Topology Control and Channel Assignment in Lossy Wireless Sensor Networks

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***Abstract*—In wireless sensor networks (WSNs), a significant amount of packets are lost when transmitted over wireless links, leading to unnecessary energy expenditure. This lossy property of a link can be described by the *packet reception ratio* (PRR) over it. In the literature, it was shown that the PRR of a link is a non-decreasing function of its *signal to interference-plus-noise ratio* (SINR), which indicates that the PRR can be improved by either enhancing the received power or reducing the interference-plus-noise level. On the other hand, a number of topology control algorithms and channel assignment algorithms have been presented for WSNs to reduce interference. However, most of them simply use the number of interfering nodes to describe the level of interference, which is inaccurate thus cannot guarantee high PRR. In this paper, we propose a joint design of topology control and channel assignment for lossy WSNs, aiming at improving the PRR of each link in the network. We first construct a maximum PRR spanning tree, then adjust the transmitting power and channel of sensor nodes to further improve the PRR of links on the tree. This way, packet retransmission due to lossy links is minimized, which leads to performance improvement in terms of network throughput, energy efficiency and end-to-end packet delay. We formulate the joint design into an optimization problem and prove its NP-hardness. We then present heuristic algorithms to give practical solutions for the problem. We have carried out extensive simulations and the results show that network performance can be significantly improved by using the topology generated by our algorithms compared to the topologies generated by other schemes under the same traffic demand.**

***Index Terms*—Wireless sensor networks (WSNs), topology control, channel assignment, lossy wireless links.**

I. Introduction and Related Work

Extensive research efforts have been devoted to wireless sensor networks (WSNs) in recent years due to their promising applications. For simplicity, in most of the work, it is assumed that there is a link between any two sensor nodes in a WSN if their distance is within the transmission range of sensors. It is further assumed that packets can be transmitted perfectly on such links as long as they are not interfered by other transmissions. However, it has been shown via experiments in [1], [2], [4] that for a large percent of links in a practical WSN, a packet needs to be retransmitted several times before being successfully delivered, and two links may have a totally different number of retransmission times to successfully deliver a packet even if they have the same distance and are close to each other. We call such property the *lossy* property of WSNs in this paper, and define the probability of successfully delivering a packet over a link without retransmission as the *packet reception ratio* (PRR) of the link. Clearly, the higher the PRR, the less lossy or higher quality the link.

The lossy property of WSNs was examined in depth in [1], [2], [3], [4]. It was found in [1] by experiments that with the same transmitter and transmission distance, the PRR of a link has high variance in different directions. A radio irregularity model was further presented to capture this phenomenon and it was shown that this property has higher impact on routing protocols than MAC protocols. In [2], the existence of lossy links in WSNs was verified by experiments, and wireless links were divided into three categories according to their distance: connected, transitional and disconnected. Transitional links are characterized by high variance in PRR and asymmetric connectivity. These properties of transitional links were analyzed in [3] and explained as a result of the Gaussian factor of a log-normal shadow path loss propagation model. In [4], lossy WSNs were studied from a statistical perspective, in which the dependencies among various factors, such as PRR, asymmetric property and distance were explored. The observations validate the existence of lossy links and reveal that the PRR of transitional links are unstable over time.

The PRR of links has been used as a metric in the literature to improve the network performance and energy efficiency of WSNs. In [5], the expected transmission count (ETX) of a link, which is defined as the reciprocal of the product of its PRRs in both directions, was used as the routing metric for DSDV and DSR routing protocols in lossy WSNs. Experiments showed that network performance can be greatly improved in terms of throughput and packet delay based on the metric. In [6], it was proved that the product of PRR and forwarding distance of a link is the optimal routing metric in terms of energy efficiency for geographic routing in lossy WSNs. A localized topology control scheme for lossy WSNs was proposed in [7], in which a high energy consuming link is replaced by a low energy consuming multi-hop link locally to minimize the energy consumption, as long as the ratio of expected retransmission counts of the new path and the old link is lower than a fixed bound. In [8], distributed clustering algorithms were presented for lossy WSNs, where sensor nodes with a maximum ratio of PRR to residual energy are selected as cluster heads locally, and each cluster member chooses the head with the least expected transmission count as its cluster head.

In all the work discussed above, interference was not considered as a factor for lossy links in WSNs, though in reality, the PRR of a perfect link drops dramatically as interference grows. In fact, the PRR of a link in lossy WSNs is highly related to the signal to interference-plus-noise ratio (SINR) [9], in which the interference is defined as the additive received power from all other links. The SINR of links has been considered in the link scheduling study [11], [12], [13], [14], in which different time slots are assigned to links of WSNs such that a minimum SINR threshold is satisfied by each link and the number of assigned time slots is minimized. The link

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scheduling problem with SINR constraint was proved to be NP-complete [11], and several approximation algorithms were provided. These approximation algorithms are analytical and centralized in nature, making them too complex to be deployed in practical WSNs. In [14], a concurrent medium access control protocol for WSNs under SINR constraint was presented, in which a new concurrent transmission is scheduled only if the SINR constraint of both current transmissions and the new transmission can be guaranteed.

As the PRR and SINR of a wireless link are highly related, clearly, the PRR of links can be improved by either enhancing the received signal level or reducing the interference level.

