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ORIGINAL PAPER

Topology design for on-demand dual-path routing in wireless networks

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Abstract One way to achieve reliability with low-latency is through multi-path routing and transport protocols that build redundant delivery channels (or data paths) to reduce end-to-end packet losses and retransmissions. However, the applicability and effectiveness of such protocols are limited by the topological constraints of the underlying communication infrastructure. Multiple data delivery paths can only be constructed over networks that are capable of supporting multiple paths. In mission-critical wireless networks, the underlying network topology is directly affected by the terrain, location and environmental interferences, however the settings of the wireless radios at each node can be properly configured to compensate for these effects for multi-path support. In this work we investigate optimization models for topology designs that enable end-to-end dual-path support on a distributed wireless sensor

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network. We consider the case of a fixed sensor network with isotropic antennas, where the control variable for topology management is the transmission power on network nodes. For optimization modeling, the network metrics of relevance are coverage, robustness and power utilization. The optimization models proposed in this work eliminate some of the typical assumptions made in the pertinent network design literature that are too strong in this application context.

Keywords Network design · Topology control · Wireless sensor networks · Multi-path transport and multi-path routing

1 Introduction

Wireless sensor networks (WSN) are key technology enablers for various systems and critical operational settings including environmental monitoring, military operations support, disaster relief, and industrial plant monitoring [3]. WSNs are often configured as mesh wireless networks, where individual sensor nodes interact only with their immediate peers (i.e. other nodes within radio range) and rely on multi-hop communications for end-to-end information sharing and coordination. As illustrated in Fig. 1, information collected by individual sensors is generally propagated through the network to a gateway node, which is responsible for bridging the WSN with a remote monitoring and control infrastructure.

The multi-hop path illustrated in Fig. 1 describes how sensor data is relayed to the gateway node. The path is dynamically constructed and maintained by distributed routing algorithms running on every node. The goal of the routing algorithm is to allow each node to determine the best next-hop (i.e the best neighbor) to deliver a data packet, given final destination. In Fig. 1 a sequence or data packets (e.g. images) is generated by the sensor, and each packet is forwarded through the nodes in the highlighted path, to the gateway node.

Routing algorithms are designed to adapt to the underlying connectivity between nodes. While there have been multiple proposals, analysis and optimization studies in ad hoc routing [18,21,24], most common algorithms rely on localized link sensing

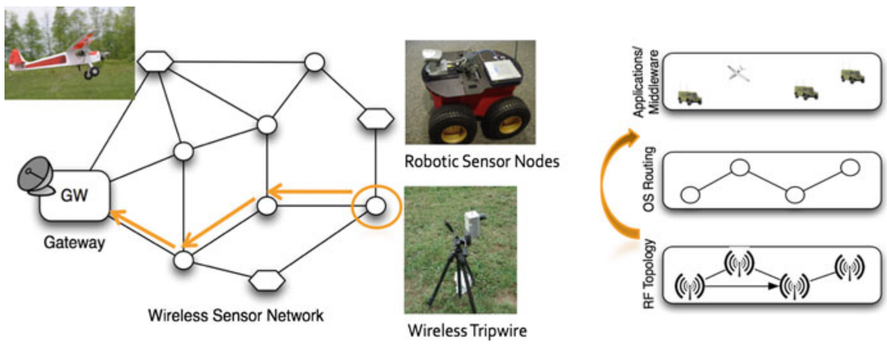

Fig. 1 Conceptual view of a wireless sensor network and an example of information flow

