Radio and Medium Access Contention Aware Routing for Lifetime Maximization in Multichannel Sensor Networks

Samina Ehsan, Bechir Hamdaoui, and Mohsen Guizani

***Abstract*—In this paper, we develop cross-layer techniques suitable for wireless sensor networks (WSNs) that are capable of multichannel access. More specifically, we propose energy and cross-layer aware routing schemes for multichannel access WSNs that account for radio, MAC contention, and network constraints. By doing so, we guarantee to meet data rate requirements of end-to-end flows while maximizing the network lifetime. When MAC contention constraints associated with the shared wireless medium are not included in routing formulations, routing solutions may not be feasible, in that the shared medium may not be able to support the required data rates of these flows. In this paper, we first derive three sets of sufficient conditions that ensure feasibility of data rates in multichannel access WSNs. Then, utilizing these sets, we devise three different MAC-aware routing optimization schemes, each aiming to maximize the network lifetime. Finally, we perform extensive simulation studies to evaluate and compare the performance of the proposed routing approaches under various network conditions.**

***Index Terms*—Cross-layer routing, multichannel access, QoS traffic, rate feasibility, wireless sensor networks.**

I. Introduction

Energy-aware routing in WSNs has received considerable attention over the past few years. Although early proposed routing approaches increase network lifetime by reducing energy consumption, the medium access control (MAC) contention constraints associated with the shared wireless medium are often ignored. As a result, the number of flows routed through nodes in the same neighborhood may be such that the shared medium may not be able to provide the data rates required to support these flows. If this happens, data rate requirements of the flows cannot be satisfied by the network. A primary reason for this discrepancy is to perform network layer optimization without considering the effects of the underlying MAC layer.

To overcome the above issues, researchers have recently shifted the focus to cross-layer designs [1–5], which typically include information exchange between different layers (not necessarily neighboring layers), adaptivity at each layer to this information, and diversity built into each layer to ensure robustness [6], yielding more practical solutions.

Capacity limitation also presents a major challenge to WSNs, mainly due to the interference arising from the wireless nature of the communication environment. It restricts the number of data flows that can occur simultaneously in a given neighborhood, thus limiting overall achievable network throughput.

This work was supported by NSF under NSF CAREER award CNS-0846044.
Samina Ehsan and Bechir Hamdaoui are with the School of EECS at Oregon State University. Mohsen Guizani is with Qatar University. Emails: ehsan@eecs.orst.edu; hamdaoui@eecs.orst.edu; mguizani@ieee.org.

Considering all the factors, in our current work we propose routing techniques for WSNs with multiple channel access capability that (i) are cross-layer aware by accounting for radio, MAC contention, and network constraints, (ii) guarantee to meet data rate requirements of end-to-end flows, and (iii) are energy efficient by increasing the lifetime of WSNs. We first derive three sufficient conditions for rate-feasibility in multichannel WSNs (referred to as rate-based, degree-based, and mixed) as the basis for ensuring feasibility of the obtained routing solutions in regard with the medium access contention constraints. Then, we propose three routing formulations, each based on one of the three derived rate-feasibility conditions, whose objective is to maximize the network lifetime. Throughout the paper, these formulations are referred to as LPM-1, LPM-2, and IPM. We show that IPM always achieves better network lifetimes than LPM-1 and LPM-2, but at the cost of larger execution times.

To recap, our contributions in this work are:

- Development of energy-aware frameworks for supporting rate-constrained traffic in multichannel access WSNs;
- Derivation of three sufficient condition sets that guarantee flow rate feasibility in multichannel access WSNs;
- Design of cross-layer routing approaches that maximize lifetime of multichannel access WSNs while accounting for MAC contention constraints.

The rest of the paper is organized as follows. Section II presents the related work. Section III describes the network model. Section IV formally presents the sufficient rate feasibility conditions. The routing schemes are presented in Section V and evaluated in Section VI. We conclude the paper in Section VII.

II. Related Work

To condense the energy deficiency problem, various energy-aware algorithms have been proposed in the literature during the last decade. A typical approach [7] to solve such a problem is to use a shortest path algorithm in which the edge cost is the power consumed to transmit a packet between the nodes on that edge. Though effectively reducing the energy consumption rate, this approach can cause unbalanced consumption distribution. To solve this problem, in [8], a distributed, power-efficient routing technique is proposed for WSNs, where the objective is to maximize network lifetime based on flow conservation constraints while balancing energy consumption in proportion to the nodes' remaining energy. In [9], a model is proposed to integrate data aggregation with the routing scheme and smoothing approximation function for the optimization problem to maximize the network lifetime. Although these reported routing approaches maximize the lifetime reasonably the adoption of layered schemes raises the question of practical feasibility.

Due to the afore mentioned fact, extensive research has been spurred to more practical cross-layer routing approaches in the recent years [1–5]. In [1], the lifetime maximization problem is considered under cross-layer constraints involving physical, MAC and routing layers. In this work, the jointly optimal route, schedule, and power allocation are computed under a general convex programming framework. But the scheme restricts the link schedules to use interference-free time division multiple access methods. Also, the PHY/MAC constraints are not modeled and the link capacity is considered unbounded. The authors in [3] also propose a decentralized, joint routing and MAC algorithm for lifetime maximization of WSNs. This algorithm solves a convex optimization problem by a distributed primal-dual approach, where the network layer problem is solved in the dual domain and the MAC layer problem is solved in the primal domain by relaxing the MAC constraints in the form of a penalty function. This scheme performs optimization adopting distributed random access MAC protocol. The most related work to ours is presented in [10], where a sufficient feasibility condition is provided to tackle both energy and bandwidth constraints using uniform transmission power for routing without data aggregation and nonuniform transmission power for routing with data aggregation. Unlike ours which is designed for multichannel access, this approach, however, is designed for single-channel access networks. Besides, as shown in Section II, our approach provides better performances in terms of its ability to admit data flows into the network. Moreover, to mitigate the effect of interference on achieving desired throughput, algorithms are proposed in [11] to compute the transmission power of each node with the objectives of minimizing the total transmission power and minimizing the total interference. Then, the maximum achievable throughput is computed from the obtained topology by using joint routing and link rate control. As transmission power control tightly affects network performance [12] and appropriate transmission power adjustment incurs extra computational burden, an alternate key emerging solution to the capacity problem is to enable WSNs with multichannel access [13, 14], which has recently been made possible by means of the newly emerging cognitive radio technology that empowers sensor nodes with the ability to switch from one channel to another [15]. The authors in [16] develop efficient algorithms that perform end-to-end flow routing and link scheduling in a multi-hop wireless network with orthogonal communication channels. To solve both the end-to-end flow routing problem and the link scheduling problem near optimally, they characterize the necessary conditions on the achievable scheduling space and propose approximation algorithms. But they model interference based on global information such as cliques on a conflict graph which is computationally expensive. Again, the authors in [17] propose an interference-aware joint broadcast routing and channel assignment scheme for IEEE 802.11-based multi-radio multi-channel mesh networks. They first use the mixed integer linear programming (MILP) to optimally solve this problem, and then a heuristic algorithm is proposed. However, this approach is not suitable for traditional WSNs as it may circumvent the sensors with additional technologies and therefore higher costs.