Topology control is an effective approach to reducing interference in WSNs, which minimizes the transmitting power of sensor nodes while maintaining the connectivity of the network. In [15], a localized minimum spanning tree algorithm was proposed for topology control, guaranteeing that the maximum node degree in the derived tree would be less than 6. The existence of asymmetric links due to various transmission power levels at each node was considered in [16] and a distributed algorithm to construct a directed minimum spanning tree was suggested. However, these works implicitly assume that a low node degree leads to low interference, which is not always true [17]. Distributed topology control algorithms that aim at minimizing interference were presented in [18], [19], [20]. Nevertheless, the number of interfering transmitters rather than the SINR of a link was used to describe interference, thus the PRR of links cannot be accurately reflected. In [21], the problem of power control with the objective of maximizing concurrent transmissions under SINR constraint in arbitrary wireless networks was proved to be NP-hard and heuristic algorithms were provided. However, the connectivity requirement of topology control was not considered.

Another approach to reducing interference in WSNs is to assign different channels to interfering links. One type of such work is multi-channel medium access control (MAC), in which the communication channel for each link is negotiated dynamically based on the channel usage information before each transmission. It either requires synchronization or has non-negligible protocol overhead. A different type of work is quasi-static channel assignment, which assigns a channel to interfering links periodically. Nevertheless, most of these works take a binary interference model, in which two links are either interfering with each other and cannot be active simultaneously if the distance between them is less than a fixed value, or do not interference with each other at all if the distance is greater than the value. Clearly, this interference model is less accurate than the SINR model, thus the algorithms based on it may lead to poor performance in reality. The problem of channel assignment for WLAN deployment under SINR interference model was studied in [22]. However, it is not suitable for WSNs.

To the best of our knowledge, most topology control algorithms for WSNs have not considered improving the PRR of links on the topology as the major objective, and there is no channel assignment scheme for WSNs that uses SINR as the interference model. Based on such observation, in this paper we propose a joint design of topology control and channel assignment aiming at finding a spanning tree in the WSN, by assigning different transmission power levels and channels to sensor nodes, such that the PRR of every link on the spanning tree is maximized. This way, the overall retransmissions for communication between any two nodes in the network are minimized, which leads to great performance improvement in terms of network throughput, energy efficiency and end-to-end packet delay. We first formalize the problem into an optimization problem and prove that it is NP-hard. We then propose heuristic algorithms to give practical solutions to the problem. We evaluate the performance of the proposed algorithms by extensive simulations, and the results demonstrate that the algorithms outperform other compared schemes.

The remainder of the paper is organized as follows. In Section II, the network model and the SINR model are discussed, and the joint design of topology control and channel assignment for lossy WSNs under these models is formulated into an optimization problem. In Sections III and IV, a centralized and a distributed algorithm are presented respectively, to construct the maximum PRR spanning tree in WSNs. Section V gives the comprehensive performance evaluation results. Finally, Section VI concludes the paper.

II. Models and Problem Formulation

A. Network Model

We assume that sensor nodes are distributed over a two-dimensional plane, and each node can be configured with different transmission power levels ranging from $p_{\min}$ to $p_{\max}$. In addition, we assume that sensor nodes can be assigned different transmitting channels, and the transmitter of a link switches to the assigned channel of the receiver before transmitting a frame. In the literature, it was usually assumed that there is a link between two nodes if and only if the distance between them is less than a fixed value. In lossy WSNs considered in this paper, we assume that there is a weighted link between any two nodes with the weight being its packet reception ratio (PRR). In other words, there is a link between two nodes as long as they are within the carrier sense range of each other, since otherwise the PRR of the link would be always zero regardless of the interference level. Even though it is difficult to accurately predict the traffic load of a node in wireless sensor networks, the traffic demand at each node can be roughly estimated based on the application type, MAC protocol, routing strategy of the network and the distance to the sink node. Thus we define a normalized traffic demand variable m for each node, including both its self-generated data and relayed data. Under these assumptions, we use a weighted undirected graph $G = (V, E, P, C, M, W)$ to denote a lossy wireless sensor network, where V is the set of all sensor nodes, E is the set of links, P denotes the set of transmission power levels, C denotes the set of available channels, M is the set of traffic demands of all nodes and W is the set of PRRs of all links. The PRR of each link may vary based on the transmission power configuration and traffic demand of the entire network. A WSN with uniform transmitting power and a single channel under this network model is given in Fig. 1.

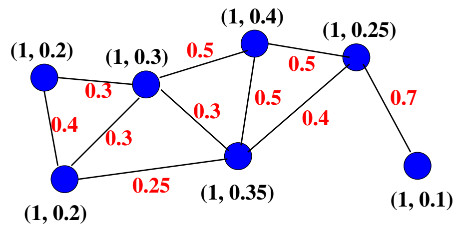


Fig. 1. An example of network graph for WSNs. In the graph, blue dots denote sensor nodes and the lines among them stand for the links. The transmission power and traffic demand of each node are given in the bracket above it and the PRR of each link is the red number nearby.

An important factor affecting the PRR of a link is the received power at both ends of a link, which can be determined by the transmission power level, transmission distance and the propagation model. The log-normal shadowing path loss model [3] is used as the propagation model in this paper, since it can reflect the characteristics of lossy WSNs more precisely than the free space model and the two-ray ground reflection model commonly used in the literature. In this propagation model, for any link (i,j), the received power at node j is given by

$$r_{(i,j)} = p_i - PL(d_0) - 10n\log\frac{d_{(i,j)}}{d_0} + X_\sigma$$

where p_i is the transmitting power level of node i, $r_{(i,j)}$ is the received power at receiver j from transmitter i, d_0 is a reference distance, $PL(d_0)$ is an empirical power loss at d_0, n is the path loss exponent, $d_{(i,j)}$ is the distance between node i and j, and X_σ is a zero-mean Gaussian RV with standard deviation σ. The received power level at node i can be obtained similarly.

