarrow w} \right) \leq T_{max}. \quad (21)$$

$$I_{w,i \rightarrow j} + I_{s,j \rightarrow k} \leq \lambda_{i,j,k,w \rightarrow s} + 1 \quad \forall i, j, k \quad (22)$$

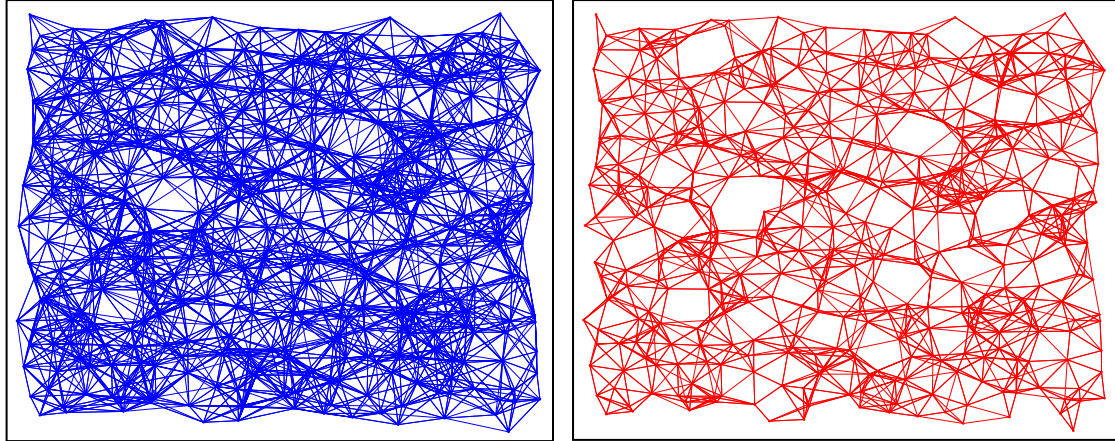
$$I_{s,i \rightarrow j} + I_{w,j \rightarrow k} \leq \lambda_{i,j,k,s \rightarrow w} + 1 \quad \forall i, j, k \quad (23)$$

We introduce new indicator functions $\lambda_{i,j,k,w \rightarrow s}$, $\lambda_{i,j,k,s \rightarrow w}$ denoting whether the interface has been switched at node j upon sending a packet from node i toward node k from 802.11 Wi-Fi interface to 802.15.4 sensor interface, and vice versa. Constraint (21) makes sure to satisfy the end-to-end delay requirement considering the switching delay δ . Constraints (22) and (23) encourage the interface selection to keep unchanged as far as it can: if the interface becomes changed, $\lambda_{i,j,k,w \rightarrow s}$ or $\lambda_{i,j,k,s \rightarrow w}$ is forced to be 1.

Given the end-to-end packet deadline T_{max} , using these definitions and constraints, the problem is to find a set of indicator functions ending up with 1 that minimizes the weighted sum of total routing cost from a data source node to a data sink node and switching penalty. From this set of indicator functions equal to 1, we obtain the selected routing path consisting of a variety of radio interfaces, and the nodes that need to switch the radio interface.

4.2.4 Solution of binary integer programs

The binary integer programs can be solved by a linear programming (LP)-based branch-and-bound algorithm [18]. The solution is known to be calculated in a pseudo-polynomial time in computation complexity [19]. AMPL/CPLEX [20] can be used to obtain the solution in our approach. Our joint optimization model applies the original binary integer programming technique, and more theoretical analyses on feasibility and computation complexity are referred to [21].



(a) 802.11 Wi-Fi topology over 518 nodes where links are shown for $\text{PRR} \geq 75\%$

(b) 802.15.4 sensor topology over 518 nodes where links are shown for $\text{PRR} \geq 75\%$

Fig. 2. Network topology for 802.11 and 802.15.4, respectively. 518 nodes are deployed in the area of $500 \times 500 \text{ m}^2$ in simulations. In 802.11 Wi-Fi topology, the larger number of longer links are seen compared to 802.15.4.

