Channel Assignment in Cognitive Wireless Sensor Networks

Mihaela Cardei and Amalya Mihnea

Department of Computer and Electrical Engineering and Computer Science

Florida Atlantic University

Boca Raton, FL 33431, USA

E-mail: {mcardei, amihnea}@fau.edu

Abstract—**Cognitive radios allow secondary users to communicate using the underutilized spectrum. However, in the presence of a primary user, the unlicensed users must vacate the spectrum, leading to a decrease in network performance or even network partition. In this paper we address the problem of robust topology control in wireless sensor networks with the objective of assigning a channel to each radio such that the resulting topology is robust to the presence of a primary user. The robustness constraint requires that if a channel is reclaimed by a primary user, then the resulting secondary user topology still preserves the connectivity between any two nodes. In this paper we propose a distributed algorithm for channel assignment which has low overhead and is scalable with the number of sensor nodes. We analyze the performance of our algorithm using ns-3 network simulator.**

Keywords: wireless sensor network, channel assignment, grid-based distributed algorithm.

I. Introduction and Related Work

Wireless sensor networks (WSNs) constitute the foundation of a broad range of applications related to national security, surveillance, military, health care, and environmental monitoring. The main type of communication used by WSNs for data gathering is *convergecast*, where data travels from many nodes (e.g. sensor nodes) to a single node (e.g. the sink).

Due to the recent growth of wireless applications, the communication on the unlicensed spectrum (e.g. ISM) has become congested, while the utilization of the licensed spectrum varies between 15% and 85% temporally and geographically [4]. Cognitive radio networks is a promising solution used to address the issue of inefficient spectrum usage.

A cognitive radio is designed to operate on a wide spectrum range and can switch to a different frequency band with limited delay. This technology allows primary users (PUs) to share the spectrum with secondary users (SUs), where SUs communicate through un-assigned spectrum bands without disrupting the regular usage of the PUs. Cognitive radio networks allow SUs to take advantage of unoccupied spectrum in an opportunistic manner using dynamic spectrum access strategies.

To avoid interference with a PU, an SU must vacate the spectrum when the channel is being used by a PU. This affects ongoing communication of the SUs. The challenge occurs due to the difficulty to predict when a PU will appear in a given spectrum. To use other channels, SUs have to spend a considerable amount of time for spectrum sensing and channel switching [3]. In addition, a change in an SU channel may trigger other nodes to change their channels in a ripple effect in order to maintain the desirable topology.

In this paper we address the issue of topology control in WSNs such that to satisfy the *robustness constraint* in the presence of a PU. The WSN is using a convergecast communication model, where data is collected from the sensors to the sink. If two sensors u and v communicate on a channel that is reclaimed by a PU, then the packet is re-routed from u to v through another radio of u. Thus packet dropping and significant delay can be avoided. There are a number of related works on channel assignment in wireless networks. Our work is different than these approaches by addressing the robust topology control issue in WSNs and by proposing a distributed approach which has low overhead and is scalable to the number of sensors, properties which are relevant to a WSN environment.

In [2] the authors introduce a centralized channel assignment algorithm, MCCA (Maxflow-based Centralized Channel Assignment), developed for multi-radio wireless mesh networks in order to maximize network capacity and reduce interference. The assignment is independent of any particular traffic profile and is done such that the most critical links (e.g. those carrying large flows) experience the least possible interference.

This paper does not address the issue of channel switching in the presence of a PU. Also the centralized mechanism proposed here is not scalable for a large network such as a WSN.

In [7], the authors proposed a semi-dynamic and distributed channel assignment mechanism called SICA that uses game theory and takes the co-channel interference into account. It uses an online learning method to

a. Partition of the monitored area into a grid. Each cell$_{i,j}$ is identified by two coordinates *i* and *j*.