B. SINR and Packet Reception Ratio

As discussed earlier, the PRR of a link is highly related to the signal to interference-plus-noise ratio (SINR) in both directions of a link. In the SINR of a link, signal is defined as the received power from the transmitter of the link, interference is defined as the sum of received power from all other transmitters, and noise is the background noise. Without knowing the traffic pattern, MAC protocol and routing protocol, it is difficult to accurately predict the concurrent transmitters in the network. Therefore, for simplicity, we assume that the probability that a node is transmitting equals its normalized traffic demand m in the long term. If the same transmitting channel is used at all nodes, then for any link $(i,j) \in E$, the contribution of node i to the SINR at node j is given by

$$SINR_{(i,j)} = \frac{r_{(i,j)}}{\sum\limits_{k\in V, k\neq i} m_k \cdot r_{(k,j)} + N_j}$$

where $r_{(k,j)}$ is the received power at node j from node k, m_k is the normalized traffic demand of node k, and N_j is Gaussian white background noise at node j. The SINR at node i can be obtained similarly.

If different transmitting channels are assigned to sensor nodes, then for each link, interference only comes from other nodes that use the same channel. Let c_i denote the channel assigned to node i, thus the multi-channel SINR of link (i,j) at node j would be

$$SINR_c^{(i,j)} = \frac{r_{(i,j)}}{\sum\limits_{k\in V, k\neq i}^{c_i=c_k} m_k \cdot r_{(k,j)} + N_j}$$

As shown in [9], for the link from node i to node j, the PRR of the link is 0 if the SINR at node j is smaller than a low threshold; it is 1 if the SINR at node j is greater than a high threshold; and it is almost linearly related to the SINR at node j if the value is between the two thresholds. For simplicity, we assume that PRR of a link is a linear function of its SINR. Furthermore, for any link (i,j), we define the PRR as a linear function of the smaller SINR among the two directions of the link. The rationale behind this assumption is two fold: First, each packet transmission in lossy WSNs needs to be acknowledged at the link layer to confirm successful delivery. The loss of either the packet transmission or the acknowledge transmission will cause a retransmission, thus the PRR of a link should be related to the smaller SINR among the two directions; Second, since links are undirected in our network model, packets from node i to node j and packets from node j to node i are all transmitted over link (i,j), thus the PRR of a link should reflect the worse case. Hence, for link $(i,j) \in E$, its PRR is given by

$$PRR_{(i,j)} = \lambda \cdot \min\{SINR_{(i,j)}, SINR_{(j,i)}\}$$

where λ is the slope of the linear function, which can be determined via experiments.

C. Connectivity Constraint

The objective of topology control in this paper is to find a subgraph of G, by assigning different transmitting power to the vertices such that the PRR of all links in the subgraph is maximized. We assume that graph G is connected before topology control. The assumption is reasonable since every sensor node needs an effective path to the sink node to deliver its collected data. The connectivity property of graph G should be maintained in topology control. In general, constructing a spanning tree is a common approach to finding a subgraph of G that maintains connectivity. Therefore, we convert our topology control problem into the problem of finding a maximum weighted spanning tree T in G, in which the weight of each link is its PRR. For any link $(i,j) \in E$, let $t_{(i,j)}$ denote whether link (i,j) is on the spanning tree or not. Then the connectivity constraint of the spanning tree can be expressed as follows

$$\sum_{\forall(i,j)\in E} t_{(i,j)} = |V| - 1$$

$$\sum_{i\in S, j\in S} t_{(i,j)} <= |S| - 1, \forall S \subset V, |S| >= 3$$

D. Problem Formulation

We can now formally formulate the joint design of topology control and channel assignment in lossy WSNs into an optimization problem as follows.

TABLE I
NOTATIONS IN THE FORMULATION

V	Set of sensor nodes
E	Set of links
P	Set of power levels
C	Set of channels
T	Spanning tree
λ	slope of PRR over SINR
p_i	Transmitting power of node i
c_i	Channel assigned to node i
m_i	Normalized traffic demand of node i
N_i	Background noise at node i
$r_{(i,j)}$	Received power at node j from i
$t_{(i,j)}$	Indicator of whether (i,j) is in T
$SINR_{(i,j)}$	Signal to Interference-plus-Noise Ratio from i to j
$SINR_c^{(i,j)}$	SINR from i to j if node i is assigned channel c
$PRR_{(i,j)}$	Packet Reception Ratio of link (i,j)

Given a weighted undirected graph $G = (V, E, P, C, M, W)$, find a spanning tree T in graph G, in which the weight of each link is maximized, by assigning proper transmitting power levels and channels to all nodes in V. The PRR is used as the weight of a link, since it reflects not only the energy efficiency but also the network performance of the link, such as throughout and transmission delay. For clarity, the symbols used in the formulation are given in Table I.