III. Network Model

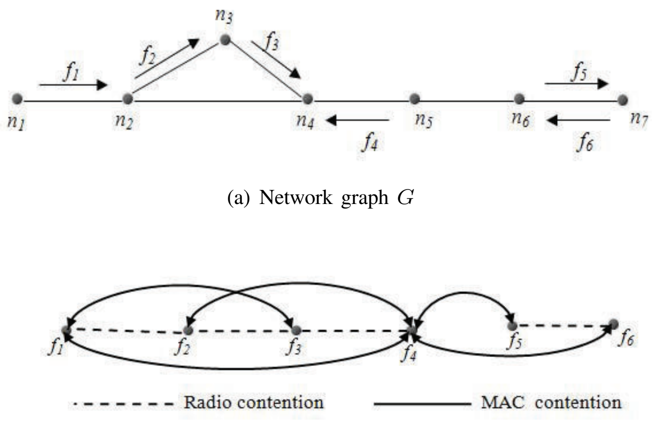
Here we model the WSN as a directed graph $G = (\mathcal{N}, \mathcal{F})$ that consists of a set of nodes $\mathcal{N}$ and a set of link flows $\mathcal{F}$. Each link flow in $\mathcal{F}$ corresponds to an ordered pair of distinct transmitter node and receiver node (n, m) such that m is within n's transmission range—i.e., m is a neighbor of n—and n needs to transmit to m. If n is currently transmitting to m, then the link flow $f \equiv (n, m)$ is said to be *active*. Throughout the paper, we refer to flow as link flow.

We assume that for every flow f in $\mathcal{F}$, there are $c(f)$, $c(f) \geq 1$, available channels on which f can communicate and also each node has one radio only, and that it can only communicate on one channel at a time.

We adopt the flow contention graph, which was proposed in [18] and also used in [3, 19] to model the set of flows $\mathcal{F}$ as a graph $H = (\mathcal{F}, C)$, where $C = C_R \cup C_I$. Here, C_R is the set of all unordered, radio-contending pairs of flows and C_I is the set of all ordered, MAC-contending pairs of flows in $\mathcal{F}$. Two flows f and g are said to radio-contend with each other (i.e., $(f, g) \in C_R$) when they cannot be active at the same time due to radio constraints. That is, when the two flows share one node. In this work, we assume that a node can either transmit or receive, but not both, at any given time. A flow f is said to MAC-contend with another flow g (i.e., $(f, g) \in C_I$) when 1) flows f and g do not share a node between them, and 2) flow f cannot be (interference-free) active when g is active because of medium access contention constraints, which are solely dictated by the underlying MAC protocol. Note that if $(f, g) \in C_I$, it does not necessarily mean that $(g, f) \in C_I$. But $(f, g) \in C_R$ implies that $(g, f) \in C_R$. Also a flow contention graph, and depends mainly on the network topology (e.g., node placement, transmit power, connectivity), routing protocol (e.g., paths nodes' traffic routes through), and the MAC protocol (e.g., medium access contention constraints).

For every $f \in \mathcal{F}$, let $\Psi_R(f)$ be the set of flows in $\mathcal{F}$ that radio-contend with f; i.e., $\Psi_R(f) = \{g \in \mathcal{F} : (f, g) \in C_R\}$ denotes the set of all flows that cannot be active with flow f at the same time, due to radio resource limitation. Let $d_R(f) = |\Psi_R(f)|$, which represents the number of flows in $\Psi_R(f)$. Likewise, let $\Psi_I(f) = \{g \in \mathcal{F} : (f, g) \in C_I\}$ be the set of flows that MAC-contend with f; i.e., if f is active on one channel and in order for f to be MAC contention-free, no flow in $\Psi_I(f)$ can be active on the same channel at the same time (so as to avoid interference due to MAC contention). Let $d_I(f) = |\Psi_I(f)|$, which represents the number of flows in $\Psi_I(f)$.

Example 1: *In this example, we derive the flow contention graph of a given network graph using the IEEE 802.11 MAC protocol. We consider the network graph $G = (\mathcal{N}, \mathcal{F})$ in Fig. 1(a) where $\mathcal{N} = \{n_1, n_2, n_3, n_4, n_5, n_6, n_7\}$ and $\mathcal{F} = \{f_1, f_2, f_3, f_4, f_5, f_6\}$. Under the IEEE 802.11 MAC protocol, two flows radio-contend with each other if they both share a node that needs to send and receive at the same time (e.g., flow f_2 radio-contends with flow f_1, as they share a common node n_2 which intends to send and receive simultaneously if f_1 and f_2 need be active simultaneously). On the other hand, a flow f MAC-contends with a flow g if g's transmission interferences with f's reception, thus disallowing receiver of f to successfully decode its signal (e.g., f_3's transmission causes interference*



(a) Network graph G

(b) Contention graph H

Fig. 1. Graphs for example 1

TABLE I
CONTENTION SETS AND DEGREE VALUES FOR EXAMPLE 1

flow $\mathcal{F}$	$\Psi_R(f)$	$d_R(f)$	$\Psi_I(f)$	$d_I(f)$
f_1	$\{f_2\}$	1	$\{f_3, f_4\}$	2
f_2	$\{f_1, f_3\}$	2	$\{f_4\}$	1
f_3	$\{f_2, f_4\}$	2	$\{f_1\}$	1
f_4	$\{f_3\}$	1	$\{f_1, f_2, f_5, f_6\}$	4
f_5	$\{f_6\}$	1	$\{f_4\}$	1
f_6	$\{f_5\}$	1	$\{f_4\}$	1

at the receiver of f_1, and hence, $(f_1, f_3) \in C_I$ and similarly f_4's reception is disrupted by the transmitter of f_2, and hence, $(f_4, f_2) \in C_I$). Note that due to IEEE 802.11 MAC's bi-directional communication nature, where DATA flows in one direction and ACK flows in the other, $(f, g) \in C_I$ implies that $(g, f) \in C_I$. The flow contention graph $H = (\mathcal{F}, C_R, C_I)$ under IEEE 802.11 MAC is shown in Fig. 1(b), where the flows in radio contention set C_R and MAC contention set C_I are represented separately. The values for the contention sets and degrees are provided in Table I. ■

Given the MAC protocol and a network topology graph $G = (\mathcal{N}, \mathcal{F})$, one can derive the corresponding flow contention graph $H = (\mathcal{F}, C)$. Note that the MAC-contention subset C_I depends on the underlying MAC, and hence so do the MAC-contention constraints.

IV. CONDITIONS FOR RATE FEASIBILITY

Let $H = (\mathcal{F}, C)$ be a flow contention graph. Let us assume that each flow f in $\mathcal{F}$ flows data traffic at a rate of x_f bits per second. Let $\mathrm{x} = (x_f)_{f \in \mathcal{F}}$ be the vector, referred to as a flow rate vector, representing the data rates of all flows in $\mathcal{F}$. The vector x is said to be a feasible flow rate vector in H if there exists a time schedule in which the rates of all flows are satisfied. Formally, x is feasible in H if there exists a time schedule $\mathcal{S} = [0, \tau]$ of length $\tau > 0$ in which every flow $f \in \mathcal{F}$ communicates τx_f bits. For each subset of $A \subseteq \mathcal{F}$, we define the weight of A under a given flow rate vector x to be $\delta(A, \mathrm{x}) = \sum_{f \in A} x_f$. Let W denote the capacity of the single channel, and c_{max} denote the total number of available channels that any link can have.

In this section, we propose three different sets of sufficient conditions under which a given flow rate vector is feasible in H. One set of conditions takes topology parameters, rates of the flows, and the availability of multiple channels into consideration. The second set of conditions accounts for the topology parameters and the availability of multiple channels only. The third set of conditions is a mix of the two previous sets. The proofs of the first two sets are provided in [20].