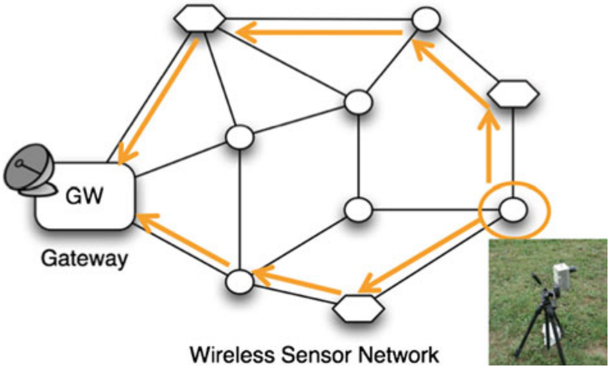

Fig. 2 Multi-path routing in wireless sensor networks

to estimate the topology and identify optimum multi-path routes for different destinations. Ad hoc protocols in particular are designed to provide that function without dependencies on fixed or centralized infrastructures, they often rely on peer-to-peer state sharing and coordination. The multi-hop path can be established with different criteria such as minimum distance (a performance metric), minimum power consumption, or geographical constraints. Based on specific goals and requirements, the algorithms weigh link information to calculate the path accordingly.

Another criterion of importance in sensor networks is their reliability. For example, in monitoring infrastructures where the loss of a critical event (such as an intruder, or a failure in a protection perimeter) can have very damaging consequences, the sensor network must provide guarantees for event delivery. For such applications, end-to-end delivery guarantees are typically provided by reliable transport protocols (operating above the routing layer). Reliable transport (such as reliable UDP [11,19,23], TCP [20] and others), generally rely on end-to-end packet acknowledgment and retransmission for reliability, which comes at a cost in induced latency and retransmission overhead. More recently, however, reliable routing protocols are being considered in order to help provide higher levels of reliability, without the implicit latencies induced by end-to-end reliable transport protocols.

Routing reliability is often implemented through constrained multi-path routing algorithms, which attempt to build simultaneous and non self-interfering data paths carrying duplicates of each data packet (see Fig. 2). Eventual losses on either path are likely to be compensated by the arrival of duplicates, trading off capacity with reliability. A major challenge, however, in multi-path routing is that global optimality under any performance metric is difficult to achieve via localized algorithms. Furthermore, individual nodes must not only make their routing decision, but they must also coordinate with remote nodes that are routing duplicate packets to ensure separation and non-interference.

While some ad hoc distributed algorithms have been proposed [9,25] for multi-path support, they are largely just reactive to changes in the physical layer, and generally limited to the physical constraints of the radio frequency (RF) topology. As previously reported in [17], the dynamics of the underlying physical topology can compromise the convergence and stability of ad hoc routing protocols. In order to mitigate such effects, cross-layer strategies for network management have recently been proposed [2,6,7,10].

1.1 Topology control in wireless sensor networks

Topology control introduces the notion of driving the lower-level RF topology, for instance through explicit node position or differentiated power control, to improve the behavior of high-level protocols and application performance. For example, topology control can be used to create optimized sensor networks for minimal power usage (to increase lifespan), minimum latency, or robust operations. Aside from environmental and interference effects, the topology of wireless networks with fixed nodes is defined by the combined allocation of transmission power and signal frequency/coding. In this work, we consider the simplified case where the only control variable for topology management is the transmission power on each node, which constrains the problem of topology control in WSNs to finding a transmission power allocation $P = \{p_1, p_2, \ldots, p_n\}$ for all nodes in the network such that it globally minimizes (or maximizes) some performance metric, while maintaining pre-defined topological properties in the designed network. The performance metric may be context dependent and could include the minimization of overall power utilization for transmitters, interference reduction, throughput maximization, etc. In this paper, we will consider the cases where the dual-paths between a designated transmitter and receiver are arc-disjoint as well as internally node-disjoint in the designed network. Each condition can be associated with a different operational context and can be dynamically enabled in the networks at run-time.

The physical wireless network topology is represented by a simple directed network $G = (V, E)$ where V represents the nodes, and $E \subseteq V \times V$ represents a set of directed arcs e_{ij}. A directed arc e_{ij} from node $i \in V$ to node $j \in V$ implies that, under no interference conditions, the tail node i (transmitter) can successfully transmit data to the head node j (receiver). The actual transmission pattern around the transmitter is a function of its antenna, the transmission power, and other environmental effects. For example, for an idealized isotropic antenna, the signal propagation from the transmitter decays equally in all directions. In practice, however, the transmission pattern of antennas is not uniform and may vary significantly. However, for the purposes of this work we will consider omnidirectional transmitters, with ideal and isotropic antennas.