5. Simulation Results

We validate our routing algorithm in a simulated network deployment of 518 sensor nodes over $500 \times 500 \text{ m}^2$ shown in **Fig. 2**. In our evaluation, sensor nodes are assumed to support two radio interfaces of 802.11 Wi-Fi and 802.15.4. Wi-Fi connectivity graph and 802.15.4 connectivity graph over 518 nodes are shown in **Fig. 2(a)** and **Fig. 2(b)**, respectively. The wireless propagation model used in simulations is based on a combined path-loss and shadowing model with a path-loss exponent of 3, a reference loss of 46.67 dB, and an additive white Gaussian noise of $N(0, 5^2)$ in dB [22]. In our simulations, the data packet size is 10 KBytes, and the data rate of 802.11 and 802.15.4 is 11 Mbps and 250 Kbps, respectively. Thus, we use $D_w = 0.89 \text{ ms}$, and $D_s = 40 \text{ ms}$ along with $C_w / C_s = 100$ for energy consumption cost [23].

We implement the simulator in MATLAB for the purpose of algorithmic validation. We do not explicitly consider MAC protocols in simulations, but our evaluation empirically verifies the correctness and feasibility of our proposed algorithm in the network layer. We use AMPL/CPLEX [20] to solve the binary integer programming problem.

We evaluate our proposed routing algorithm in terms of energy consumption cost, total incurred delay, and total number of hops for the selected route path. We examine how performance metrics above change with respect to radio interface and packet deadline. We measure the size of appended information (i.e., control overhead) regarding the complete route and interfaces beyond packet payload. Also, we validate the practical feasibility in computational complexity by measuring the computation time with respect to network size.

We first analyze how radio interface types that the routing algorithm uses affect network performance in **Fig. 3**. We consider relative energy consumption cost with a basic unit of the lowest power wireless, 802.15.4 (where $C_s = 1$) in our simulation. As shown in **Fig. 3(a)**, energy consumption for only 802.11 multi-hop routing is significantly larger than that for only 802.15.4 multi-hop routing. Using mixed interfaces between these two extremes, energy