Using the constraints discussed in previous subsections, the optimization problem can be formulated as

Maximize

$$\min\{PRR_{(i,j)}, \forall (i,j) \in T\}$$

Subject to

$$p_{\min} \le p_i \le p_{\max}, \forall i \in V \quad (1)$$

$$1 \le c_i \le |C|, \forall i \in V \quad (2)$$

$$r_{(i,j)} = p_i - PL(d_0) - 10n \log \frac{d_{(i,j)}}{d_0} + X_\sigma \quad (3)$$

$$t_{(i,j)} = 1, \forall (i,j) \in T \quad (4)$$

$$\sum_{\forall (i,j) \in E} t_{(i,j)} = |V| - 1 \quad (5)$$

$$\sum_{i \in S, j \in S} t_{(i,j)} \le |S| - 1, \forall S \subset V, |S| \ge 3 \quad (6)$$

$$SINR_c^{(i,j)} = \frac{r_{(i,j)}}{\sum_{k \in V, k \ne i}^{c_k = c_i} m_k \cdot r_{(k,j)} + N_j} \quad (7)$$

$$PRR_{(i,j)} = \lambda \cdot \min\{SINR_c^{(i,j)}, SINR_c^{(j,i)}\} \quad (8)$$

In the formulation, Equations (1) and (2) specify the set of transmitting power levels and the set of available channels, respectively; Equations (4), (5) and (6) are the constraints for spanning tree T; and Equations (3), (7) and (8) are used to determine the received power level, SINR and PRR of each link, respectively.

E. NP-Hardness

We have the following lemma concerning the NP-hardness of the optimization problem.

Lemma 1: The joint topology control and channel assignment problem in lossy WSNs under SINR constraint is NP-hard.

Proof: We prove the lemma by reducing the *max-connections* problem in [21] that maximizes the capacity of an arbitrary wireless network under the SINR model to our problem. In the max-connections problem, a group of wireless links are distributed arbitrarily over a geometric field, and transmission over a link is successful only if the SINR at the receiver is over a threshold. The goal of the problem is to choose transmitting power for each link so as to maximize the number of connections satisfying the SINR threshold. The NP-hardness of this problem was proved by reducing the Maximum Independent Set problem, which is a well-known NP-complete problem, to it.

Our joint optimization problem formulated above can be expressed as the following decision problem by giving a fixed SINR threshold: Is there such a spanning tree that by assigning power to nodes and channels to links, both directions of each link in the spanning tree satisfy the SINR threshold requirement? Now consider a special case of this problem. Assume that the traffic demand on each node is 1. Then the SINR definition in our problem is the same as the SINR definition in the above max-connections problem. We further assume that a spanning tree is already given and only one channel is available. The decision version of this problem is whether a minimum SINR threshold can be satisfied on each link in the spanning tree by assigning different power levels to sensor nodes, which is essentially the decision version of the max-connections problem. Therefore, the joint optimization problem is NP-hard. ■

To give practical solutions to the joint problem, we solve the problem in two steps: construct a maximum PRR spanning tree, and improve the minimum PRR on the spanning tree by adjusting the transmitting power and the channel of nodes. We will provide a centralized algorithm and a distributed algorithm using such a strategy. The centralized algorithm can give better results by using global information, while the distributed algorithm is more scalable in large WSNs.

III. CENTRALIZED PRR MAXIMIZATION ALGORITHM

A maximum PRR spanning tree can be found by using Prim's algorithm, if the transmitting power and the channel of each node in the network is provided. On the other hand, given a spanning tree, the minimum PRR among the links in the tree can be improved by adjusting the transmitting power and channel of sensor nodes. Motivated by this, we propose a *centralized PRR maximization algorithm* in this section, which iteratively performs these two operations, until the minimum PRR can no longer be improved.

In the centralized algorithm, we assume that the received power of all other nodes in the network can be measured at each node regardless of their transmitting power levels. We also assume that each node is notified the channel assignment of all other nodes in the network. The channel assignment information of all nodes can be broadcast to the entire network. To reduce the high message complexity of fully broadcast, each node aggregates its own channel information when forwarding channel broadcast messages. Then the SINRs in both directions of a link can be obtained by Equation (7). Initially, each node is assigned a random channel and configured with the medium transmitting power. After that, each sensor node broadcasts a *beacon* message sequentially, and all other nodes measure the received power from it. The SINR of all links are calculated after the measurement and their PRRs are derived based on the received power level and the channel assignment of other nodes. With this information, a maximum PRR spanning tree is constructed using Prim's Algorithm.

After the spanning tree is constructed, each node first checks whether the minimum PRR on the spanning tree can be improved by adjusting its transmitting power. If so, it chooses the new power level that increases the minimum PRR most; Otherwise, the node examines whether the minimum PRR on the spanning tree can be improved by assigning itself a different channel. If so, it assigns the channel that boosts the minimum PRR most. The adjustment of transmitting power and channel is performed sequentially for all nodes, and each node makes its decision based on the updates of all other nodes.

When every node has completed the update of its transmitting power and channel, the algorithm goes back to the spanning tree construction process, to see whether there a better spanning tree with the updated SINR matrix. This iteration is performed until the minimum PRR cannot be further improved. In each iteration, the time cost includes the running of Prim's algorithm, and the adjustment of transmitting power or channel for each node, thus the time complexity is $O(|V|^2 + |V| \cdot |T| \cdot (|C| + |P|)) = O(|V|^2)$, in which $|V|$, $|T|$, $|C|$ and $|P|$ are the number of sensor nodes, the number of links on the spanning tree, the number of channels and the number of transmitting power levels, respectively.

An iteration step size β can be defined for this algorithm, such that the iteration terminates if the minimum PRR on the spanning tree cannot be increased by at least β within an iteration. As the maximum value of PRR is less than one, the iteration is guaranteed to terminate after $\frac{1}{\beta}$ times of execution. The convergence speed is determined by the step size β. The pseudo code of the algorithm is given in Table II.