Proposition *1:* (*Rate-based conditions*) The flow rate vector x is feasible in H if, for every flow $f \in \mathcal{F}$, $x_f \leq \min\{W - \delta(\Psi_R(f), \mathrm{x}), c(f)W - c(f)\delta(\Psi_R(f), \mathrm{x}) - \delta(\Psi_I(f), \mathrm{x})\}$.

Proposition *2:* (*Degree-based conditions*) The flow rate vector x is feasible in H if, for every flow $f \in \mathcal{F}$, $x_f \leq \min\{\frac{W}{d_R(f)+1}, \frac{c(f)W}{(d_R(f)+1)(d_I(f)+1)}\}$.

One important point that requires mentioning here is that none of the two above sets of sufficient conditions (i.e., rate-based and degree-based conditions) is better than the other. That is, flow rate vectors satisfying the degree-based conditions do not necessarily satisfy the rate-based conditions and vice versa.

Next, we present a new set of conditions that we prove to be better than each of these two stated sufficient conditions (rate-based and degree-based) in terms of admitting more flow rate vectors (but at a cost to be discussed later). That is, any flow rate vector passing any of the two previously stated sets of conditions will always pass this new set of conditions, whereas the opposite is not always true.

Proposition *3:* (*Mixed conditions*) The flow rate vector x is feasible in H if, for every flow $f \in \mathcal{F}$, $x_f \leq \max\{\min(W - \delta(\Psi_R(f), \mathrm{x}), c(f)W - c(f)\delta(\Psi_R(f), \mathrm{x}) - \delta(\Psi_I(f), \mathrm{x})), \min(\frac{W}{d_R(f)+1}, \frac{c(f)W}{(d_R(f)+1)(d_I(f)+1)})\}$.

Proof: See Appendix. ■

It is important to mention that the mixed condition set is always better than any of the two other (rate-based and degree-based) sets, in the sense that flow rate vectors that satisfy rate-based and/or degree-based conditions must satisfy the mixed conditions, whereas the opposite is not necessarily true, as these stated sufficient conditions are not necessary. Now we compare the performance of our proposed conditions to those proposed in [10]. For this, we generate random flow contention graphs, test each of them against both our proposed conditions and those of [10], and measure the percentage of admitted vectors (those that satisfy the conditions) under each of the two condition sets.

We set the average of flow rates to 0.11 and vary the coefficient of variations of these rates between 0 and 40%, and plot in Fig. 2 the percentage of admitted vectors as a function of the coefficient of variations for the two condition sets. Observe from the figure that our proposed condition set outperforms that of [10], especially when the coefficient of variations increases.

The derived rate-based, degree-based, and mixed condition sets can be very useful in network routing problem formulations. Routing problems can often be formulated as optimization problems with the aim to maximize some performance metrics, such as network lifetime and network throughput. However, when the medium contention constraints are not accounted for, rate solutions provided by these approaches may be infeasible, meaning that the shared wireless medium may not be able to satisfy these rates. To mitigate the above limitation, we next use the derived sufficient conditions (proposed and proved in this section) to propose energy-efficient, cross-layer aware routing schemes for multichannel access WSNs that account for the MAC

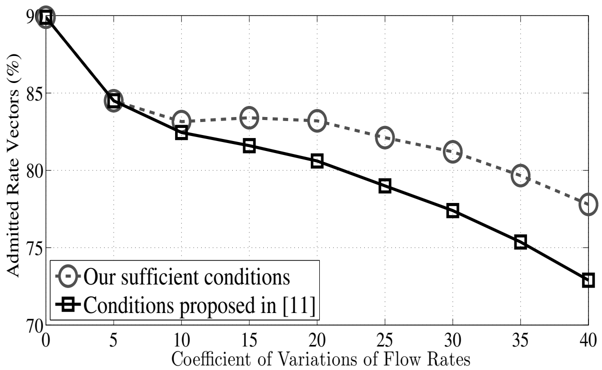


Fig. 2. Comparing sufficient conditions.

contention constraints, and that by doing so, guarantee to meet data rate requirements of end-to-end flows while maximizing the network lifetime.

V. Energy-Efficient MAC-Aware Routing

Let $G = (\mathcal{N}, \mathcal{F})$ represent a WSN, where $\mathcal{N}$ is the set consisting of a number of sensor nodes (SNs) and a single sink or access node (AN). Let us assume that each SN i generates data traffic destined to the AN at a rate of R_i bits per second. Let $B_i(t)$ denote the energy resources available at SN i for network communications at a given time instant t. Also, let e_{ij} denote the energy required to transmit a bit from node i to node j (this designates the cost of transmitting one bit over a wireless link). Let x_{ij} denote the number of bits per second forwarded by node i to a neighboring node j, and $\mathbf{x} = [x_{ij}]_{1 \le i,j \le |\mathcal{N}|}$ be the vector representing the rates of all flows. We define the *network lifetime* to be the amount of time for the first node to die—a node dies if either it runs out of its energy resources, or it becomes disconnected due to the death of other nodes; denote this lifetime by T. Given the required rate vector $R = [R_i]_{1 \le i \le |\mathcal{N}|}$, our objective is to find a routing solution that maximizes the network lifetime, T, while meeting the data rate requirements of all the flows. We will first begin by presenting the routing constraints which rely on the derived sets of rate feasibility, and then present the routing formulation.

A. Routing Constraints

Independent of the routing objectives, given the required rate vector $R = [R_i]_{1 \le i \le |\mathcal{N}|}$, the following set of constraints must be satisfied.

- Flow balance constraints:
  At each SN, the total outgoing traffic rate must equal the sum of the rate of the incoming traffic and the rate of the traffic generated by the SN. That is, for each SN i,
  $$\sum_{j \in \mathcal{N}} x_{ji} + R_i = \sum_{j \in \mathcal{N}} x_{ij} \tag{1}$$
  For the AN, the total incoming traffic rate must equal the total traffic generated by all SNs.
  $$\sum_{j \in \mathcal{N}} x_{ji} = \sum_{j \in \mathcal{N}} R_j \quad \text{for } i = AN \tag{2}$$
  Since no traffic is generated from the AN to SNs, then for each SN j,
  $$x_{ij} = 0 \quad \text{for } i = AN \tag{3}$$
  Finally, all rates must be positive; i.e.,
  $$x_{ij} \ge 0 \quad \text{for all } i, j \in \mathcal{N} \tag{4}$$
- Energy consumption constraints:
  Let t_0 be the initial time. If SN i has $B_i(t_0)$ amount of energy at time t_0, then the remaining energy at any future time $t_0 + T$ must be greater than or equal to zero. The AN is assumed to have an infinite amount of energy. Formally, for each SN i,
  $$B_i(t_0) \ge T \sum_{j \in \mathcal{N}} e_{ij} x_{ij} \tag{5}$$
- Medium contention constraints:
  For ease of notation, hereafter, a flow f between two nodes i and j will be referred to as (i, j) or simply ij instead of f. As a result, the number of channels $c(f)$ available at flow $f \equiv (i, j)$ will also be denoted by c_{ij}. Now we use the derived three sets of sufficient conditions as a means of ensuring that the routing solutions meet the MAC constraints:
  1) **Rate-based Constraints**: The rate vector $\mathbf{x}$ is feasible—i.e., it satisfies the medium access constraints—if for each flow $(i, j) \in \mathcal{F}$ the following MAC constraints hold.
  $$\begin{aligned} x_{ij} &\le W - \delta(\Psi_R(ij), \mathrm{x}) \\ x_{ij} &\le c_{ij}W - c_{ij}\delta(\Psi_R(ij), \mathrm{x}) - \delta(\Psi_I(ij), \mathrm{x}) \end{aligned} \tag{6}$$
  2) **Degree-based Constraints**: The rate vector $\mathbf{x}$ is feasible if for each flow $(i, j) \in \mathcal{F}$ the following medium contention constraints hold.
  $$\begin{aligned} x_{ij} &\le \frac{W}{d_R(ij) + 1} \\ x_{ij} &\le \frac{c_{ij}W}{(d_R(ij) + 1)(d_I(ij) + 1)} \end{aligned} \tag{7}$$
  3) **Mixed Constraints**: The rate vector $\mathbf{x}$ is feasible if for each flow $(i, j) \in \mathcal{F}$ the following MAC constraints hold.
  $$\begin{aligned} &x_{ij} \le \max\{\min(W - \delta(\Psi_R(ij), \mathrm{x}), c_{ij}W - \\ &c_{ij}\delta(\Psi_R(ij), \mathrm{x}) - \delta(\Psi_I(ij), \mathrm{x})), \min(\\ &\frac{W}{d_R(ij) + 1}, \frac{c_{ij}W}{(d_R(ij) + 1)(d_I(ij) + 1)})\} \end{aligned} \tag{8}$$

