Using Reconfigurable Radios to Increase Throughput in Wireless Sensor Networks

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***Abstract*—In traditional wireless sensor networks communicating on a single channel the data throughput measured at the sink is constrained by the radio capability, contentions, and collisions, which increase in the region closer to the sink. Using SDR technology, different levels of configuration within a transceiver are allowed. In this paper we assume that the sink and sensor nodes are equipped with reconfigurable radios. We design a distributed algorithm used by sensor nodes to reconfigure their radio according to some predefined radio-modes, such that the resulting topology is connected to the sink. Collecting sensor data using this topology reduces the interference and increases the network throughput and the data delivery rate. We analyze the performance of our algorithm using ns-3 simulations.**

Keywords: wireless sensor network, radio-mode assignment, multi-radio sink, distributed algorithm.

I. Introduction and Related Works

A wireless sensor network (WSN) consists of sensor nodes that are densely deployed either inside the phenomenon or very close to it. Sensor nodes measure various parameters of the environment and transmit collected data to the sink. Once a sink received sensed data, it processes and forwards them to the users. The nodes closer to the sink are involved in more data transmissions and they consume more energy than sensors deployed farther away from the sink. This is because, besides their own packets, they forward packets on behalf of other sensors.

When the whole WSN communicates on only one channel, the data throughput measured at the sink is constrained by the radio capability, contentions, and collisions which increase in the region closer to the sink. These lead to retransmissions and packets being dropped. With the development of Software Defined Radio (SDR) technology, different levels of reconfiguration within a transceiver are allowed. Multi-band, multi-channel, multi-standard, multi-service systems can be achieved with SDR. Cognitive radios enable WSNs to use vacant licensed channels. The advanced technology makes multi-channel communication realistic.

A cognitive radio can be programmed to transmit and receive on a variety of frequencies and to use different transmission technologies supported by its hardware design. A radio is *reconfigurable* if it has the capability to adjust its transmission parameters on the fly, without any modifications to the hardware. These parameters include spectrum band, transceiver parameters, and modulation scheme.

Cognitive radio networks can operate in both licensed and unlicensed bands [1]. When operating on licensed bands, the objective is to exploit spectrum holes through cognitive communication, giving priority to the primary users. In unlicensed bands, all users have the same priority. ISM bands are used nowadays by many radio technologies and has started to decrease in efficiency with an increase in interference. Cognitive radio networks can be used to increase efficiency and QoS through intelligent spectrum sharing. Our work fits in this category. We propose a distributed algorithm that improves network performance through spectrum sharing.

Many approaches proposed for traditional multichannel WSNs mainly focus on reducing the interference caused by simultaneous transmissions. Most of the works are exploiting the 802.15 channels. A tree-based multichannel scheme is proposed in [3]. This approach partitions the network into different subtrees communicating on different channels thus eliminating the inter-tree interference. First, a fat tree routed at the base station is computed based on the breadth first search algorithm. Then channels are allocated from top to bottom, partitioning the network into different subtrees communicating on different channels.

In our work we assume that sensor nodes can reconfigure their radios to some predefined radio-modes selected by the sink. A radio-mode is characterized by spectrum band, communication parameters, and modulation scheme. Thus different modes may have different communication ranges and different transmission data rates. This aspect was not accounted for in [3]. In addition, in our algorithm data collection is not performed at the same time as the radio-mode selection.

Another tree-based joint channel selection and routing scheme is proposed in [4], which aims to improve the network lifetime by reducing the energy consumed on overhearing. Beacon messages containing the receiver channel are sent on different channels in rotation. The receiver channel is chosen to be the least used channel between neighbors after a random backoff though a common default channel. The transmit channel is chosen dynamically based on the battery health among all upstream nodes. All nodes listen on the receiver channel and switch to the transmit channel for data transmission. Data may be transmitted on different channels at each hop thus the overhearing is minimized. This approach leads to a frequent channel switching and to a restricted broadcast.