In the types of networks under consideration, for a given uniform power setting (i.e., $p_1 = p_2 = p_3 \ldots = p_n$), the RF topology is solely defined by the relative position between nodes as illustrated in Fig. 3. This approximate model is widely used in mobile ad hoc network (MANET) applications, where the topology is primarily affected by the relative mobility of nodes [3]. Conversely in WSNs, nodes tend to be fixed and topology is primarily managed through changes in power or frequency allocation. A uniform change in transmission power for all nodes will increase (or decrease) the density of the network. Higher power levels will increase the average degree of the nodes and interference, while reduced power levels will reduce the average degree and possibly the interference, but will likely increase the path lengths in the network

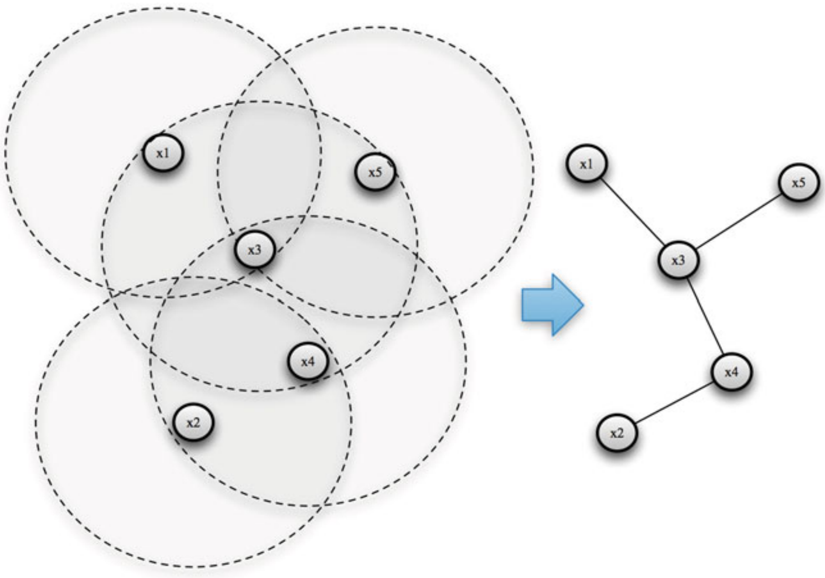

Fig. 3 Symmetric network topology

and possibly cause network segmentation. Uniform power control is generally not very effective as it treats different parts of the network (dense or sparse areas) with a common strategy.

A more flexible approach to the problem is the use of differentiated power settings for each node. In this case, each node may be assigned a different transmission power, and different areas of the network can be separately and more effectively managed. Geographically dense areas of the network may use less power for data transmission than sparse regions, reducing power requirements and self-induced interference.

However, differential allocation of power between transmitters may lead to asymmetric data links, as illustrated in Fig. 4. While asymmetric data networks are theoretically possible, in practice they are not compatible with most common communication protocols. Layer two protocols, for instance, rely on frame acknowledgments at the link level for coordination, and most common routing protocols ignore asymmetric links to mitigate complexity and timing issues to transport protocols.

So, directed arcs in the network are often ignored by higher level protocols, but still play a very important role in the topological properties and interference metrics for the network. For the purposes of this work, we will consider the power allocation strategies that result in asymmetric data links modeled by directed arcs in the network. It is important to highlight that bi-directional links at the RF-level do not necessarily imply the same differentiated power allocation.