It is worth mentioning that (6), (7), and (8) are all sufficient conditions that ensure rate feasibility while accounting for the medium access contention; i.e., if $\mathbf{x}$ satisfies any of these, then $\mathbf{x}$ satisfies the medium access contention constraints. Recall that none of (6) and (7) implies the other. But (8) is superior to (6) and (7) (any vector $\mathbf{x}$ satisfying either (6) or (7) also satisfies (8); the opposite is not true). However, although (8) results in more relaxed constraints (using (8) would result in better objective values), these constraints are not linear. As we shall see in the next section, one can make them linear (and hence easy to solve) by writing the formulation problem as a mixed integer program (MILP). Unlike (8), the other two sets (i.e., the rate-based and degree-based constraints) are linear and hence their associated routing formulations can simply be written as linear programs

(LPs). These constraints are more conservative than the mixed-constraint set, yielding a routing solution quality (i.e., network lifetime) poorer than the solution quality that the mixed set yields. Therefore, there is a clear tradeoff between the complexity of the approach and the quality of the solution. In the next subsection, we formulate the routing problem using each of these sufficient conditions.

B. Routing Formulation and Implementation

The routing problem consists of determining the rate vector $\mathbf{x}$ that maximizes the network lifetime T subject to (1)–(5) and either (6), (7), or (8). Note that the constraints stated in (5) are not linear, and thus, as they are, the routing problem cannot be formulated as an LP. To formulate the routing problem as an LP, we introduce a new variable F, replace the variable T by $\frac{1}{F}$, rewrite constraints (5) as

$$F \geq \frac{1}{B_i(t_0)} \times \sum_{j \in \mathcal{N}} e_{ij} x_{ij}, \tag{9}$$

Since minimizing variable F is equivalent to maximizing variable T [21], the routing problem can be formulated as

Minimize F
Subject to:
FLOW BALANCE CONSTRAINTS:$(1)-(4)$
ENERGY CONSUMPTION CONSTRAINTS:(9)
MEDIUM CONTENTION CONSTRAINTS:
$(6), or(7), or(8).$

Note that the MAC constraints can be expressed through either (6), (7), or (8). The use of either (6) or (7) yields a LP (termed LPM-1 and LPM-2), whereas the use of (8) yields a MILP (termed IPM), and is done as follows: To formulate (8) as integer constraints, for each flow (i, j) in $\mathcal{F}$, we introduce a new binary variable y_{ij}, and rewrite (8) as

$$\begin{aligned} x_{ij} + c_{ij} \sum_{(p,q) \in \Psi_R(ij)} x_{pq} - & \\ c_{ij} W + \sum_{(p,q) \in \Psi_I(ij)} x_{pq} \leq & \quad (1 - y_{ij}) M_1 \end{aligned} \tag{10}$$

$$x_{ij} + \sum_{(p,q) \in \Psi_R(ij)} x_{pq} - W \leq \quad (1 - y_{ij}) M_1 \tag{11}$$

$$x_{ij} - \frac{W}{d_R(ij) + 1} \leq \quad y_{ij} M_2 \tag{12}$$

$$x_{ij} - \frac{c_{ij} W}{(d_R(ij) + 1)(d_I(ij) + 1)} \leq \quad y_{ij} M_2 \tag{13}$$

where M_1 and M_2 are two large numbers to relax the constraints (e.g., $M_1 = M_2 = |\mathcal{N}|^2 W$).

To summarize, the routing problem can be formulated as either LPM-1 (use of (6)), LPM-2 (use of (7)), or IPM (use of (10), (11), (12), and (13)). To implement the routing scheme, we assume that the AN is provided with unconstrained energy resources, hence it is liable for most of the intensive computational processing such as solving LPM-1, LPM-2 or IPM. The optimal rate solution $\mathbf{x}$ obtained by solving the routing problem is then sent to the sensor nodes. On receiving the flow rates from the AN, each SN forwards every packet to its immediate neighbor with certain probability and this forwarding process is iterated periodically after every T seconds. Nodes use the rate solution to forward packets for the next T seconds. At the end of each optimization horizon T, each node sends its battery level information and its neighbor list to the AN which uses to determine the optimal rates for the next horizon. Note that, for the initial computation, information is sent to AN using the flooding scheme. It is worth mentioning that our routing approach assures that if T is sufficiently large, the rates provided by the optimal solution are met on the average (by taking average rates over the horizon T) even though instantaneous rates may deviate considerably from the optimal rates. In the next section, we will solve these problems for many instances to evaluate the proposed routing formulations with regards to the following performance metrics: network lifetime, solution feasibility, and approach complexity.

VI. PERFORMANCE EVALUATION

We now evaluate, analyze and compare the performance of the proposed routing schemes (LPM-1, LPM-2, and IPM) described in Section V. The performance metrics that we consider evaluating are: network lifetime, solution feasibility, and execution time. In this evaluation, we use CPLEX and MATLAB as tools to solve the formulated routing optimization problems.

A. Simulation Setting and Method

We simulate random WSNs, each of which has a set of $|\mathcal{N}|$ nodes consisting of a single sink or access node AN, located at the center of a square area, and $|\mathcal{N}| - 1$ sensor nodes SNs uniformly distributed in the square area. Each SN is assumed to generate and send data traffic with a fixed rate requirement of R ($R = R_i \quad \forall i \in \mathcal{N}$) to the AN. Without loss of generality, we assume $W = 1$. All simulated WSNs are connected, and each pair of nodes can communicate through c available channels ($c_{ij} = c \ \ \forall (i, j)$). Each SN can communicate with the AN either directly or through a set of intermediate relay nodes. We consider the IEEE 802.11 MAC protocol [22] for our simulation; i.e., a node cannot send and receive simultaneously (radio contention) and if node i is in communication with node j, then all nodes within the same communication range of i or j cannot communicate on the same channel (MAC contention).