TABLE II
CENTRALIZED PRR MAXIMIZATION ALGORITHM

```
Input:
  Graph G = (V, E, P, C, M, W);
Output:
  Maximum PRR spanning tree T;
  Transmitting power level vector Q;
  Transmitting channel vector S;
Algorithm:
  minPRR1 = −∞;
  Assign the medium power level to each node;
  Assign a random channel to each node;
  do
   minPRR1 = minPRR2;
   Determine the received power matrix for the network;
   Determine the SINR matrix for the network;
   Determine the PRR for all links in the network;
   Find a maximum weighted spanning tree T by Prim's algorithm;
   minPRR2 = min{PRR_t | ∀t ∈ T};
   for each node i in V
    if ∃ p'_i ∈ P that improves minPRR2 most
     Update Q: p_i = p'_i;
     Update PRR and SINR matrix of T;
    else
     if ∃ c'_i ∈ C that improves minPRR2 most
      Update S: c_i = c'_i;
      Update PRR of SINR matrix of T;
     end if
    end if
   end for
  while (minPRR1 + β < minPRR2)
```

IV. DISTRIBUTED PRR MAXIMIZATION ALGORITHM

In large WSNs, it is usually too costly to schedule the received power measurement at each node and to broadcast the updates of transmitting power and channel in the entire network. Therefore, in this section we present a distributed algorithm for large WSNs.

We define the *1-hop neighbors* of node i as all the reachable nodes when node i transmits at the maximum power level, and assume that the interference from nodes more than *2-hops* away can be ignored. This assumption is reasonable because as will be seen, the transmitting power of most nodes will be adjusted during the execution of the algorithm, leading to a much lower transmitting power for later data transmissions. Under such an assumption, we propose a *distributed PRR maximization algorithm* using the similar idea of the centralized algorithm, for large WSNs. The distributed algorithm includes five phases: discovery of 2-hop neighbors, measurement of received power level, calculation and exchange of SINR, construction of the spanning tree and adjustment of transmitting power and channel. The last two phases can be performed iteratively to further boost the minimum PRR. Although different channels and transmitting power levels are assigned to sensor nodes for later data transmissions, during the execution of the algorithm all communications are over the default channel. In addition, each sensor node transmits all messages at the maximum power level except the message for received power measurement. The details of each phase are given in following subsections.

A. Discovery of 2-hop Neighbors

To measure the received power level and calculate the SINR for all adjacent links at each node, a node should be aware of its 2-hop neighborhood. In this phase, each node broadcasts a *hello1* message using CSMA/CA, including its node ID and traffic demand. A node updates its 1-hop neighbor list after receiving a hello1 message. When the channel is free for over a fixed time, a node determines that it has received the hello1 messages from all its 1-hop neighbors. After that, each node broadcasts a *hello2* message using CSMA/CA as well, including its 1-hop neighbor list. Each node updates its 2-hop neighbor list based on its own 1-hop neighbor list and the received hello2 messages. Again, a node determines that it has received all 2-hop neighbor information after the channel is free for a fixed time. After this phase, each node is aware of its 2-hop neighbors. The message complexity of this phase is $O(1)$ as each node broadcasts only one hello1 message and one hello2 message.

B. Measurement of the Received Power Level

In this phase, each node broadcasts a *beacon* message at its chosen transmitting power level on the default channel, and all nodes in its 2-hop neighborhood measure the received power level from it. Initially, each node chooses the medium power level and a random channel as its transmitting power and channel. To avoid collisions, a node will not send out its beacon message until it has measured the received power level from all nodes with lower IDs in the 2-hop neighborhood, or an idle channel timer has expired due to the transmission failure of beacon messages. As there is no guarantee that the beacon message can be successfully decoded by all 2-hop neighbors, 2-hop neighbors should be notified by the transmitter of the beacon message before the message is broadcast. Therefore, a node first broadcasts a *notify* message at the maximum power level, including the chosen transmitting power and channel of the node. After receiving a notify message, a node rebroadcasts it at the maximum power level if the message is from a 1-hop neighbor so as to notify the 2-hop neighbors. To avoid conflicts among forwarded notify messages, each forwarding node delays its transmission for a period corresponding to its ID. After receiving the notify message, each node in the 2-hop neighborhood learns who is about to send out a beacon message and measures its received power level when the message is transmitted. After this phase, each node has a list of the received power and transmitting channel of all neighbors within 2-hop range.

C. Calculation and Exchange of SINR

In this phase, each node calculates the SINR of all the links with it as the destination. A neighbor within 2-hops has interference to a link only if the link shares the transmitting channel of the neighbor, The noise level at the destination can be obtained by measuring the received power level when the channel is free. Let N_2^j denote all the neighbors of node j within 2-hop range. Then for link (i, j), the SINR at node j is given by

$$SINR_{(i,j)} = \frac{r_{(i,j)}}{\sum\limits_{\forall k \in N_2^j, k \neq i}^{c_k = c_i} m_k \cdot r_{(k,j)} + N_j} \tag{9}$$

After the calculation, each node broadcasts a *candidate* message to its 1-hop neighbors. The candidate message includes an entry for every adjacent link with the node as the destination. Each entry consists of the received signal level, interference level, noise level and the SINR of the link. This way, each node is aware of the SINR level of both directions for all its adjacent links, then it can derive the PRR for each of them.