In this paper we propose new global topology design models to support on-demand dual-path routing in WSNs. We employ power consumption as our performance metric and design the topology to contain at least two arc-disjoint or internally node-disjoint paths from the designated transmitter to the designated receiver. Such designs could

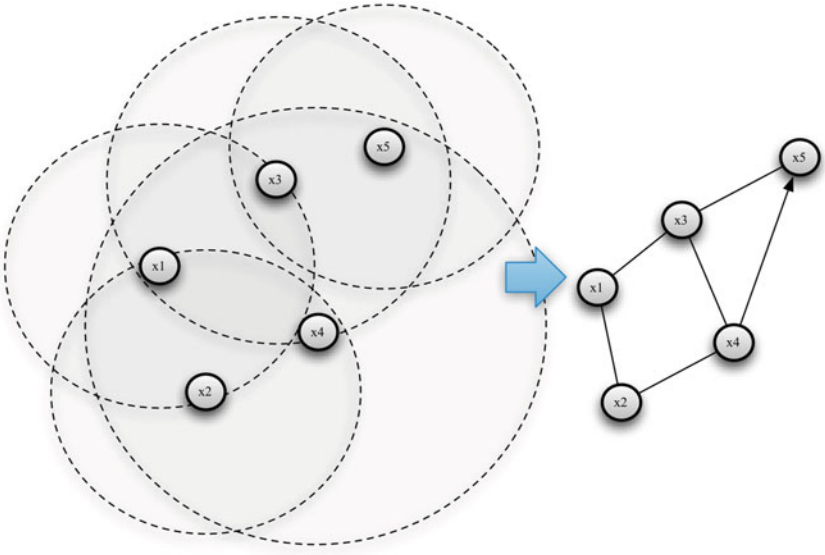

Fig. 4 Asymmetric network topology

be implemented on-demand where a centralized algorithm monitors the topology (for example through a link state routing algorithm) and computes optimal, separate paths for data transmission from a given source and to a given destination. It should be noted that we use a quadratic objective in the optimization models since power consumption can be assumed to increase as a quadratic function of the transmission radius required, which is more realistic than assuming linearity. The proposed models also capture dependence in communication link creation in our models. That is, as power setting is increased at a transmitter, links are established to all receivers in the transmission radius. While these choices complicate model development and solution, they remove some typical but unrealistic assumptions made in such applications. In Sect. 2, we introduce the different mixed integer nonlinear optimization formulations studied. Sect. 3 presents the results of our preliminary numerical experiments in solving the problems using a commercial solver. Finally, we conclude by identifying some directions for future research in Sect. 4.

2 Optimization models

The *on-demand dual-path network design* (ODDPND) problem can be stated as follows. Given a set of wireless nodes denoted by $V = \{1, \ldots, n\}$, located in the Euclidean plane, determine the transmission radius of each node $i \in V$ that minimizes total energy consumption (assumed to be additive and proportional to the square of the transmission radius), and ensures that the resulting topology satisfies the following conditions:

1. There is a directed communication link from i to j *if and only if* the transmission radius of i is at least d_{ij}, the Euclidean distance between nodes i and j;

2. For a distinguished pair of nodes $s, t \in V$, where s is the origin and t is the destination, there exist at least 2 arc- or internally node-disjoint directed paths from s to t;
3. For every distinct pair of nodes $i, j \in V$, there exists a directed path from i to j.

The ODDPND problem is very similar to the survivable network design (SND) problems with prescribed node connectivity [8,16,22], or prescribed arc-connectivity (see [14] and references therein), as well as network augmentation (by arc addition) problems to produce a network with desired arc [4] or node connectivity [13]. The ODDPND problem differs from SND because of the assumptions we relax in this particular application setting. Consequently, the key distinctions are the use of a quadratic objective and the dependence in arc creation (as prescribed by the Condition 1). By contrast, SND problems employ a linear objective and the arcs are assumed to be independent of each other and any subset of arcs can be created/added. Despite these differences, the basic formulation ideas developed for SND can be adapted as we demonstrate in the following sections. The assumptions relaxed clearly result in more complicated models, but are considered a worthwhile trade-off given that the solutions obtained are more realistic with regards to power consumption and link interference.