b. Channel allocation of each grid cell. Each cell has a *representative*, colored red.
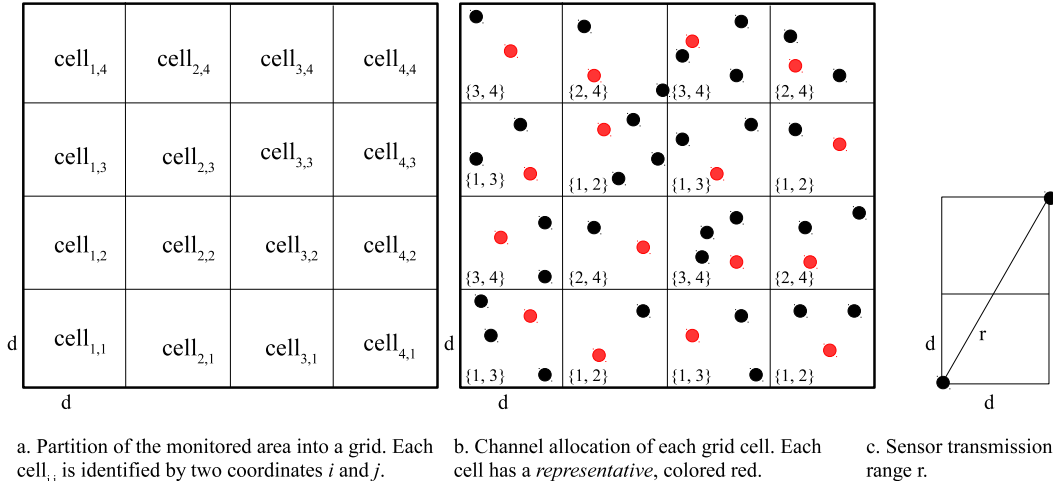
c. Sensor transmission range r.

Fig. 1. The Grid Representation

assign the best channel to each radio using information gathered during the channel sensing periods. The nodes continuously refine their decision based on changes in the wireless environment. SICA outperforms Urban-X [6], another interference-aware channel assignment mechanism, even using fewer radio interfaces per node (2 instead of 3).

Urban-X assigns channels giving priority to nodes based on the number of active flows they have: nodes having higher priority have more chances to occupy the best channels. Nodes broadcast control messages over a common channel up to two-hops neighbors. Unlike Urban-X and many other channel assignment algorithms, SICA does not use a common channel between all nodes but the synchronization is achieved through exchanging messages. The use of a common channel can be wasteful when only a few interfaces are available.

In [11] network robustness and channel interference are jointly considered when developing centralized and distributed algorithms. The proposed solutions outperform existing interference-aware approaches when primary users appear, and achieve similar performance at other times. The algorithms are compared with INSTC [9]. The problem that we address is similar to the one presented in this article. We are focusing on distributed algorithms which are applicable to large scale WSNs. The distributed algorithm presented in [11] requires multiple negotiations between nodes and may require cascaded switching of multiple users.

In [1] fairness is taken into account in a constant factor approximation algorithm for the joint channel assignment, routing, and scheduling problem in multiradio wireless mesh networks. First, the network is transformed by creating copies of the nodes such that each node has approximately I radios, where $I \leq K$, K is

the number of available channels. The algorithm assigns channels to every node in the new network and then tries to spread the interference uniformly such that the maximum interference on each channel is bounded. This channel assignment is changed so that all K channels are used and only one channel is assigned per node interface. In the final phase, the channel assignment and flow solution are mapped back to the original network. This algorithm can effectively exploit the increased number of channels and radios, and it performs much better than the theoretical worst case bounds.

The remainder of the paper is organized as follows. In section II we formally define the channel assignment for a robust topology control problem and in Section III we present our grid-based channel assignment approach. Section IV presents simulation results using ns-3 network simulator and Section V concludes the paper.

II. PROBLEM DEFINITION

In this paper we consider a WSN consisting of n homogeneous sensor nodes $s_1, s_2, ..., s_n$ and a sink node S. We assume the nodes are densely deployed and the WSN is connected. The sink node S is used to collect data and is connected to the network of sensors. Data collection follows a convergecast communication model, where data flow from many nodes (e.g. the sensors) to a single node (the sink).

We model the network as an undirected graph $G = (V, E)$, with the set of vertices (or nodes) being the set of sensors and the sink. An edge exists between two nodes if they are within each other's communication range.