D. Construction of the Spanning Tree

In this phase, a maximum weighted spanning tree is constructed, in which the PRR of a link is used as the link weight. The Nearest Neighbor Tree (NNT) algorithm proposed in [23] will be used in this subsection to construct an approximate spanning tree in a distributed manner. In NNT algorithm each node chooses a unique rank, which is a quantity from a totally ordered set. A node connects to the nearest node of higher rank. It is proved to have $O(\log n)$ approximation ratio to the optimal algorithm, where n is the number of vertices in the graph.

In our implementation of NNT, the sensor node ID is used as the node rank and the PRR of a link is regarded as the distance. Thus after running our implementation of NNT, a maximum PRR spanning tree is found. A node should know the PRR of all links on the spanning tree that are within its 2-hop neighborhood, to prepare for the later adjustment of transmitting power and channel phase. Thus after the spanning tree is constructed, each node broadcasts a *PRR* message, including the PRR and the SINR entry of all links adjacent to it on the spanning tree. Each node rebroadcasts a received PRR message if it is from 1-hop neighbors. This way, each node is aware of the PRR of all links on the tree that are within its 2-hop neighborhood.

E. Adjustment of Transmitting Power and Channel

In this phase, each node tries to improve the minimum PRR of the links in its 2-hop neighborhood by adjusting its transmitting power or channel. A node first checks the possibility of improving the minimum PRR by adjusting its transmitting power. It is assumed that the channel condition in the network remains unchanged in a short period. Then the amount of received power variation between any two nodes is roughly the same as the variation of the transmitting power according to Equation (3). Thus a node can estimate the PRR change of all links in its 2-hop neighborhood caused by the adjustment of its transmitting power. If the minimum PRR can be improved, the node chooses the power level that gives the maximum improvement. Otherwise, the node examines whether the minimum PRR can be boosted by choosing a different transmitting channel. If so, the node assigns the channel that leads to the largest improvement. After that, an *update* message is broadcast and forwarded to 2-hop neighbors so neighbors can update their PRR and SINR records. A node will not begin to adjust its transmitting power and channel until all 2-hop neighbors whose adjacent links have lower PRR have broadcast an update message. This adjustment phase terminates when all nodes have adjusted their transmitting power or channel. An example WSN after running the distributed algorithm is given in Fig. 2.

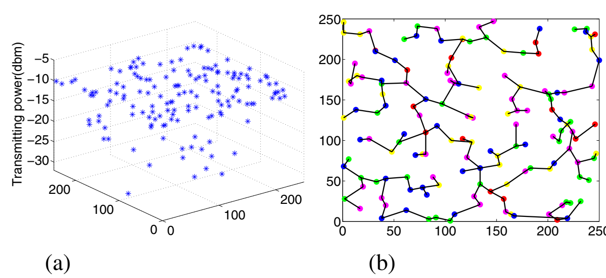


Fig. 2. An example WSN after running the distributed algorithm. (a) Transmitting power of sensor nodes; (b) Channel assignment and the spanning tree of the WSN, in which dots denote sensor nodes, lines stand for links on the spanning tree and the color of each node represents the assigned channel for the node.

The spanning tree construction and transmitting power and channel adjustment can be performed iteratively to maximize the minimum PRR on the spanning tree. The number of iterations should be proportional to the average traffic load of the network, to ensure that the energy overhead of this algorithm is negligible compared to the energy saved from the boosted PRR of links. Let the maximum degree of sensor

TABLE III
SYSTEM PARAMETERS FOR SIMULATION

Parameter	Value
Bandwidth	$2Mbps$
Field	$250m \times 250m$
Packet Size	$100bytes$
Duration	$180s$
Traffic Pattern	Poisson
Maximum Pt	0 dbm
Minimum Pt	-32 dbm

nodes be δ, which is in general a small constant number. Then in each iteration, the message complexity is $O(\delta)$ since each node has to forward at most δ notify, PRR and update messages. Moreover, this distributed algorithm should be performed periodically to reflect the slow change of the channel condition in the network.

V. PERFORMANCE EVALUATIONS

In this section, we evaluate the performance of the proposed centralized and distributed algorithms through simulations, and compare them with the LMST algorithm in [15], which builds a minimum-transmitting-power spanning tree locally, while maintaining a low degree for all nodes to reduce interference. We implement the algorithms in NS-2 simulator and evaluate the performance of the algorithms in terms of system throughput and energy efficiency. The effect of the number of channels on the performance is examined as well.

To eliminate the effect of different routing protocols, in our simulation, each node generates data following a Poisson process with the expected data rate being the traffic demand defined earlier, and chooses a random neighbor in the network as the destination. All sensor nodes are randomly deployed over a $250 \times 250m^2$ field. In addition, the traffic demand of each node is a random number ranging from 0 to 0.4 to determine the parameters for the Poisson process. The system parameters listed in Table III are used in the performance evaluation.