When the total network area is $\mathcal{A}$ and the transmission range is r, the maximum number of concurrent transmissions at any time on a single channel is roughly $\frac{\mathcal{A}}{\pi r^2}$. Therefore, the maximum bit-meter per second per channel the network can support is (roughly) $Wr(\frac{\mathcal{A}}{\pi r^2})$. On the other hand, the aggregate data rates generated from all the $|\mathcal{F}|$ flows, where each flow i using a path of length l_i meters generates a data rate of R bits per second is $R \sum_{i \in \mathcal{F}} l_i$. Taking both of these metrics into consideration, we can then define the normalized network load per channel as

$$\eta = \frac{R. \sum_{i \in \mathcal{F}} l_i}{W.r.(\frac{\mathcal{A}}{\pi r^2})} \tag{14}$$

Throughout, we use this normalized load metric η instead of the aggregated data rate of all the flows as a means of assessing the network traffic load.

B. Network Lifetime Analysis

In this section, we present and analyze the obtained network lifetime performance of the three routing approaches under various network parameters.

1) Impact of Node Degree: We first fix the network area and the transmission range, and vary the number of nodes. With this setting, an increment in the number of nodes leads to an increment in the node degree. Since the transmission range remains the same, the hop length does not change much (it almost remains the same) when the number of nodes is being increased. Hence, this allows the study of the effect of node degree while masking the impact of hop length and transmission range.

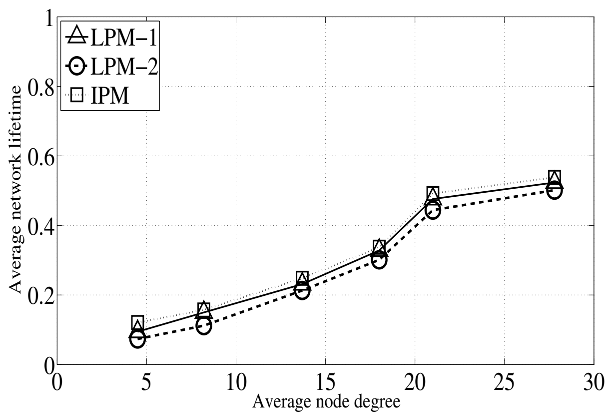


Fig. 3. Average network lifetime (hour) for $r = 30m$, $\mathcal{A} = 100 \times 100m^2$, $\eta = 0.3$, and $c = 3$.

Fig. 3 shows the network lifetime when varying the average node degree (by varying the number of nodes from 20 to 70) while fixing the transmission range, area size, number of channels, and network load per channel. First, note that regardless of the routing approach, as the number of nodes increases, the network lifetime increases. This happens because nodes in graphs with higher average node degrees are likely to have more neighbors, which offer them more path options to route their data to the sink. When the average node degree is low, nodes are likely to be forced to route through the same path, thus resulting in shorter lifetimes due to early node failures. Second, as expected, IPM always achieves better lifetime performance than LPM-1 and LPM-2. While IPM is expected to outperform LPM-1 and LPM-2 at all time in terms of lifetime, LPM-1 and LPM-2 are independent from each other. Simulations, however, show that LPM-1 achieves better network lifetime (though the difference is minimal) than LPM-2 when the number of nodes increases (at a moderate network load per channel). Now, note that as indicated via (7), LPM-2 conditions on a flow (i, j) depend on the node degree (which is reflected via $d_R(ij)$ and $d_I(ij)$), and not on the rates of other flows (i.e., x_{pq}). LPM-1 conditions on a flow (i, j), on the other hand, depend (as shown via (6)) on the other flows' rates, and not so much on the average node degree[1]. Therefore, increasing the average node degree tightens the constraints on the achievable rates under LPM-2 more than it does under LPM-1, which results in less routing choices, thereby decreasing the network lifetime. This explains why the network lifetime under LPM-2 is shorter than that achievable under LPM-1 when the number of nodes is large.

[1]To be exact, LPM-1 conditions also depend on the average node degree, but implicitly and loosely

2) Impact of Transmission Range: Here, we fix the network area and the number of nodes, and vary the transmission range. Usually, the higher the transmission range, the greater the interference, but also the higher the node degree. Typically, a higher interference results in less throughput, while a higher node degree yields more throughput. Unlike the previous case, however, the average hop length decreases when the transmission range increases. We consider and simulate the following transmission ranges: 30, 40, 50, 60, and 70m.

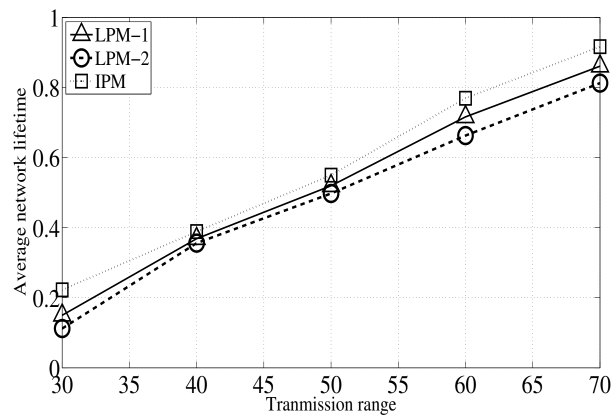


Fig. 4. Average network lifetime (hour) for $|\mathcal{N}| = 30$, $\mathcal{A} = 100 \times 100m^2$, and $c = 3$.

Fig. 4 shows the network lifetime when varying the transmission range while fixing the number of nodes, the number of channels, and the area size. First, note that regardless of the routing approach, as the transmission range increases, the network lifetime increases. Second, as expected, IPM always achieves better lifetime performance than LPM-1 and LPM-2, and the performance difference is more pronounced for higher numbers of nodes than smaller numbers. We also observe that LPM-1 achieves slightly longer lifetimes than LPM-2.

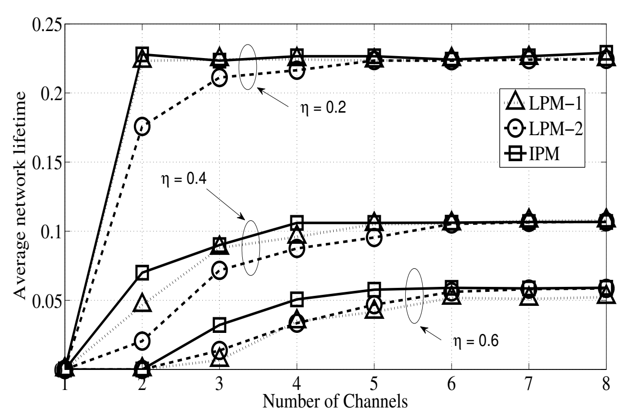


Fig. 5. Average network lifetime (hour) for $r = 30m$, $|\mathcal{N}| = 30$, and $\mathcal{A} = 100 \times 100\ m^2$.