We assume that each sensor node is equipped with Q radios and there are C channels available, where $C \geq Q$. The objective is to find a channel assignment A which assigns to each node radio a channel such that

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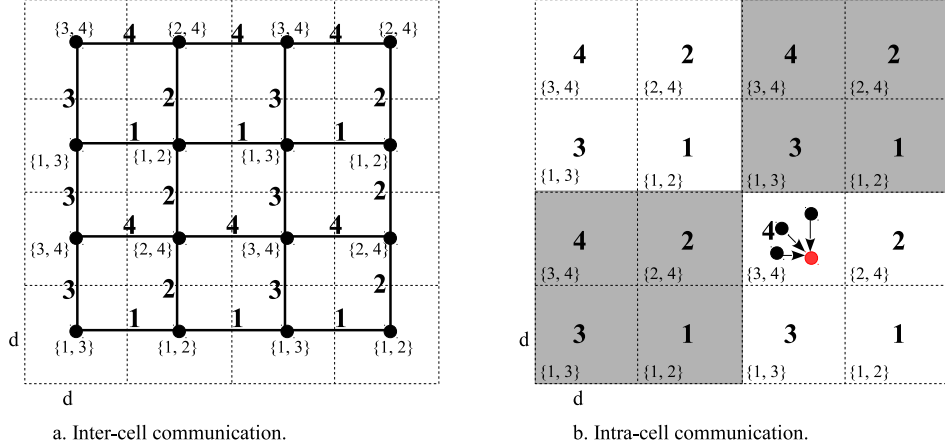a. Inter-cell communication.

b. Intra-cell communication.

Fig. 2. Channel Assignment for Inter-cell and Intra-cell Communication

the resulting topology is connected, robust to a primary user, and has a reduced interference.

Let $A(u)$ denote the set of channels assigned to the node u, where $|A(u)| = Q$. Based on the channels assigned to the radios at each node, a channel assignment A generates a new undirected graph $G_A(V, E_A)$ where $E_A = \{(u, v, c) : (u, v) \in E \text{ and } c \in A(u) \cap A(v)\}$. Note that multiple edges may exist between two nodes if they share more than one channel, where one edge corresponds to a channel.

The *robustness constraint* requires that G_A is not partitioned in the presence of a primary user which communicates on a channel c_p. In that case, all the edges in G_A assigned to c_p are removed. The resulting graph must be connected. In this paper we assume that the primary user can affect part of the network or the entire network (e.g. transmission of the TV tower), but only one channel is used by the primary user at one time. We assume that the primary user is using the reclaimed channel for some amount of time.

It is easy to observe that if each node has at least two radios, then there exists a channel assignment that satisfies the robustness constraint. Just consider the case when all nodes have assigned the two channels c_1 and c_2 to both radios. Then, if the primary user uses one of the channels, let's say channel c_1, then the topology remains connected using the channel c_2. The drawback of such an assignment is a high interference.

Transmissions on different channels can run in parallel, thus reducing the network interference. This results in an increased network capacity and a reduced communication delay.

Channel Assignment for a Robust Topology Control (CA-RTC) Problem: Given a graph G find a channel assignment A such that $G_A = \{(u, v, c) : (u, v, c) \in E_A\}$ is robustly connected for any channel

c and the network interference is minimized.

According to the proof in [11], the CA-RTC problem is NP-complete. We consider that the WSN is homogeneous and all the sensor nodes have the same transmission range and the same interference range.

III. GRID-BASED CHANNEL ASSIGNMENT APPROACH

In this section we present our solution to the CA-RTC problem. The monitored area is divided into grids, see Figure 1a. The technique of dividing the monitored area into grids has been used previously in a number of WSN approaches [10].

Let us denote the communication range of each sensor by r. We assume that sensors know their location information using GPS or other localization protocols [5]. In addition, since sensor wireless networks are densely deployed, we assume that each grid cell has at least one sensor.

The *neighboring cells* of a certain cell are those placed above, below, left, and right. The grid size is $d = r/\sqrt{5}$, see Figure 1b., so that any two sensors in neighboring cells can communicate directly.

Let us assume the case when each sensor node has $Q = 2$ radios and there are $C = 4$ channels available. Each sensor computes the grid $cell_{i,j}$ that it belongs to based on its GPS coordinates. A static channel assignment can be allocated in this case, as illustrated in the Figure 2. Nodes will allocate their channels based on their location.

Figure 2a. shows the channels used to communicate between neighboring cells, while Figure 2b. shows the channels allocated for the communication inside a cell. That means for example that the representative of the $cell_{2,3}$ is assigning the channels $\{1, 2\}$ to its radios, it uses channel 1 to communicate with the left and

3

right representatives, and channel 2 to communicate with the representatives placed above and below. Also, the representative of the $cell_{2,3}$ uses channel 1 for intra-cell communication.