An application based clustering mechanism is proposed in [5]. Nodes with similar sensed data (e.g. temperature) are assigned to the same channel, forming a data plane. It is assumed that geographical proximity implies high data correlation. Cluster heads (CHs) in each data plane and the sink communicate though a common control channel while sensor nodes send data to their CH though the assigned intra-cluster channel. The application dependent assumption makes this approach hard to extend for different sensing mechanisms.

The remainder of the paper is organized as follows. Section II presents motivation and we formally define the radio-mode assignment for increased throughput in WSNs problem. In Section III we propose a distributed algorithm whose performance is simulated in Section IV. Section V concludes the paper.

II. Motivation and Problem Definition

The objective of this paper is to provide a mechanism that improves network capacity and data throughput. In WSNs data is collected using convergecast. The bottleneck is at the sink which receives data from a large number of sensors and in the region closer to the sink where the traffic is higher. To deal with this issue, we propose to use a sink with multiple radios.

We consider a WSN consisting of n homogeneous sensor nodes $s_1, s_2, ..., s_n$ and a sink node S. We assume that sensor 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 one (the sink). Sensor nodes are resource constrained devices, while the sink is a more resource-powerful device. Each sensor node is equipped with one reconfigurable radio and the sink is equipped with k reconfigurable radios.

We assume that both the sensors and the sink can adjust the transmission parameters of their radios to radio-modes from the set $\{rm_0, rm_1, ..., rm_{m-1}\}$, where $m \geq k$.

The objective is that sensor nodes assign radio-modes to their radios such that the resulting topology is connected and data throughput is increased.

Radio-Mode Assignment for Increased Throughput in WSNs (RMA) Problem: Given a WSN with n sensors and a sink S, where each sensor has 1 reconfigurable radio and the sink has k reconfigurable radios, assign to each radio a radio-mode from the set $C = \{rm_0, rm_1, ..., rm_{m-1}\}$, $m \geq k$, such that the resulting topology is connected and the throughput is increased assuming a high data traffic application.

III. Distributed Algorithm for the RMA Problem

In this section we present our solution for the RMA problem. Different radio-modes are illustrated in section III-A. The objective is that each sensor node assigns its radio to a radio-mode such that the overall topology is connected.

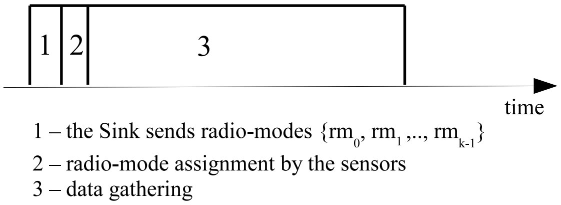

1
2
3
time
1 – the Sink sends radio-modes {rm$_0$, rm$_1$,.., rm$_{k-1}$}
2 – radio-mode assignment by the sensors
3 – data gathering

Fig. 1. Network Organization

We propose the network organization from Figure 1. The sink S is equipped with k radios and chooses k radio-modes from the set C. Let us denote the set of radio-modes selected by the sink with C_{sink}, where $C_{sink} \subseteq C$. The sink assigns each radio a radio-mode from C_{sink}. All the sensor nodes in the network assign their radios to rm_0 during phases 1 and 2. $rm_0 \in C_{sink}$ is the radio-mode with the smallest transmission range (and the highest frequency).

In the *phase 1*, the sink broadcasts a message containing C_{sink} by flooding. In the *phase 2*, the nodes are involved in a distributed algorithm during which each sensor node selects a radio-mode from C_{sink} such that the overall topology remains connected. Each sensor assign its radio to the selected radio-mode at the end of phase 2.

Phase 3 is the data gathering phase. Data is generate by sensor nodes and collected by the sink. The overall topology contains t connected topologies using different radio-modes. Any data collection mechanism can be used in this phase. One such example is data collection using shortest-path trees.