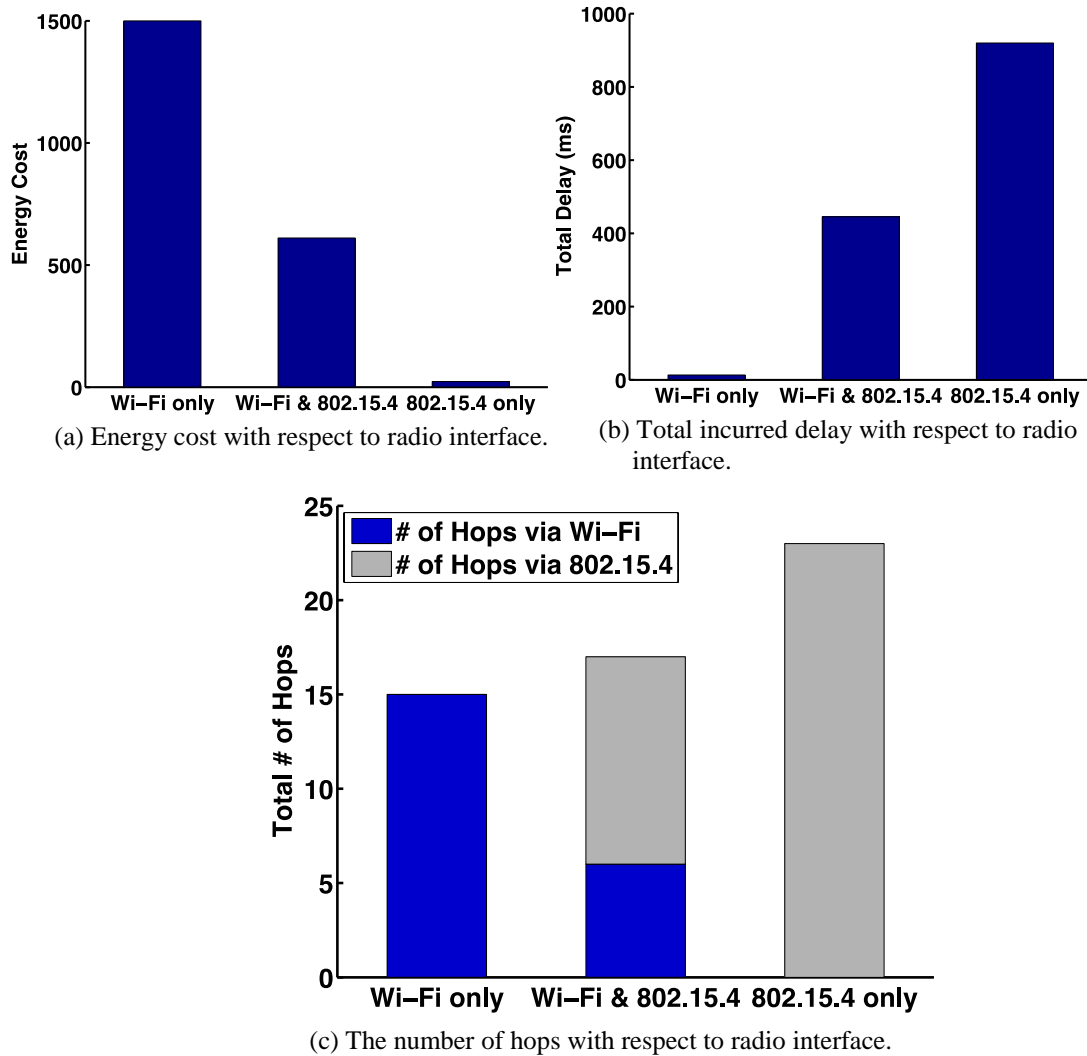


Fig. 3. Network performance with respect to radio interface. As the 802.15.4 sensor interface instead of 802.11 is selected for the entire routing, energy cost significantly decreases whereas the end-to-end delay increases along with increase in the number of hops.

consumption cost is significantly less than Wi-Fi only interface scenario. In terms of total incurred end-to-end delay, using only 802.15.4 sensor radio interface (see [Fig. 3\(b\)](#)) incurs the largest delay over the largest number of hops ([Fig. 3\(c\)](#)) toward destination. This means that if data is more delay-sensitive, the route path should rely on more Wi-Fi interfaces (which takes fewer hops), to satisfy the given deadline requirement, even if it would take larger energy consumption cost in return.

We look into how the packet deadline affects radio interface selection and the resulting energy consumption cost in [Fig. 4](#). If the deadline constraint is very small, the route path fully utilizes only Wi-Fi interfaces to meet the deadline by consuming large transmission energy (see [Fig. 4\(a\)](#)). As the deadline requirement becomes more relaxed, the routing path starts mixing 802.15.4 radio interfaces with 802.11 radio interface. This means that as long as the routing path and corresponding radio interfaces meet the end-to-end deadline, the routing algorithm finds a more energy-efficient routing path. Our routing algorithm allows sensor

networks to fully exploit the remaining packet delivery time to benefit the entire network with reduced energy consumption as in Fig. 4(b). This plot explicitly shows a trade-off relationship