A. SINR and System Throughput

In this set of simulations, we evaluate the performance of the proposed algorithms in terms of SINR and system throughput. The number of sensor nodes varies from 50 to 250. The minimum SINR, average SINR and system throughput for different number of sensor nodes are plotted in Fig. 3, where LMST stands for the localized minimum spanning tree algorithm [15], tc-sc-fp stands for the single channel topology control with each node transmitting at full power level, tc-sc denotes the topology control with a single channel and regulated power levels, and tc-mc-3 and tc-mc-5 are the multi-channel topology control with 3 and 5 available channels, respectively. Here system throughput is defined as the aggregated throughput of all links on the spanning tree. The results illustrated in Fig. 3 are based on the power and channel assignments from the distributed algorithm. The results from the centralized version of the algorithm have been evaluated as well and are slightly better. Due to limited space, the corresponding figures are omitted. From Fig. 3(a), we can see that as the number of sensor nodes grows, the minimum SINR of tc-sc-fp and LMST decreases while the minimum SINR of other algorithms remains generally unchanged. This is because that as the network density grows, the interference of full power transmission to other links becomes more severe. On the contrary, we can observe from Fig. 3(b) that the average SINR of all algorithms remains almost unchanged, since the distribution of links with good SINR and poor SINR does not depend on the number of sensor nodes. We can also see that the average SINR of tc-sc-fp is greater than that of tc-sc. This is because that though the interference to other receivers can be reduced by lowering transmitting power, the received signal level at the destination is reduced as well. Both Fig. 3(a) and (b) demonstrate that the minimum and average SINR can be greatly enhanced by adopting multiple channels. The advantage of multi-channel topology control over single-channel topology control is further validated by the system throughput illustrated in Fig. 3(c). For the same reason, the throughput of tc-sc-fp is higher than that of tc-sc.

B. Energy Efficiency

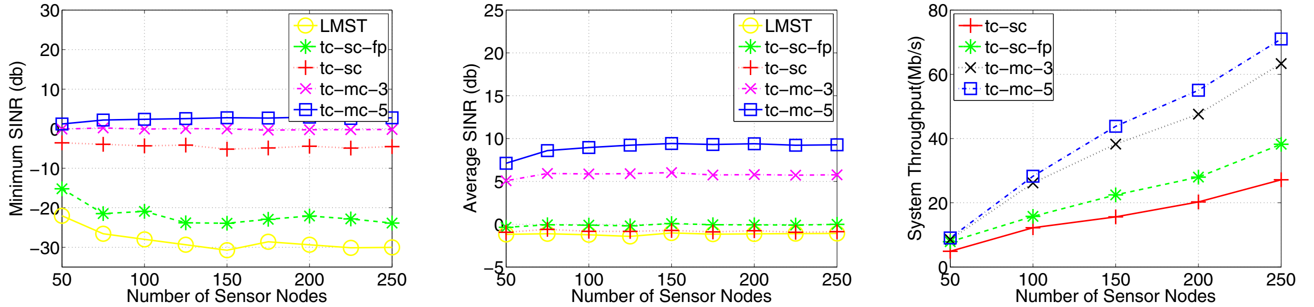
In this set of simulations, we evaluate the energy efficiency of the proposed algorithms in terms of transmission power consumption and average PRR. The number of sensor nodes varies from 50 to 250 and the transmission power consumption is defined as the weighted summation of the transmission power of all nodes. The simulation results are shown in Fig. 4, in which tc-sc-c and tc-sc-d denote the centralized and distributed topology control algorithms, respectively, while other notations are the same as those in Fig. 3. In Fig. 4(a), the total transmitting energy consumption of all sensor nodes is examined. We can observe that power adjustment can dramatically save transmission energy, while the centralized algorithm has no obvious difference compared to the distributed algorithm. The average PRR of all links in the spanning tree is shown in Fig. 4(b). It is noticeable that the trends of PRR for all algorithms are similar to their corresponding trends of average SINR. This is due to the high correlation between SINR and PRR. We also note that the performance of the centralized algorithm is slightly better than the distributed algorithm. This is because that the interference from far away nodes may still cause packet loss, which is neglected in the distributed algorithm.

C. Impact of Available Channels

In this set of simulations, we vary the number of available channels from 1 to 7 to see its impact on the average PRR. The simulation was conducted for WSNs with 50 nodes, 150 nodes and 250 nodes, respectively, and the results are plotted in Fig. 5. We can see that in all scenarios, the average PRR is higher if assigned more channels, as the packet loss due to interference is reduced by assigning more channels. However, the average PRR can hardly be improved when the number of channels is further increased. This is because that as most interference is already eliminated by assigning so many channels, packet loss due to multi-path effect and burst noise cannot be reduced by assigning more channels.

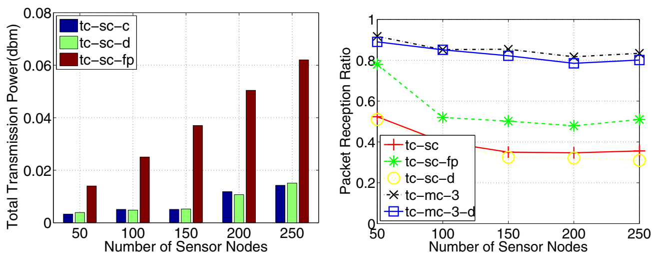
VI. CONCLUSIONS

In this paper, we have studied the topology control and channel assignment problem in lossy WSNs. We incorporated



(a) (b) (c)

Fig. 3. The SINR and system throughput for the spanning tree generated for WSNs. (a) Minimum SINR. (b) Average SINR. (c) System throughput.



(a) (b)

Fig. 4. Energy efficiency of the proposed algorithms. (a) Transmission power consumption. (b) Average PRR.