TABLE I
COMPARISON OF VARIOUS WIRELESS SENSOR RADIO-MODES

SensorMotes	TX Range	Frequency Band	Data Rate(max)	Radio Module
Mica2 [6] 868/916MHz	152m,outdoor	868/916MHz	38.4Kbps	CC1000
Mica2 [6] 433MHz	304m,outdoor	433MHz	38.4Kbps	CC1000
Mica2Dot [7] 868/916MHz	152m,outdoor	868/916MHz	38.4Kbps	CC1000
MicaZ [8]	75-100m,outdoor	2.4GHz	250Kbps	CC2420
Waspmote [9][10] 2.4GHz	7000m,outdoor	2.4GHz	250Kbps	XBee-PRO-ZB
Waspmote [9][11] 900MHz	10km	900MHz	156Kbps	XBee-900
Waspmote [9][12] 868MHz	12km	868MHz	24Kbps	XBee-868

A. Characteristics of Radio Module of Various Sensor Platforms

Wireless sensor motes are mostly equipped with dipole antennas. Compared to channels at higher frequency, those at lower frequency have better propagation characteristics and achieve larger transmission range when they use the same transmitting power.

Existing commercial sensor motes operating on different channel frequencies achieve different transmission ranges and different data rates. For example, sensor motes using lower frequency bands such as 868/900 MHz achieve lower data rate than those at 2.4 GHz band and they have a larger transmission range.

In Table I we examine different wireless sensor radios and compare RF modules operating at different frequencies. We can observe that sensor motes transmitting on lower frequency bands are characterized by a larger transmission range and have a smaller data rate.

With the development of the SDR technology, different levels of reconfiguration within a transceiver are possible. Multi-band, multi-channel, multi-standard, multi-service systems can be achieved. Using SDR, radios can be configured to different schemes as used in the existing RF modes, according to different needs. Our construction of the t-overlapping topologies accounts for the fact that different radio-modes may be characterized by different transmission ranges.

B. A Distributed Algorithm for Radio-Mode Assignment

This algorithm is executed in phase 2 and has two steps:

- Step 1 - neighbor discovery and setting up the distance (hop count) to the sink
- Step 2 - radio-mode selection by the sensor nodes.

Let us assume without loss of generality that the k radio-modes selected by the sink are $C_{sink} = \{rm_0, rm_1, ..., rm_{k-1}\}$, ordered such that $tx_0 \leq tx_1 \leq ... \leq tx_{k-1}$, where tx_i is the transmission range of the radio-mode rm_i. In both steps 1 and 2 sensor nodes configure their radio to rm_0. In step 2, each sensor node selects a radio-mode from C_{sink}, and at the end of the step 2 sensors reconfigure their radio to the selected radio-mode.

The objective is that each sensor node selects a radio-mode from C_{sink}, such that the resulting topology remains connected to the sink after sensors reassign their radios at the end of step 2.

1) Step 1- Neighbor Discovery and Setting up the Distance to the Sink: Let us denote by $N_k(u)$ the k'th neighborhood of a node u, where $N_k(u) = \{v|dist(u,v) \leq k\ hops\}$.

The sink S constructs $N_1(S)$ and $N_2(S)$, while each other sensor node v constructs $N_1(v)$. All the nodes including the sink S broadcast a *Hello* message containing the node ID. The message is sent with a small random delay to avoid collisions. After a short time interval, each node u which is 1-hop away from the sink sends a second *Hello* message, containing the node ID and $N_1(u)$. Based on this information, S computes $N_2(S)$. Each other sensor node v knows $N_1(v)$.

In the second part of this step, the sink broadcasts a message *Hops* which contains a parameter *hops* - the number of hops to the sink. A sensor node receiving a *Hops* message retransmits the message in two cases: (i) if this is the first *Hops* message received, or (ii) if this message contains a shorter distance to the sink. In both cases the node updates its shortest distance to the sink, increments the *hops* counter, and then retransmits the *Hops* message. At the end of this step, each sensor node knows its smallest number of hops to the sink using rm_0.

2) Step 2 - Radio-Mode Selection by Sensor Nodes: The number t of topologies connected to the sink S is upper-bounded by $k = |C_{sink}|$ and by the number of nodes in $N_1(S)$, that is t =*min*{ k, $|N_1(S)|$ }.