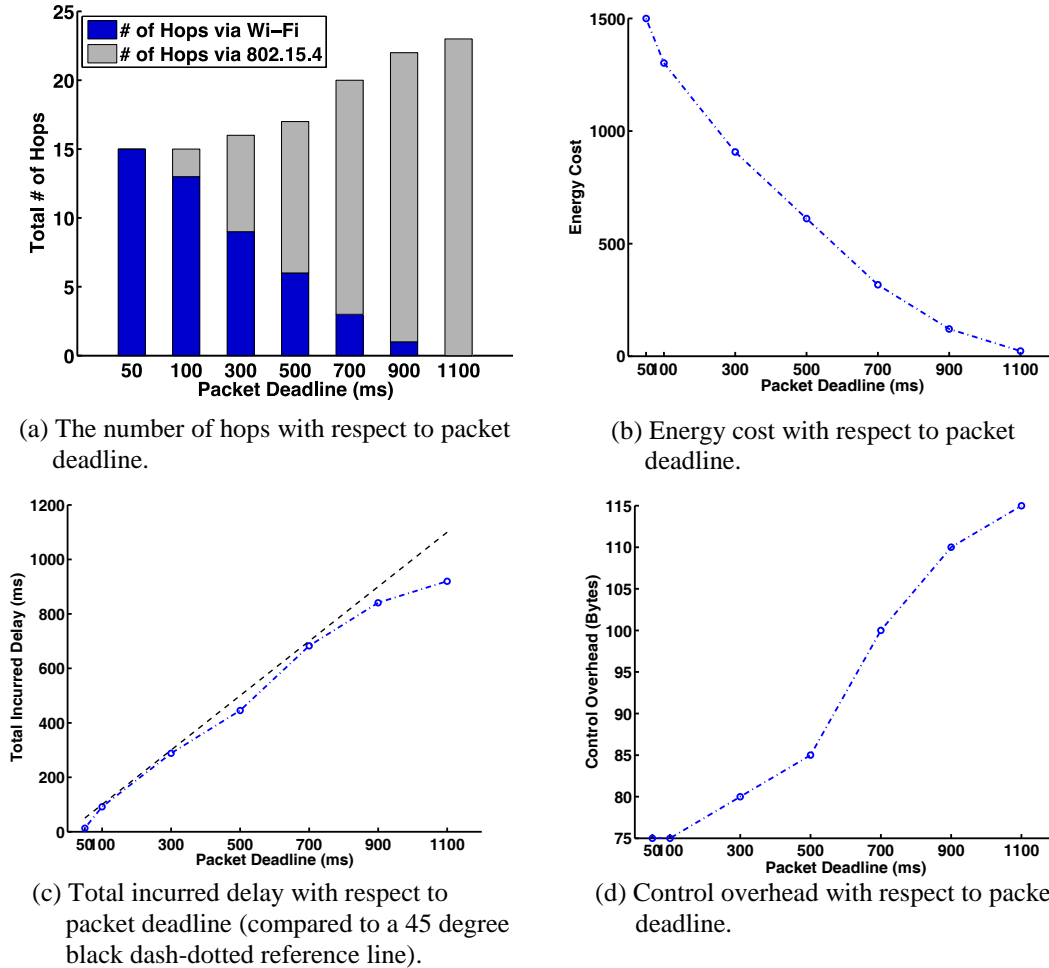
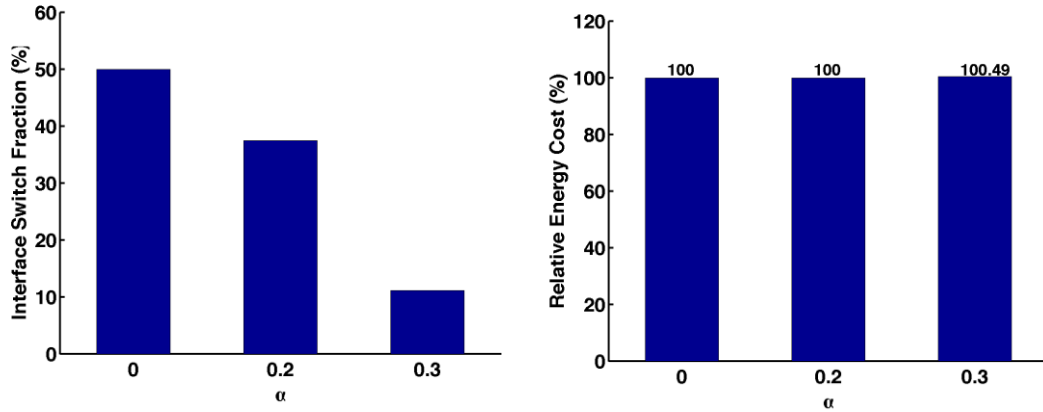


Fig. 4. Network performance with respect to packet deadline. As the packet deadline becomes more relaxed, the routing path starts mixing low-power radio interface (i.e., 802.15.4) together with 802.11 to reduce energy consumption, but with sacrifices of the number of hops and total delay.

between energy consumption and delay. Fig. 4(c) shows that the proposed scheme guarantees packet delivery within given packet deadlines. The incurred packet delay is slightly smaller than the packet deadline, while fully exploiting the given time for reducing packet transmission cost.

We measure the control overhead for appending the complete route and interfaces chosen by the data source. Our protocol uses 4 bytes for node ID and 1 byte for radio interface ID. This means that our routing protocol requires additional 5 bytes per hop for informing en-route sensor nodes of routing information. We evaluate total number of bytes consumed for the longest route in the network (from the lower-left-most node to the upper-right-most node in Fig. 2) depending on the permitted delay requirement as in Fig. 4(d). Even with the longest path in Fig. 1 (b) traversing 23 hops from the source to the destination through sensor interfaces, the relatively small control overhead of 115 bytes are required to provide the complete route information of *how* to route with *which* radio interface.



(a) Interface switch fraction (defined as the number of switching over the number of total hops).

(b) Relative energy cost compared to $\alpha = 0$.