2.1 Arc-disjoint ODDPND formulation

The transmission radius of node $i \in V$ is denoted by the decision variable y_i. Parameter M_i is either the maximum transmission radius that node $i \in V$ can support, or $\max_{j \in V} d_{ij}$, whichever is smaller. Constraint (8) enforces this bound on y_i. If the binary variable $x_{ij} = 1$, constraint (6) ensures that $y_i \geq d_{ij}$ and it is redundant otherwise. Constraint (7) enforces that $y_i \leq d_{ij}$ if $x_{ij} = 0$. Together they capture the dependence in link creation as the node power is increased.

We need to ensure that the whole network is strongly connected and from node s to node t, there are 2 arc-disjoint paths. This is accomplished via flow balance constraints similar to a multi-commodity network flow problem [1]. Node $k \in V$ will have a supply of $n-1$ units of "commodity $k \in V$" whereas all other nodes will have a demand of one unit for commodity k. By imposing these constraints we ensure that there is a directed path from every node to every other node in the network. In constraints (2), for $k \in V$, $b^k(i) = n-1$ if $i = k$, and $b^k(i) = -1$ for $i \in V \setminus \{k\}$. The requirement that there should be at least two paths between nodes s and t is imposed by constraints (3), where $b^{n+1}(s) = 2$, $b^{n+1}(t) = -2$, and $b^{n+1}(i) = 0$ for $i \in V \setminus \{s, t\}$. Constraints (4) and (5) ensure that flows can only go though arcs created in the network.

$$\text{Minimize} \sum_{i \in V} c_i y_i^2 \tag{1}$$

subject to:

$$\sum_{j \in V \setminus \{i\}} f_{ij}^k - \sum_{j \in V \setminus \{i\}} f_{ji}^k = b^k(i), \ \forall\, i \in V, \ k \in V \tag{2}$$

$$\sum_{j \in V \setminus \{i\}} f_{ij}^{n+1} - \sum_{j \in V \setminus \{i\}} f_{ji}^{n+1} = b^{n+1}(i), \ \forall\, i \in V \tag{3}$$

$$f_{ij}^k \leq (n-1)x_{ij},\ \forall\, i, j \in V : i \neq j,\ k \in V \tag{4}$$

$$f_{ij}^{n+1} \leq x_{ij},\ \forall\, i, j \in V : i \neq j \tag{5}$$

$$d_{ij}x_{ij} \leq y_i,\ \forall\, i, j \in V : i \neq j \tag{6}$$

$$M_i x_{ij} \geq y_i - d_{ij},\ \forall\, i, j \in V : i \neq j \tag{7}$$

$$0 \leq y_i \leq M_i,\ \forall\, i \in V \tag{8}$$

$$f_{ij}^k \geq 0\ \forall\, i, j \in V : i \neq j, k \in V \cup \{n+1\} \tag{9}$$

$$x_{ij} \in \{0, 1\}\ \forall\, i, j \in V : i \neq j \tag{10}$$

2.2 Node-disjoint ODDPND formulation

Formulation (1)–(10) can be modified to ensure two internally node-disjoint directed paths from node s to node t. For that purpose the incoming flow for commodity $n+1$ must be limited to one unit at each node in the network. This can be done by adding the following constraints to Formulation (1)–(10)

$$\sum_{j \in V \setminus \{i\}} f_{ji}^{n+1} \leq 1,\ \forall\, i \in V \setminus \{s, t\} \tag{11}$$

Constraint (11) ensures that every node except the origin and the destination may have no more than one unit of flow of commodity $n+1$ incoming. That is, there is only one path from s to t traversed by commodity $n+1$ coming through any particular node.