First, the sink S assigns radio-modes to the

Algorithm 1 SinkAssignRadioModesN_1(S)

```
ComputeRadioModes$N_1(S)$
broadcast *SinkRMSet*$N_1$(S, $N_1(S)$, radio-modes assigned to the sensors in $N_1(S)$, TTL = 1)
```

Algorithm 2 ComputeRadioModes$N_1(S)$

```
1: $t$ = min{ k, $|N_1(S)|$ }
2: let $C_t = \{rm_0, rm_1, ..., rm_{t-1}\}$
3: **if** $t == |N_1(S)|$ **then**
4:    assign nodes in $N_1$ radio-modes $rm_0, rm_1, ..., rm_{t-1}$
5:    return
6: **end if**
7: for each $rm_i \in C_t$ compute $Nrm_i$ - number of sensors in $N_1(S)$ with primary radio-mode $rm_i$, such that $|Nrm_i - Nrm_j| \leq 1$ for any $rm_i, rm_j \in C_t$
8: $U = N_1(S)$
9: **for** each radio-mode $rm_i$, $i$ = 0 to k-1 **do**
10:    /* assign the radio-mode $rm_i$ to $Nrm_i$ nodes */
11:    **for** each node x in U **do**
12:       $x.confl = 0$
13:    **end for**
14:    **for** i = 1 to $Nrm_i$ **do**
15:       pick up a node x in U with the smallest $x.confl$ value
16:       assign $x$ the radio-mode $rm_i$
17:       $U = U - \{x\}$
18:       **for** each node $y$ in $U$ which is neighbor of $x$ **do**
19:          $y.confl = y.confl + 1$
20:       **end for**
21:    **end for**
22: **end for**
```

Algorithm 3 AssignRadioMode(v)

```
**if** $v$ receives a radio-mode assignment $rm_i$ in the message *SinkRMSet*$N_1$ **then**
   wait a random time and broadcasts *RMSet*(v, $rm_i$, TTL = 1)
   assign the radio-mode $rm_i$ to its radio after sending *RMSet*
   return
**else**
   set a waiting time $t_{wait} = Time(v_{hops})$
   record radio-modes assigned by neighbor nodes based on *RMSet* messages received
   when $t_{wait}$ expires, $v$ examines the recorded neighbor radio-modes and select a radio-mode, let us say $rm_i$ (see explanation in the text)
   wait a random time and broadcasts *RMSet*(v, $rm_i$, TTL = 1)
   assign the radio-mode $rm_i$ to its radio after sending *RMSet*
**end if**
```

sensor nodes in $N_1(S)$ using the algorithm *SinkAssignRadioModes*N_1*(S)* which is explained next.

The sink computes radio-modes for the nodes in $N_1(S)$ using the function *ComputeRadioModes*N_1*(S)*. If $t == |N_1(S)|$, then each node in $N_1(S)$ receives a different radio-mode $rm_0, rm_1, ..., rm_{t-1}$.

If $|N_1(S)| > k$, then $t = k$. There will be multiple nodes in $N_1(S)$ with the same radio-mode assigned. Line 7 computes Nrm_i - the number of sensor nodes in $N_1(S)$ to be assigned the radio-mode rm_i, for i = 1 to k. The objective is to balance the number of sensors that use each radio-mode, thus $|Nrm_i - Nrm_j| \leq 1$ for any $rm_i, rm_j \in C_t$. For example if $|N_1(S)|$ = 10 and $k = 3$, then $Nrm_0 = 4$, $Nrm_1 = 3$, and $Nrm_2 = 3$.

The radio-modes $rm_0, rm_1, ..., rm_{k-1}$ are assigned in order. We denote by U the nodes in $N_1(S)$ which have not been assigned a radio-mode yet. Nodes are selected from U in a greedy manner, choosing the one with the smallest conflict in each iteration. In order to update the conflict values, the information in $N_1(S)$ and $N_2(S)$ is needed by S.