Fig. 5. Impact of the interface switching on energy cost. As the interface switching gets more penalized, the number of interface switching is significantly reduced, while lowering the energy consumption level close to the optimal case ($\alpha = 0$).

We compare our proposed scheme with an existing multi-radio routing principle [24] that selects an interface with the highest utility metric considering the remaining energy on node, transmission energy, and transmission delay among available interfaces. Since the counterpart routing does not consider the hard delay constraint, it selects the lowest energy interface as long as the remaining energy is available for transmission. We ran two schemes for a scenario of sending 10 packets where all 518 nodes can initially have the total energy that can consume the energy for sending 10 packets in Wi-Fi. If the packet deadline of 1100 ms is permitted, there is no difference between two schemes since both schemes select the lowest energy interface, 802.15.4 radio interface. However, if the permitted deadline is less than 1100ms, our scheme tries to select Wi-Fi radio interface in some parts of routes to meet the deadline constraint, whereas the counterpart routing does not change the decision while keeping using 802.15.4 radio interface with the lowest energy consumption. Since the results show the exactly same performance as in Fig. 4(b), we omit its corresponding evaluation plot.

We evaluate how the interface switching affects energy cost as in Fig. 5. We consider the delay due to interface switching into our joint optimization. In this experiment, we used 5 ms for the switching delay [25]. As the switching penalty factor α increases from 0.2 to 0.3, our joint optimization significantly reduces the number of interface switching due to the increased penalty cost. However, as the return, it increases the energy cost by only 0.5%. This implies that our algorithm (as in Sec. 4.2.3) provides an efficient solution for achieving the goal of minimizing both energy consumption and interface switching, while meeting the deadline constraint.

Finally, we evaluate the feasibility of efficiently computing our proposed routing algorithm through optimization. In order to see computational complexity, we measure the running time for solving the binary integer program in Section 4. We tested the performance on Dell Precision 390 PC with 2.66 GHz Core 2 CPU 6700 and Ubuntu 12.04 Linux. Fig. 6 shows that as network size increases, the required computation time also increases (also refer to Table 1). It should be noted that a data source does not necessarily calculate a routing path for every data delivery. Instead, each sensor node (or a central server) pre-computes a routing path to any

sensor node given various packet deadline cases, and records them in a routing table and uses the table for incoming data delivery, making more practically feasible.

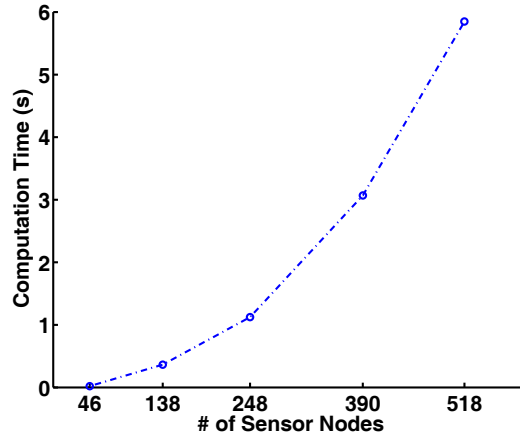


Fig. 6. Computation complexity for solving the binary integer program. We measure the running time to compute the solution with respect to the number of sensor nodes (which corresponds to a certain number of variables).

Table 1. Computation complexity for solving our proposed routing algorithm with respect to network size.

# of sensor nodes	# of variables	Computation time (sec)
46	698	0.02
138	2974	0.36
248	5262	1.12
390	9238	3.07
518	12163	5.85

6. Conclusion

Energy awareness has recently got more attention to achieve energy-efficient utilization of resources. Since radio transmission consumes most of energy resources, it is of great significance to design an energy-aware routing protocol in the era of ubiquitous wireless networks. We have presented an energy-efficient routing algorithm that finds the optimal mesh nodes and radio interfaces, through an optimization model. We provide an explicit way to fully exploit the given packet deadline requirement to turn into network benefit of reducing energy consumption.

As for interesting future direction, we may take dynamic link variations into account and include them in the energy cost parameter so that the entire network can adaptively find a more reliable multi-hop path. To achieve this goal, the current table-based routing approach would not be feasible in terms of computation time. A distributed optimization for updating the routing table periodically or aperiodically would be an interesting future work. Also, it would be interesting to consider additional energy inefficiency due to MAC dynamics for a more advanced MAC and network layer optimization.

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