Communication between cells is accomplished through cell *representatives*, as illustrated in Figure 1b. Each cell locally selects a representative, which can be for example the sensor node with the largest remaining energy. In case of a tie, the representative role is assumed by the sensor node with the largest ID.

The representative election is conducted locally. For the communication inside the cell, each sensor is using a transmission range $r' = d\sqrt{2}$, in order to reduce the interference between cells with the same channel.

Since the representative election process can cause interference between cells with the same channel, e.g. $cell_{1,1}$ interferes with $cell_{3,1}$ and $cell_{1,3}$, we can use two time intervals. Here are the cells that choose representatives in:

- The first time interval: $cell_{1+4i,1+4j}$, $cell_{1+4i,2+4j}$, $cell_{2+4i,1+4j}$, $cell_{2+4i,2+4j}$, $cell_{3+4i,3+4j}$, $cell_{3+4i,4+4j}$, $cell_{4+4i,3+4j}$, $cell_{4+4i,4+4j}$
- The second time interval: $cell_{1+4i,3+4j}$, $cell_{1+4i,4+4j}$, $cell_{2+4i,3+4j}$, $cell_{2+4i,4+4j}$, $cell_{3+4i,1+4j}$, $cell_{3+4i,2+4j}$, $cell_{4+4i,1+4j}$, $cell_{4+4i,2+4j}$

where $i \geq 0$ and $j \geq 0$.

For example, in Figure 2b., the gray cells choose their representative in the first time interval, while the white cells choose their representative in the second time interval.

Sensor nodes wait a random time interval and then broadcast a message *Hello (sensor id, remaining energy, cell id)* inside their cell. They wait a random time to avoid collisions. The node with the largest remaining energy and in case of a tie with the largest ID becomes the cell representative. The representative then broadcasts a message *Representative (sensor id, cell id)*.

The cell representative is in charge with forwarding messages between cells and with transmission of messages from/to the nodes inside the cell. It has to be noted that the representative consumes the largest amount of energy in the cell. In order to avoid sensor energy depletion, representatives have to be re-elected periodically.

The proposed channel assignment satisfies the robustness constraint. The topology resulting from the channel assignment is robust when a primary user reclaims any of the channels. Figure 3 shows the resulting topology when channel 1 is reclaimed. The inter-cell communication topology still ensures communication between any cells. Intra-cell communications which originally were scheduled on the channel 1 now take place on the backup channel 2 .
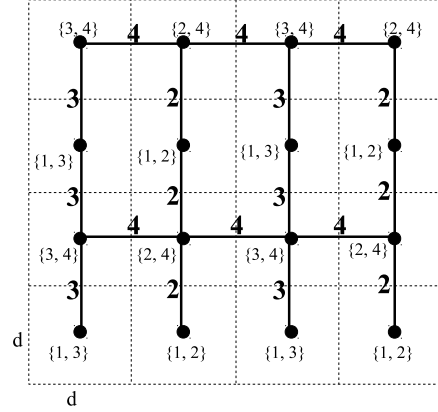
Channel assignment when channel 1 is used by the primary user.

Fig. 3. Channel Assignment when Channel 1 is reclaimed by the Primary User

Communication on different channels can be done in parallel. Interference between nodes that have been assigned (or reassigned in the presence of a PU) the same channel will be resolved at the MAC level.

The interference can be reduced if more channels or radios are available. For example, if 8 channels are available, then the communication pattern on horizontal changes from 1, 4, 1, 4, ... to 1, 4, 5, 8, ... and the communication pattern on vertical changes from 3, 2, 3, 2, ... to 3, 2, 7, 6, ...

If 3 radios are available, then the third radio can be used for intra-cell communication. If more radios are available, they can be used to reduce the interference for the inter-cell communication.

The advantage of using this mechanism is the low overhead of the channel assignment mechanism. The nodes will assign channels to their radios immediately after deployment, based on their location. The drawback of this method is that it requires sensors to know or to be able to compute their location.

IV. SIMULATION

In this section we evaluate the performance of our Grid-based Channel Assignment mechanism using ns-3 network simulator [8].