2.3 Cut covering formulation

The so called *cut covering formulation* [5] uses an implication of the theorems of Menger [15] and Ford-Fulkerson [12], that for distinct vertices $s, t \in V$ in a directed network $G = (V, E)$, the minimum size of an s, t-cut equals the maximum number of pairwise arc-disjoint s, t-dipaths. We develop a cut covering formulation only for the arc-disjoint case of the ODDPND problem as it requires an exponential number of constraints. Note that this formulation is best solved with a specialized row-generation/cutting-plane approach where violated constraints are detected and added during the course of the solution process and not in advance. As our intention in this preliminary paper is to solve the formulation using basic algorithms available in a commercial solver, we do not consider the internally node-disjoint case of the ODDPND problem. We limit ourselves exploring such a formulation for just one of the two cases for the sake of comparison.

$$\text{Minimize} \sum_{i \in V} c_i y_i^2 \tag{12}$$

subject to:

$$\sum_{i \in S, j \in V \setminus S} x_{ij} \geq \begin{cases} 2 & \text{if } s \in S, t \in V \setminus S, \quad \forall \emptyset \neq S \subset V \\ 1 & \text{otherwise} \end{cases} \tag{13}$$

$$d_{ij} x_{ij} \leq y_i, \ \forall i, j \in V : i \neq j \tag{14}$$

$$M_i x_{ij} \geq y_i - d_{ij}, \ \forall i, j \in V : i \neq j \tag{15}$$

$$0 \leq y_i \leq M_i, \ \forall i \in V \tag{16}$$

$$x_{ij} \in \{0, 1\} \ \forall i, j \in V : i \neq j \tag{17}$$

3 Computational experiments

This section summarizes computational experiments for cut covering arc-disjoint (CCAD), multi-commodity arc-disjoint (MCAD) and multi-commodity node-disjoint (MCND) problem formulations presented. The formulations were implemented in C++ and solved by CPLEX® 12.1 on a computer with Intel® Core i7 2.8GHz processor and 2GB of RAM available for computations. Although the processor had 4 cores, we limited the number of threads CPLEX can use up to 1 for comparison purposes. For every problem instance we used a 2-dimensional plane with coordinates from 0 to 100 for both of the axes. The coordinates of the nodes were generated randomly and the first node was assigned to be s-node, whereas the last node was t-node. The cost coefficients c_i in the objective function were the same for all the nodes from the assumption that all the sensors in the network were identical. Parameter M_i, which corresponds to maximum transmission radius was also the same for all the nodes and equal to 35. Computational time presented is in seconds and relative gap is a percentage. Every group consists of 30 randomly generated problem instances. Table 1 presents average computational times as well as minimum computational time, standard deviation (SD) and maximum time for each group of instances.

One of the potential problems with the proposed approach of centralized topology control arises from the fact that after a sensor sends a request for a topology change it has to wait until an optimal solution is computed and transmitted back to sensors

Table 1 Running time (s) for solving to optimality

n	CCAD Average (Min, SD, Max)	MCAD Average (Min, SD, Max)	MCND Average (Min, SD, Max)
10	0.1	0.3	0.3
	(0.1, 0.1, 0.3)	(0.1, 0.2, 0.9)	(0.1, 0.2, 0.9)
15	4.1	2.7	2.9
	(0.4, 7.1, 32.8)	(0.3, 2.8, 13.9)	(0.4, 3.7, 20.0)
20	–	85.6	62.4
	(–)	(3.7, 133.6, 635.1)	(3.4, 85.3, 371.6)
25	–	2035.3	2152.9
	(–)	(116.0, 2242.3, 9570.0)	(127.7, 2400.5, 11231.0)

Table 2 Average time to the first feasible solution and relative gap to the optimal value