After all the nodes in $N_1(S)$ have been assigned radio-modes, S broadcasts a message *SinkRMSet*N_1*(S,* $N_1(S)$*, radio-modes assigned to* N_1*(S), TTL =* 1*)*.

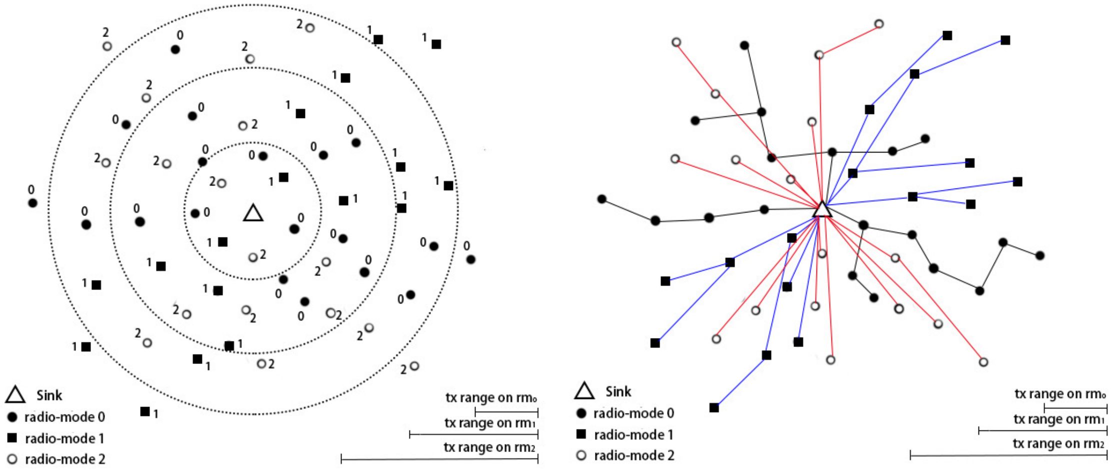
Each sensor node v assigns a radio-mode using the procedure *AssignRadioMode(v)*. If the node $v \in N_1(S)$, then it receives the *SinkRMSet*N_1 message from the sink, which contains the radio-mode selected by S for v.

All other nodes assign their radio-modes in increasing order of their distance (number of hops) to the sink. Once a sensor selects its radio-mode, it broadcasts a *RMSet* message, informing its neighbors of its radio-mode decision. After broadcasting the *RMSet* message, the node configures its radio to the new radio-mode selected.

A node v sets up a waiting time t_{wait} during which it waits to receive messages from neighbors. t_{wait} is proportional with the distance to the sink v_{hops} - the number of hops to the sink. The waiting time is computed as $Time(v_{hops}) = v_{hops} \times hopDelay$, where $hopDelay$ is the delay per hop and it must account for the propagation delay, algorithm execution time, and the maximum waiting time of a node before sending the *RMSet* message. In this way the nodes at distance 1 will set up their radio-mode first, followed by the nodes at distance 2, then 3, and so on.

When the timer expires, the node takes a decision on selecting a radio-mode among those already advertised by the neighbors. Node v maintains a map with pairs containing node ID and radio-mode selected. The mechanism for selecting a radio-mode works as follows.

First, the objective is to distribute nodes on all topologies, so that messages are transmitted simultaneously on various radio-modes. We define a threshold value *th*, which is a small number, for example $th = 3$. If the map contains radio-modes assigned to less than th nodes, then the selected radio-mode is the one assigned to the smallest number of nodes. In case of a tie, a radio-mode



(a) Radio-mode assignment by the sensor nodes

(b) Multiple tree construction

Fig. 2. Example of radio-mode assignment by the sensors and trees construction.

is selected arbitrarily. For example, if node v has the map $\{(a, rm_0)$, (b, rm_1), (c, rm_0), (d, rm_2), (e, rm_0), $(f, rm_1)\}$ then v selects the radio-mode rm_2.