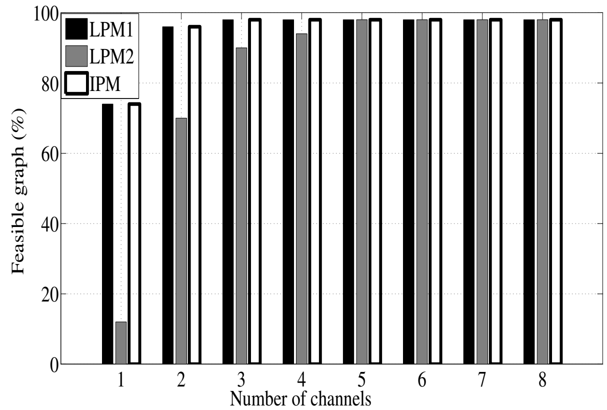
3) Impact of Number of Channels: In this section, we show the impact of the number of channels on the network lifetime performance. Results are shown in Fig. 5 for 3 different values of network loads: $\eta = 0.2, 0.4$, and 0.6. First, regardless of the network load η, as the number of channels increases, the average network lifetime achievable under any of the routing approaches also increases at first, but then flattens out. This happens because an increase in the number of channels provides nodes with more routing alternatives/options (i.e., greater solution space), thus resulting in a lifetime increase. But after reaching a certain number of channels, a further increase in the number of channels can no longer increase the solution space, which explains why the lifetime remains constant. Also, note that when the number of channels is high, all three approaches result in similar lifetimes, simply because the medium contention constraints are likely to be relaxed when the number of channels is high, and when this is the case, all three approaches become equivalent. Second, we also observe that IPM always exhibits better performance than LPM-1 and LPM-2, and the performance gain is more significant under medium to high network loads than under low loads. This is because when the network load is low, the medium contention constraints will not present a bottleneck, and hence, all approaches result in similar network lifetimes. Also, note that for lower normalized network loads, LPM-1 performs better than LPM-2, but as we increase the load, LPM-2 performs better than LPM-1. Although LPM-1 and LPM-2 are independent from each other, (6) and (7) imply that when the network load per channel is increased, the contention condition of LPM-1 (as it depends on the rate of the flows) becomes more strict than LPM-2, yielding shorter lifetimes.

Third and as expected, when the network load increases, the network lifetime decreases, and this is regardless of the routing approach being used.

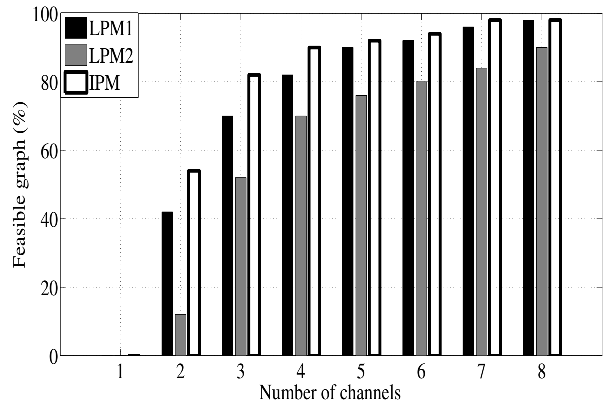
C. Feasibility Analysis

We further investigate the physical feasibility performance of the routing solutions obtained under each of the proposed approaches. Each bar of Fig. 6 corresponds to a combination of a routing scheme and a number of channels, and represents the percentage of feasible graphs out of all simulated graphs. For given network parameters, a simulated graph is considered feasible if there exists a solution to the corresponding routing approach; i.e., the obtained routing solution satisfies the MAC contention constraints as well as the other constraints. Figs. 6(a), 6(b) and 6(c) correspond to network loads η of respectively 0.2, 0.4, and 0.6.

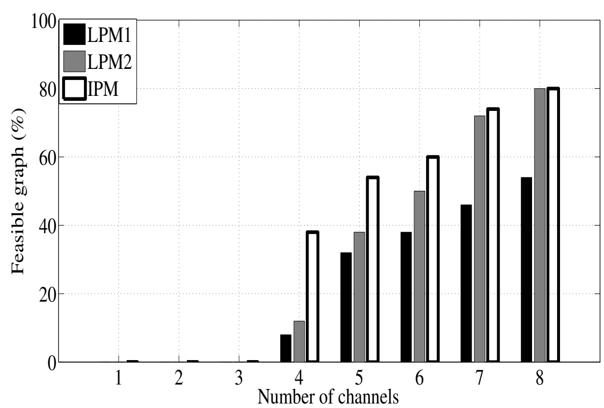
Note that for a given network load, the number of feasible solutions increases with the number of channels at first, but then flattens out (this is more pronounced in Fig. 6(a) when $\eta = 0.2$). When the number of channels increases (i.e., more channel resources become available), chances of finding routing solutions increase as well, thus increasing the number of feasible graphs. But when the number of channels exceeds a certain threshold, the chances of finding solutions no longer increase, because MAC contention constraints would have been relaxed, and feasibility will be determined by other constraints. Second, the figure also shows that IPM gives better feasibility solutions than the other two schemes, regardless of the network load. Similar behaviors of LPM-1 and LPM-2 to those observed in Section VI-B3 are also observed in this study: For light and medium loaded networks, LPM-1 performs better than LPM-2. But when the network is heavily loaded, LPM-1 results in lesser



(a) η = 0.2



(b) η = 0.4



(c) η = 0.6

Fig. 6. Feasible Graph (%) with values r = $30m$, $\mathcal{N}$ = 30 and $\mathcal{A}$ = $100 \times 100m^2$

numbers of feasible solutions than LPM-2. Explanation of this behavior is given in Section VI-B3.

D. Comparative Analysis

In this section, we compare our approaches with the existing ones to investigate the lifetime performance. In order to do that we consider the routing approaches proposed in [23] (here named as 'Maxlife Routing', computes the maximum lifetime without accounting for any MAC constraints, and hence provide an upper bound on the optimal solution) and in [24] (here referred to as

'NC', maximizes the lifetime while considering MAC constraints based on interference cliques). To draw an accurate comparison, we modified our simulation set-up with varying number of nodes from 30 to 70 (hence, varying the average node degree) randomly deployed in a $100 \times 100m^2$ region, and transmission range is set to $30m$. Each node uses a single channel to transmit and generates data at a fixed but lower than what was used before.

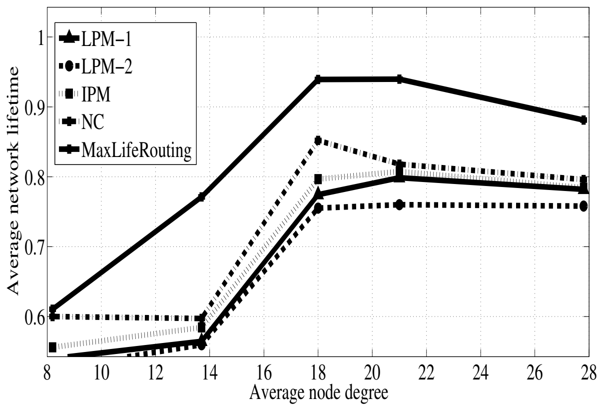


Fig. 7. Average network lifetime (hour) for $r = 30$, $\mathcal{A} = 100 \times 100m^2$, and $c = 1$.

Fig. 7 plots the average network lifetime for different schemes. Due to the changes in data rate and channel availability, it is noticable that regardless of the approaches, generally lifetime increases as average node degree increases at first (as more nodes provide more routing options) and saturates afterwards (as interferences of neighboring nodes become more pronounced).

When comparing to the 'Maxlife Routing' approach, we observe that even the IPM results in degraded lifetime by 32% and LPM-1 and LPM-2 by 37.8% at worst, the former provides no assurance that the routing solution is physically attainable (i.e., a valid flow schedule may not be found at the MAC layer to support the routing). Whereas our approaches guarantee the fact the obtained flows' rate are always achievable.

Conversely, as illustrated in Fig. 7, the proposed approaches perform almost as well as the 'NC' approach (as IPM approach has a degradation gap with only 6.9%, LPM-1 has 10% and LPM-2 has 12.82% in average lifetime at worst). Although 'NC' takes account of MAC constraints, our approaches are better and acceptable in the sense that relying on a necessary condition, the 'NC' routing approach doesn't imply the feasibility of the resulting flows.

E. Complexity Analysis

We now study the tradeoffs between the solution quality (i.e., network lifetime) and the complexity (i.e., execution time). Since both theoretical and simulation results show that IPM always outperforms LPM-1 and LPM-2 in terms of network lifetime (solution quality) but at the expense of some added complexity due to the integer programming formulation, it is worth investigating the tradeoffs between the added complexity and the improved solution quality.