A. Simulation Environment

In the simulations, we set the node communication range $r = 100$m. The cell size is computed as $d = r/\sqrt{5}$. We consider that the deployment area is a square and we vary the number of cell rows (which is the same as the number of columns) between 5 and 25 with increment of 4, see Figure 4. As a result, the deployment area side varies between 223m and 1118m and the number of sensor nodes n varies between 75 and 1875. The sensors

Number of rows	Number of cells	Area side length, m	Number of sensors
5	25	223.607	75
9	81	402.4926	243
13	169	581.3782	507
17	289	760.2638	867
21	441	939.1494	1323
25	625	1118.035	1875

Fig. 4.   Simulation parameters

are deployed randomly in the monitoring area, and we place the sink S in the middle of the area.

The transmission rate for the wireless radio is 1Mbps. In our simulation, we consider that the nodes have $Q = 2$ radios and $C = 4$ channels. Once the sensors are deployed, they assign channels to their radios based on their location. To test the performance of the resulting topology, we employ the following shortest-path data gathering protocol.

The sink S broadcasts a beacon message in the whole network. Each sensor node sets up its routing table with the next hop being the node from which the beacon with the smallest number of hops to the sink was received.

We use the convergecast communication model where traffic flows from the sensor nodes to the sink. At the MAC level we use CSMA for the wifi channels. Each sensor node has a parameter p - probability that the node sends a message in each iteration (e.g. each second). Sensors send 656 bytes data packets every second. In the simulations, we represent two cases: when $p = 100\%$ and $p = 30\%$. We run each simulation scenario 5 times using different seed numbers and report the average values in the graphs. Each simulation scenario is run for 20 seconds.

B. Simulation Results

In the first experiment we compare the performance of the network when the nodes are equipped with multi-radios multi-channels, versus the case when nodes have single-radio single-channel. Simulation results are presented in Figure 5. Two cases are presented, when nodes send data packets every second with probability $p = 30\%$ and $p = 100\%$. In Figure 5a. we represented both data transmitted by the sensors as well as data received by the sink. We can observe that in both cases a higher throughput is received for multi-radio WSNs. Some of the data packets are lost due to collisions. It is known that collisions increase as packets get closer to the sink. In these simulations we didn't test a more sophisticated data delivery mechanism since the main objective is to provide a robust topology.

Figure 5b. compares the end to end delay for single-radio and multi-radio networks. The end to end delay is larger when $p = 100\%$ since more packets are being transmitted. We also observe that the single-radio network has a slightly smaller delay. This is because any two neighbor nodes can communicate on the common channel, while in the multi-radio network it depends on whether they have a common channel.

In Figure 5c. we can observe that the delivery ratio decreases with an increase in the number of sensors, due to the collisions in the network. If nodes send with $p = 30\%$, then a higher delivery ratio is achieved. This graph also illustrates the advantage of a multi-radio network, which has an increased delivery ratio compared to single-radio networks.

In the second experiment we test the behavior of the network in the presence of a primary user. In Figure 6 the percentage of the area affected by the primary user varies between 0 (no PU) to 1 (PU is affecting the whole area). The PU is using a single channel and two scenarios were considered depending on whether the PU channel is identical to a sink channel or not. When the PU is on the same channel as the sink, the sink will use the other radio for wireless communication.

In the presence of a PU the topology is still connected, even though it is sparser, see Figure 3. Note that in our simulations we consider that the sink is placed in the middle of the monitored area. We take the monitored area to be a square with side L. The area affected by the PU is taken to be the rectangle with height L and width $PU_{fraction} \times L$, starting from the origin.

In Figure 6a. we can observe that a higher drop in data rate occurs when $PU_{fraction} \geq 0.6$ and the PU is using one of the sink channels. In these cases the sink is in the area affected by the PU and it can communicate on a single radio only. This will reduce network capacity at the sink.

If the sink is in the area affected by the PU we can also see an increase in the end to end delay, especially in the case when the PU is on a sink channel, see Figure 6b.

Figure 6c. is consistent with the previous graphs and it shows a decrease in the delivery ratio as the sink is affected by the primary user. Even though not represented in this graph, it is evident the drastic impact of a PU on a single-radio network. In such a case, for $PU_{fraction} \geq 0.6$ the delivery ratio is 0.