n	Relative gap RG (%)			CPU time (s)		
	CCAD Average (Min, SD, Max)	MCAD Average (Min, SD, Max)	MCND Average (Min, SD, Max)	CCAD Average (Min, SD, Max)	MCAD Average (Min, SD, Max)	MCND Average (Min, SD, Max)
10	6.1	10.4	9.7	0.1	0.1	0.1
	(0.0, 5.9, 20.0)	(0.0, 9.9, 35.6)	(0.0, 9.9, 34.3)	(0.0, 0.0, 0.1)	(0.1, 0.1, 0.3)	(0.1, 0.1, 0.4)
15	8.7	14.9	13.2	0.6	0.8	0.8
	(0.0, 6.3, 23.0)	(0.0, 13.9, 55.8)	(0.0, 13.6, 47.9)	(0.3, 0.3, 1.37)	(0.1, 0.7, 2.6)	(0.2, 0.7, 3.0)
20	–	26.2	20.6	–	6.6	6.0
	(–)	(5.0, 22.3, 70.3)	(3.4, 18.2, 65.3)	(–)	(0.5, 4.1, 14.5)	(0.5, 3.8, 14.1)
25	–	61.5	50.9	–	37.0	35.1
	(–)	(6.9, 21.6, 80.0)	(3.9, 28.1, 78.3)	(–)	(8.9, 18.6, 81.0)	(11.0, 16.9, 73.9)

from the computational cluster. To overcome that problem the computational cluster can transmit a good feasible solution as soon as it is obtained. For that purpose we calculated average time of getting first feasible solutions for the same problem instances. With F_{opt} denoting the optimal objective function value and F_{feas} denoting the objective function value at the first feasible solution, the relative gap RG of the objective function value at the first feasible solution with respect to the optimal solution is calculated according to the following formula:

$$RG = \frac{F_{feas} - F_{opt}}{F_{feas}}. \tag{18}$$

The average time to the first feasible solution and the average relative gap RG are reported in Table 2.

In the Tables 1 and 2, "–" corresponds to the cases that CPLEX could not solve to optimality due to a large number of constraints in the cut covering formulation and consequently large memory requirements. As one can see from the Table 1, node-disjoint solutions take approximately as much time as arc-disjoint solutions, consequently the requirement for the paths to be node-disjoint does not make the problem more difficult to solve for this configuration. Table 1 also shows that as expected, the cut covering formulation is not suitable for explicit use on problems with more than 15 nodes. The relative gap between first feasible solution and optimal solution for node-disjoint formulation appears to be smaller than a corresponding gap for arc-disjoint formulation.

An illustration that demonstrates the difference between arc-disjoint dual paths and node-disjoint dual paths is presented in Fig. 5. In the figure, the size of each node represents its relative transmission power: larger nodes are transmitting with higher power than that of smaller ones. The differential power allocation creates directed links between each node that create an optimal, directed topology to support arc-disjoint dual paths (Fig. 5a) and node-disjoint dual paths (Fig. 5b).

Figure 6 shows an example of a dual data path created by a routing protocol over the provided topologies for the arc-disjoint (Fig. 6a), and node-disjoint (Fig. 6b) cases,

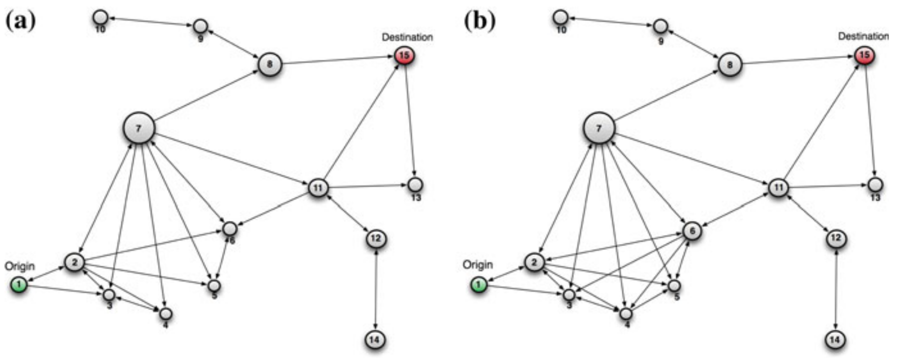

Fig. 5 Illustrative examples of arc-disjoint and node-disjoint ODDPND solutions. **a** Arc-disjoint ODDPND solution. **b** Node-disjoint ODDPND solution