For this, we collect the obtained network lifetime (in sec) and the execution time (i.e., CPLEX runtime also in sec) for different numbers of nodes when the transmission range is set to $30m$, the network area is set to $100 \times 100m^2$, the network load is set to 0.3, and the number of channels is set to 3. To study complexity-quality tradeoffs and see whether IPM is worthwhile, we compute and compare the *reduced complexity* (decrease in execution time) due to the constraint linearity of LPM-1 (respectively of LPM-2) with the *degraded performance* (decrease in lifetime) of LPM-1 (respectively of LPM-2) due to the tightness of these linear constraints. Both *reduced complexity* and *degraded performance* are evaluated with respect to IPM, and are presented in Table II for various numbers of nodes. As expected, both LPM-1 and LPM-2 achieve solution quality (network lifetime) lower than that achieved under IPM, but are less complex than IPM.

Observe that when the number of nodes is small, the performance degrades much less under LPM-1 than under LPM-2. For example, when the number of nodes is 30, the performance under LPM-2 is degraded by about 29%, but the complexity is reduced by about 50%. LPM-1, on the other hand, degrades the performance by only 5%, but still reduces the complexity by about 20%. Note also that LPM-1's degraded performance is relatively small; i.e., LPM-1 achieves performance that is closer to that achievable under IPM, yet it reduces execution time substantially. We conclude that for small numbers of nodes, when combining complexity and quality together, LPM-1 is recommended over both IPM and LPM-2, as it provides a solution quality that is almost as good as that IPM provides while reducing complexity significantly.

Now observe that as the number of nodes increases, the performance degradation gap reduces; i.e., LPM-1 and LPM-2 tend to achieve similar performances to IPM, yet the reduced complexity under LPM-2 is more substantial than under LPM-1. Hence, when the number of nodes in the network is large, the little improvement of IPM's performance due to the looseness of its constraints does not then payoff its increased complexity due to the non-linearity of the constraints. Here, the best candidate among all three approaches is LPM-2, which yields a network lifetime that is almost as long as that provided by IPM while reducing the execution time substantially.

VII. Conclusion

We derived three sufficient conditions for rate-feasibility in multichannel WSNs. Using the three derived sets of conditions, we propose three routing techniques, LPM-1, LPM-2, and IPM, whose objective is to maximize the network lifetime while ensuring the feasibility of the obtained routing solutions. Results show that IPM always achieves better network lifetime than both LPM-1 and LPM-2, but at the cost of longer execution times. We conclude that when combining both execution times and network lifetimes, LPM-1 (respectively LPM-2) is the best routing approach among the three studied schemes when the number of nodes is small (respectively large).

Appendix

We now provide the proof of our *mixed conditions* proposed in Proposition 3.

Proof: Let $\mathcal{N}$ denote $|\mathcal{F}|$ and $\mathrm{x} = (x_f)_{f \in \mathcal{F}}$ be a flow vector that satisfies the conditions stated by the proposition. Similar to the previous proof, we arrange the flows in $\mathcal{F}$ as

TABLE II
COMPLEXITY VS. PERFORMANCE.

Number of nodes	20		30		40		50		60		70	
	LPM-1	LPM-2	LPM-1	LPM-2	LPM-1	LPM-2	LPM-1	LPM-2	LPM-1	LPM-2	LPM-1	LPM-2
Degraded performance (%)	21.76	39.13	4.57	28.65	6.78	14.18	3.00	10.79	2.98	9.70	2.73	6.81
Reduced Complexity(%)	10	50	21.6	52	24.6	77.49	35.10	79.34	52.46	86.6	53.17	87.13

$\{1, 2, \ldots, \mathcal{N}\}$ such that $x_p \leq x_q$ for all $1 \leq p \leq q \leq \mathcal{N}$, let $\mathcal{F}^i$ denote the set of flows $\{1, 2, \ldots, i\}$, and let $\mathcal{S} = [0, \tau]$ be a time schedule of length $\tau > 0$ seconds. We show by induction that for all $n = \{1, 2, \ldots, \mathcal{N}\}$ the flows in the subset $\mathcal{F}^n \subseteq \mathcal{F}$ are schedulable in $\mathcal{S}$.

BASIS: $\mathcal{F}^1 = \{1\}$. When the conditions stated by the proposition are satisfied for x_1, it can easily be verified that $x_1 \leq W$ and consequently $\mathcal{F}^1$ is schedulable in $\mathcal{S}$.

INDUCTION STEP: Let us now assume that all the flows in $\mathcal{F}^{n-1}$ are schedulable in $\mathcal{S}$ for any n, $1 \leq n \leq \mathcal{N}$, and let us show that flows in $\mathcal{F}^n$ are also schedulable in $\mathcal{S}$. Since $\mathcal{F}^n = \mathcal{F}^{n-1} \cup \{n\}$, then it suffices to prove that flow n can be scheduled, provided that all flows in $\mathcal{F}^{n-1}$ are already scheduled. Let $\Phi_R(n)$ be the set of flows in $\mathcal{F}^{n-1}$ that radio contend with n, i.e., $\Phi_R(n) = \mathcal{F}^{n-1} \bigcap \Psi_R(n)$. There are two cases to consider: Case (i): Suppose $\min\{\frac{W}{d_R(n)+1}, \frac{c(n)W}{(d_R(n)+1)(d_I(n)+1)}\} \leq \min\{W - \delta(\Psi_R(n), \mathrm{x}), c(n)W - c(n)\delta(\Psi_R(n), \mathrm{x}) - \delta(\Psi_I(n), \mathrm{x})\}$. Now because $x_n \leq \min\{W - \delta(\Psi_R(n), \mathrm{x}), c(n)W - c(n)\delta(\Psi_R(n), \mathrm{x}) - \delta(\Psi_I(n), \mathrm{x})\}$, then, from Proposition 1, it follows that flow n is schedulable. Case (ii): Suppose $\min\{\frac{W}{d_R(n)+1}, \frac{c(n)W}{(d_R(n)+1)(d_I(n)+1)}\} \geq \min\{W - \delta(\Psi_R(n), \mathrm{x}), c(n)W - c(n)\delta(\Psi_R(n), \mathrm{x}) - \delta(\Psi_I(n), \mathrm{x})\}$. Now because our conditions state that $x_n \leq \min\{\frac{W}{d_R(n)+1}, \frac{c(n)W}{(d_R(n)+1)(d_I(n)+1)}\}$, proving that flow n is schedulable follows from Proposition 2. ■

REFERENCES

[1] R. Madan, S. Cui, S. Lall, and A. Goldsmith, "Cross-Layer Design for Lifetime Maximization in Interference-Limited Wireless Sensor Networks," *IEEE Trans. on Wireless Communications*, vol. 5, no. 11, pp. 3142–3152, November 2006.

[2] H. Kwon, T. Kim, S. Choi, and B. G. Lee, "Lifetime maximization under reliability constraint via cross-layer strategy in wireless sensor networks," in *Proceedings of IEEE Wireless Communications and Networking Conference*, 2005.

[3] S. J. K. Seung-Jun, X. W. Xiaodong, and M. Madihian, "Distributed Joint Routing and Medium Access Control for Lifetime Maximization of Wireless Sensor Networks," *IEEE Trans. on wireless communications*, vol. 7, no. 6, July 2007.