Let us consider the case when all the advertised radio-modes are assigned to at least *th* nodes in the map. Assume that the advertised radio-modes are $\{rm_{i1}, rm_{i2}, ..., rm_{ij}\}$. Node v computes the probability of selecting the radio-mode rm_{ir} as $p_{ir} = \frac{d_{ir}}{\sum_{x=1}^{j} d_{ix}}$, where $r = 1, 2, .., j$ and d_{ir} is the data rate of the radio-mode rm_{ir}. Once a radio-mode rm_i is selected, node v waits a random time to avoid collisions and transmits a *RMSet* message to inform neighbors of its selection.

At the end of this step, each sensor node v switches its radio to the selected radio-mode. Such an example is illustrated in Figure 2a, where $k = 3$. Each sensor node has selected one of the three radio-modes rm_0, rm_1, or rm_2.

Theorem Assuming that the initial topology is connected on rm_0, at the end of phase 2, when sensor nodes configure their radios to the newly selected radio-modes, the resultant overall topology is connected.

Proof: Take Figure 2a as an example first. The sink has 3 radios, each with radio-modes rm_0, rm_1, and rm_2. All sensors have assigned one of the radio-modes rm_0, rm_1, or rm_2. Sensors with rm_0 form a connected topology, which is connected to the sink. The same applies to radio-modes rm_1 and rm_2.

We claim that sensor nodes on a certain radio-mode rm_i form a connected topology, connected to the sink. First, all sensors use radio-modes among those used by the sink, so rm_i must be used by the sink for one of its radios.

We prove that each sensor v selecting a radio-mode rm_i is connected to the sink at the time it switches its radio to rm_i. The proof is by mathematical induction. Sensor nodes in $N_1(S)$ have the radio-mode assigned by the sink, thus they are connected to the sink after switching their radio-mode. Let us consider a sensor node v. It builds a map containing pairs with neighbors and the radio-mode selected. In the inductive step, we assume those neighbors are connected to the sink using the corresponding modes.

When v selects one of the radio-modes in the map, let us say rm_i, it automatically becomes connected to at least one node in the map, let us call it u, which is connected to the sink on the radio-mode rm_i. It should be noted that since v and u are neighbors using rm_0, they remain connected when both u and v switch to rm_i since the transmission range $tx_i \geq tx_0$. It follows that v is connected to the sink after switching to the radio-mode rm_i.

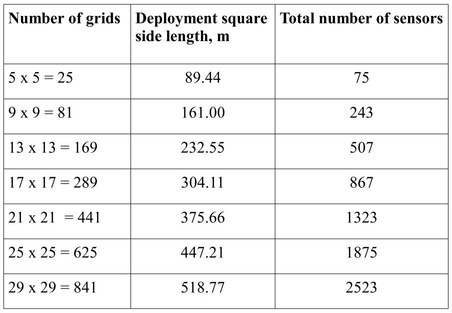
C. Data Gathering

The data gathering protocol explained in this section the uses shortest-path routing. This protocol can be replaced accordingly by a more sophisticated protocol, as required by the WSN application.

As discussed in the previous sections, each sensor node has assigned one of the radio-modes rm_0, rm_1, ..., rm_{t-1} and the sink has k radios, where $t \leq k$. The sink sends messages *SetParent*(S, rm_i, hops = 0) on each of the t radio-modes using the transmission range corresponding to each radio-mode. The transmission range varies with the frequency: for higher frequencies the transmission range is smaller.

Each sensor-node receiving the *SetParent* message for the first time (or with a shorter distance) sets-up its parent node (on the same radio-mode) and the number of hops to the sink. Then it increments the variable *hops* and retransnmits the *SetParent* message. Figure 2b shows three resulting data collection trees, each on a different radio-mode, after each node sets up its parent.

Data generated by sensor nodes flow to the sink along the t trees, using the parent node as next hop.



Number of grids	Deployment square side length, m	Total number of sensors
5 x 5 = 25	89.44	75
9 x 9 = 81	161.00	243
13 x 13 = 169	232.55	507
17 x 17 = 289	304.11	867
21 x 21 = 441	375.66	1323
25 x 25 = 625	447.21	1875
29 x 29 = 841	518.77	2523

Fig. 3. WSN deployment parameters.