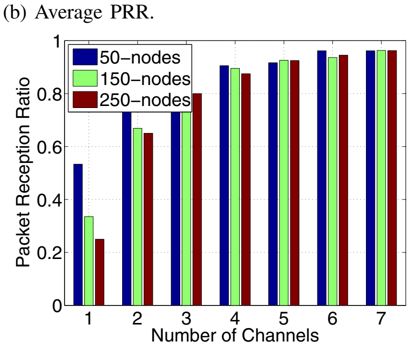


Fig. 5. Average PRR for varying number of available channels.

the effect of interference into lossy wireless links and the traffic demand of links into the SINR model. Based on this model, we then proposed a joint design of topology control and channel assignment with the objective of maximizing the minimum PRR among all links in the WSN, which is proved to be NP-hard. We provided heuristic algorithms to give practical solutions to the problem. We have conducted extensive simulations and the results demonstrate that both the system throughput and energy efficiency can be significantly enhanced through boosting the minimum PRR in the WSN.

REFERENCES

[1] G. Zhou, T. He, S. Krishnamurthy and J.A. Stankovic, "Impact of radio irregularity on wireless sensor networks,", *ACM MobiSys '04*, pp. 125-138, 2004.
[2] J. Zhao and R. Govindan, "Understanding packet delivery performance in dense wireless sensor networks," *ACM SenSys '03*, pp. 1-13, 2003.
[3] M. Zuniga and B. Krishnamachari, "Analyzing the transitional region in low power wireless links," *IEEE SECON*, pp. 517-526, October 2004.
[4] A. Cerpa, J.L. Wong, L. Kuang, M. Potkonjak and D. Estrin, "Statistical model of lossy links in wireless sensor networks," *Information Processing in Sensor Networks, Fourth International Symposium on*, pp. 81-88, April 2005.
[5] D.S. De Couto, D. Aguayo, J. Bicket and R. Morris, "A high-throughput path metric for multi-hop wireless routing," *ACM MobiCom '03*, pp. 134-146, September 2003.
[6] M.Z. Zamalloa, K. Seada, B. Krishnamachari and A. Helmy, "Efficient geographic routing over lossy links in wireless sensor networks," *ACM Trans. Sensor Networks*, pp. 1-33, May 2008.
[7] G. Xing, C. Lu and R. Pless, "Localized and configurable topology control in lossy wireless sensor networks," *IEEE ICCCN*, pp. 75-80, August 2007.
[8] Z. Pan, Y. Yang and D. Gong, "Distributed clustering algorithms for lossy wireless sensor networks," *IEEE NCA*, pp. 36-43, July 2010.
[9] R. Maheshwari, S. Jain and S.R. Das, "A measurement study of interference modeling and scheduling in low-power wireless networks," *ACM SenSys '08*, pp. 141-154, 2008.
[10] H. Li and P.D. Mitchell, "Full interference model in wireless sensor network simulation," *6th International Symposium on Wireless Communication Systems*, pp. 647-651, September 2009.
[11] O. Goussevskaia, Y.A. Oswald and R. Wattenhofer, "Complexity in geometric SINR," *ACM MobiHoc '07*, pp. 100-109, September 2007.
[12] D. Chafekar, V.S.A. Kumart, M.V. Marathe, S. Parthasarathy and A. Srinivasan, "Approximation algorithms for computing capacity of wireless networks with SINR constraints," *IEEE INFOCOM*, pp. 1166-1174, April 2008.
[13] T. Moscibroda, R. Wattenhofer and A. Zollinger, "Topology control meets SINR: the scheduling complexity of arbitrary topologies," *ACM MobiHoc '06*, pp. 310-321, 2006.
[14] M. Sha, G. Xing, G. Zhou, S. Liu and X. Wang, "C-MAC: model-driven concurrent medium access control for wireless sensor networks," *IEEE INFOCOM*, pp. 1845-1853, April 2009.
[15] N. Li, J.C. Hou and L. Sha, "Design and analysis of an MST-based topology control algorithm," *IEEE INFOCOM*, pp. 1702-1712, April 2003.
[16] J. Liu and B. Li, "Distributed topology control in wireless sensor networks with asymmetric links," *IEEE GLOBECOM*, pp. 1257-1262, December 2003.
[17] M. Burkhart, P. von Rickenbach, R. Wattenhofer and A. Zollinger, "Does topology control reduce interference?," *ACM MobiHoc '04*, pp. 9-19, May 2004.
[18] X. Li, K. Moaveni-Nejad, W. Song and W. Wang, "Interference-aware topology control for wireless sensor networks," *IEEE Communications Society Conference on Sensor and Ad Hoc Communications and Networks*, pp. 263-274, September 2005.
[19] Y. He and Y. Zeng, "Interference-aware topology control problem in wireless sensor networks," *ITS Telecommunications Proceedings, 2006 6th International Conference on*, pp. 969-972, June 2006.
[20] Y. Gao, J.C. Hou and H. Nguyen, "Topology control for maintaining network connectivity and maximizing network capacity under the physical model," *IEEE INFOCOM*, pp. 1013-1021, April 2008.
[21] M. Andrews and M. Dinitz, "Maximizing capacity in arbitrary wireless networks in the SINR model: complexity and game theory," *IEEE INFOCOM*, pp. 1332-1340, April 2009.
[22] X. Qin, X. Guo and R. Berry, "SINR-based channel assignment for dense wireless LANs," *International Conference on Wireless Networks, Communications and Mobile Computing*, pp. 692-697, June 2005.
[23] M. Khan, G. Pandurangan and V. S. Anil Kumar, "Distributed algorithms for constructing approximate minimum spanning trees in wireless sensor networks," *IEEE Transactions on Parallel and Distributed Systems*, vol. 20, pp. 124-139, Jan. 2009.