In summary, the topology resulted by applying our channel assignment mechanism is robust to the presence of a primary user. Simulation results show the benefit of using multi-radio networks and show the network performance in the presence of a primary user.
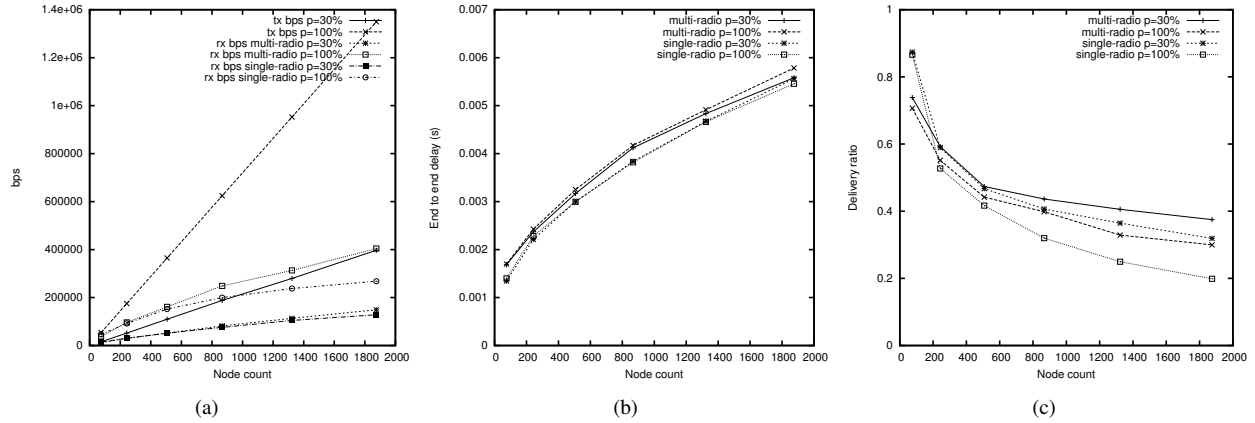
(a)   (b)   (c)

Fig. 5.   Comparisons between multi-radio and single-radio WSNs (a)Data throughput. (b)End to end delay. (c)Delivery ratio.

(a)   (b)   (c)
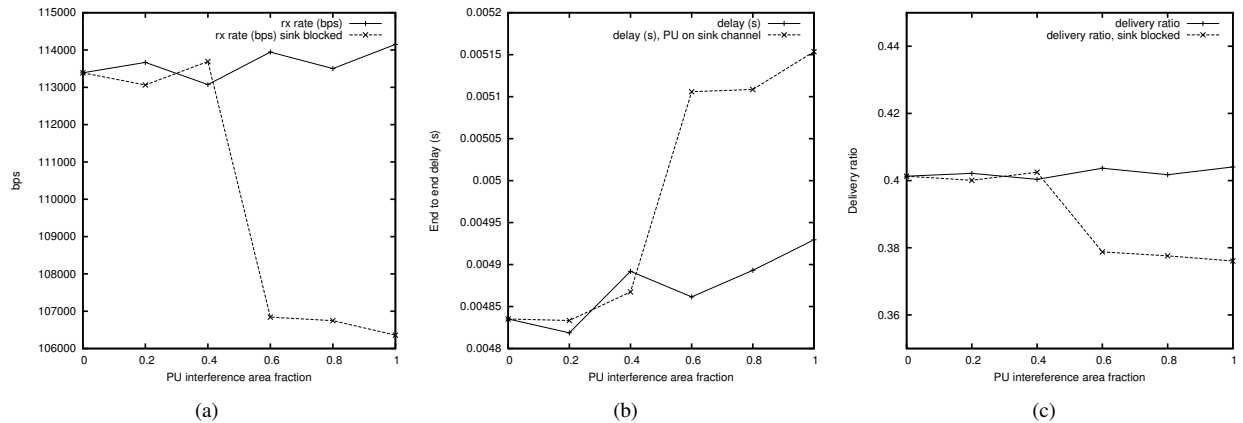
Fig. 6.   The impact of Primary User on WSN performance (a)Data throughput. (b)End to end delay. (c)Delivery ratio.

V. CONCLUSIONS

In this paper we propose a Grid-based Channel Assignment mechanism which is robust to the presence of a primary user on a certain channel. In such an event, the nodes are able to continue to deliver data to the sink following the same or a different path. The algorithm virtually divides the monitored area into a grid and performs channel assignment based on node location in the grid. Simulation results using ns-3 show the advantage of using a multi-radio multi-channel topology and the robustness of the proposed mechanism in the presence of a primary user.

ACKNOWLEDGMENT

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