[4] B. Hamdaoui and P. Ramanathan, *Energy-efficient and MAC-aware routing for data aggregation in sensor networks*. Sensor Network Operations, Wiley-IEEE Press, March 2006, March 2006.

[5] B. DeCleen, V. Firoiu, M. Dorsch, and S. Zabele, "Cross-Layer Protocols for Energy-Efficient Wireless Sensor Networking," in *Proceedings of IEEE MILCOM*, October 2005.

[6] A. J. Goldsmith, *Wireless Communications*. Cambridge University Press, 2005.

[7] J. Gomez, A. Campbell, M. Naghshineh, and C. Bisdikian, "Conserving Transmission Power in Wireless Ad Hoc Networks," in *Proceedings of 9th International Conference on Network Protocols (ICNP)*, 2001.

[8] J. Chang and L. Tassiulas, "Energy Conserving Routing in Wireless Ad-hoc Networks," in *Proceedings of IEEE INFOCOM*, 2000.

[9] A. Sankar and Z. Liu, "Maximum lifetime routing in wireless ad hoc networks," in *Proceedings of IEEE INFOCOM*, March 2004.

[10] M. Cheng, X. Gong, and L. Cai, "Joint Routing and Link Rate Allocation under Bandwidth and Energy Constraints in Sensor Networks," *IEEE/ACM Transactions on Wireless Comminication*, vol. 8, July 2009.

[11] M. Cheng, X.Gong, L. Cai, and X. Jia, "Cross-Layer Throughput Optimization With Power Control in Sensor Networks," *IEEE Transactions on Vehicular Technology*, vol. 60, no. 7, September 2011.

[12] M. Krunz, A. Muqattash, and S.-J. Lee, "Transmission power control in wireless ad hoc networks: challenges, solutions and open issues," *IEEE Network*, vol. 18, September- October 2004.

[13] X. Wang and T. Berger, "Spatial channel reuse in wireless sensor networks," *Wireless Networking*, vol. 14, no. 2, 2008.

[14] Y. Wu, J. Stankovic, and T. He, "Realistic and Efficient Multi-Channel Communications in Dense Wireless Sensor Networks," in *Proceedings of IEEE INFOCOM*, 2008.

[15] J. M. III and G. Maguire, "Cognitive radio: making software radios more personal," *IEEE Personal Communications*, August 1999.

[16] M. Kodialam and T. Nandagopal, "Characterizing Achievable Rates in Multi-Hop Wireless Mesh Networks With Orthogonal Channels," *IEEE/ACM Trans. on Networking*, vol. 13, no. 4, 2005.

[17] L. Li, B. Qin, and C. Zhang, "Interference-Aware Broadcast Routing and Channel Assignment in Multi-Radio Wireless Mesh Networks," in *Proceedings of IEEE 70th Vehicular Technology Conference (VTC 2009-Fall)*, 2009.

[18] S. Ramanathan, "A unified framework and algorithm for channel assignment in wireless networks," *Wireless Networks*, vol. 5, no. 2, p. 8194, March 1999.

[19] P. Djukic and S. Valaee, "Delay aware link scheduling for multi-hop TDMA wireless networks," *IEEE/ACM Transactions on Networking*, vol. 17, June.

[20] S. Ehsan, B. Hamdaoui, and M. Guizani, "Feasibility conditions for rate-constrained routing in power-limited multichannel WSNs," in *Proceedings of GLOBECOM*, December 2011.

[21] R. J. Vanderbei, *Linear prgramming: foundations and extensions*. Kluwer academic publishers, 1997.

[22] "Wireless LAN medium access control (MAC) and physical layer (PHY) specification: High speed physical layer in the 5 GHz band," *IEEE 802.11a*, 1999.

[23] R. Madan and S. Lall, "Distributed algorithms for maximum lifetime routing in wireless sensor network," in *IEEE Trans. on Wireless Communications*, vol. 5, August 2006, pp. 2185–2193.

[24] S.-J. Kim, X. Wang, and M. Madihian, "Joint Routing and Medium Access Control for Lifetime Maximization of Distributed Wireless Sensor Networks," in *Proceedings of IEEE International Conference on Communications*, June 2006.

PLACE
PHOTO
HERE

Samina Ehsan received the BS and MS degrees in Computer Science and Engineering from University of Dhaka, Bangladesh, in 2005 and 2007, respectively. She has received PhD degree in Computer Science at Oregon State University in June 2012. Her research interest includes energy efficient and rate-constrained routing, QoS, and performance modeling and analysis of wireless communication networks.

PLACE PHOTO HERE

Bechir Hamdaoui received the Diploma of Graduate Engineer (1997) from the National School of Engineers at Tunis, Tunisia. He also received M.S. degrees in both Electrical and Computer Engineering (2002) and Computer Sciences (2004), and the Ph.D. degree in Computer Engineering (2005) all from the University of Wisconsin at Madison. In September of 2005, he joined the RTCL Lab at the University of Michigan at Ann Arbor as a postdoctoral researcher. Since September of 2007, he has been with the School of EECS at Oregon State University as an assistant professor. His research focus is on cross-layer protocol design, system performance modeling and analysis, adaptive and learning technique development, and resource and service management for next-generation wireless networks and communications systems. He has won the NSF CAREER Award (2009), and is presently an Associate Editor for IEEE Transactions on Vehicular Technology (2009-present) and Wireless Communications and Computing Journal (2009-present). He also served as an Associate Editor for Journal of Computer Systems, Networks, and Communications (2007-2009). He served as the chair for the 2011 ACM MobiCom's Student Research Competition, and as the program chair/co-chair of the Pervasive Wireless Networking Workshop (PERCOM 2009), the WiMAX/WiBro Services and QoS Management Symposium (IWCMC 2009), the Broadband Wireless Access Symposium (IWCMC 2010), the Cooperative and Cognitive Networks Workshop (IWCMC 2011 and 2012), and the Internet of Things, Machine to Machine, and Smart Services Applications Workshop (CTS 2012). He also served on program committees of several IEEE conferences. He is a member of IEEE, IEEE Computer Society, IEEE Vehicular Society, and IEEE Communications Society.

PLACE PHOTO HERE

Mohsen Guizani S'85-M'89-SM'99-F'09) is currently a Professor and the Associate Vice President for Graduate Studies at Qatar University, Doha, Qatar. He was the Chair of the Computer Science Department at Western Michigan University from 2002 to 2006 and Chair of the Computer Science Department at University of West Florida from 1999 to 2002. He also served in academic positions at the University of Missouri-Kansas City, University of Colorado-Boulder, Syracuse University and Kuwait University. He received his B.S. (with distinction) and M.S. degrees in Electrical Engineering; M.S. and Ph.D. degrees in Computer Engineering in 1984, 1986, 1987, and 1990, respectively, from Syracuse University, Syracuse, New York. His research interests include Computer Networks, Wireless Communications and Mobile Computing, and Optical Networking. He currently serves on the editorial boards of six technical Journals and the Founder and EIC of "Wireless Communications and Mobile Computing" Journal published by John Wiley (http://www.interscience.wiley.com/jpages/1530-8669/). He is the author of seven books and more than 270 publications in refereed journals and conferences. He guest edited a number of special issues in IEEE Journals and Magazines. He also served as member, Chair, and General Chair of a number of conferences. Dr. Guizani served as the Chair of IEEE Communications Society Wireless Technical Committee (WTC) and Chair of TAOS Technical Committee. He was an IEEE Computer Society Distinguished Lecturer from 2003 to 2005. Dr. Guizani is an IEEE Fellow and a Senior member of ACM.