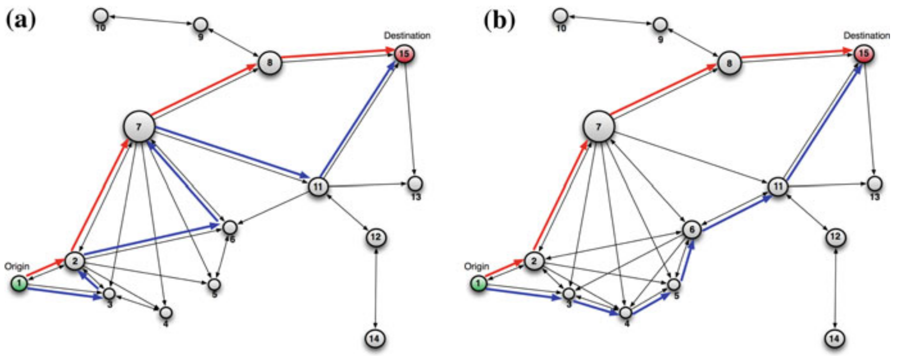

Fig. 6 Illustration of possible arc-disjoint and node-disjoint dual data paths. **a** Possible arc-disjoint dual data paths. **b** Possible node-disjoint dual data paths

for a given origin and destination nodes. It is important to note that this may not be the only possible dual-path combination for each topology. The proposed approach ensures that the minimum overall power allocation will result in at least one dual-path combination. It is possible, due to the wireless connectivity constraints that more than one path is created for the minimum power allocation. It is also important to highlight that our algorithm does not optimize the length of the path in number of hops, but the overall power utilization for a given source and destination pair. Additional constraints such as the maximum number of hops could also be added to formulation to address other protocol level constraints.

4 Conclusions and future work

Mission critical and time sensitive applications of sensor networks may benefit from multi-path data transport from a source node (sensor) to a destination node (gateway). Previous research on multi-path routing and transport algorithms have traditionally started from a given network topology at the physical (RF) level, with little attention to a coordinated runtime design of the network topology itself. In this paper, we introduce a centralized optimal network design approach that enables the existence of dual paths between any given source and destination nodes in the network. In designing the network topology, our approach takes into account practical constraints associated with the physical characteristics of wireless links, and rely solely on the use of transmission power control for network design.

There are basically three levels of topology designs that could be constructed to enable disjoint data paths between nodes. The less restrictive implementation is an arc-disjoint topology design, which has little practical use, since it relies on the possible use of common nodes for the different data paths. A second level of design involves the construction internally node-disjoint data paths, ensuring that the paths have no common arcs or nodes between any given source or destination. A third and even more restrictive design approach is the construction of paths that are *non-interfering*. The design of non-interfering paths imposes a stricter constraint on the topology, requiring not only that paths are arc-disjoint and internally node-disjoint, but also that no arc directly connects a node from one data path with a node from the other, with the exception of the source and destination nodes. In this paper we have focused on the first two topology designs, leaving the more restrictive design as part of our future work.

While centralized, the proposed allocation techniques are progressive, providing increasingly better power configuration at each iteration. At each step solution, a new configuration can be deployed in the network, enabling a new partial multi-path solution that will be improved in the subsequent iteration, and it is guaranteed not to degrade between iterations. In the proposed formulations, we have focused on the identification of edge construction to minimize the overall transmission power of all nodes, but other objectives and constraints could also have been considered in our formulation.

Our first results, still preliminary at this point, show the potential for a practical calculation of optimal network design for multi-path data support. Possible future research directions include adding the constraints needed to enable non-interfering multi-path calculation and the design of a distributed version of the proposed approach. Non-interfering paths will ensure that multi-hop transmissions taking place at one of the paths, will not affect (through interference) the multi-hop transmissions taking place on the second path. For example, referring back to Fig. 6b, a non-interfering design would prevent a direct arc between a node in $\{2, 7, 8\}$, and a node in $\{3, 4, 5, 6, 11\}$. Also, some of the constraints often adopted in wireless sensor network for maximum transmission length, and asymmetric data paths can be incorporated into the formulated problems.

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