IV. Simulation

In this section we use ns-3 network simulator [2] to evaluate the performance of our RMA distributed algorithm. We compare RMA with data gathering in traditional WSNs, when all nodes are using the same radio-mode.

A. Simulation Environment

The current ns-3 release does not provide full support for wireless IEEE 802.15.4 networks. To test our algorithm, we used IEEE 802.11 2.4 GHz band with the following radio-modes:

- *radio-mode 0* on channel 1, tx range 40m , DSSS rate 11Mbps
- *radio-mode 1* on channel 6, tx range 101m, DSSS rate 5.5Mbps
- *radio-mode 2* on channel 11, tx range 151m, DSSS rate 1Mbps.

Our algorithm starts from the assumption that the network is connected when all nodes are using rm_0, that is the transmission range tx_0. For the sensor deployment, we divide the square area into a number of virtual grids with size $tx_0/\sqrt{5}$ and then deploy one sensor randomly in each grid. We deploy the rest of the sensors randomly in the whole square area. The deployment parameters are specified in Figure 3. The sink S is placed in the middle of the area.

In the RMA algorithm, after sensors switch their radio to the selected radio-mode, data gathering is performed along the shortest-paths. Each sensor node has a parameter p - the probability the node generates a data message in each interval. We consider two cases: $p = 100\%$ and $p = 30\%$. The size of messages varies between 100 and 2000 bytes. We run each simulation scenario 5 times using different seed values and report the average values in the graphs. Each simulation scenario is run for 20 seconds.

Beside the RMA algorithm, we test the case when the whole network uses the same radio-mode. For example, in the “radio-mode 0” case all the nodes assign their radio to the radio-mode 0. Data collection is performed along the shortest-paths as well.

B. Simulation Results

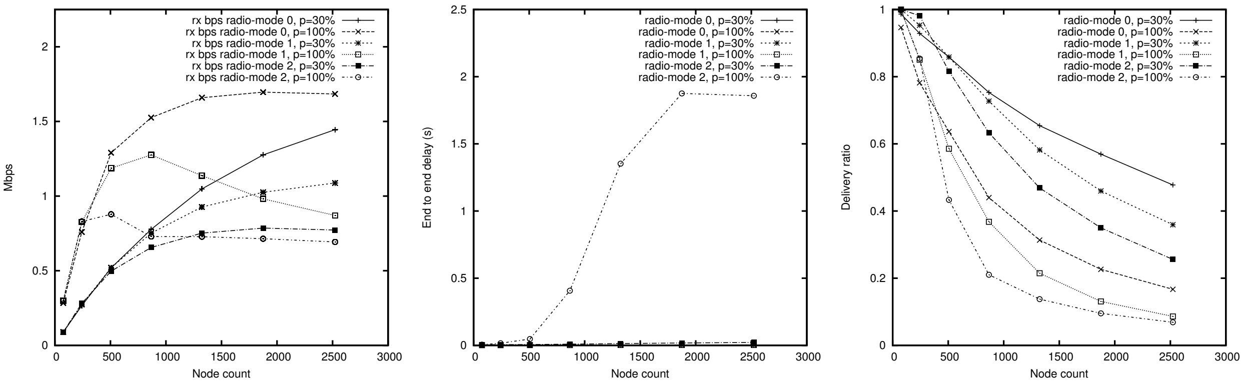
In the first experiment we compare traditional WSNs operating on a single radio-mode. In Figure 4 we compare radio-mode 0, radio-mode 1, and radio-mode 2 when message size is 500 bytes. Figure 4a shows the data throughput or received data rate at the sink. The highest throughput is received by the radio-mode 0, followed by radio-mode 1 and radio-mode 2. These are in the decreasing order of the data-rate of the corresponding modes. As the network becomes overloaded, queuing delays increase, triggering packets to be dropped.

Figure 4b shows the end-to-end delay which is computed as the average of the end-to-end delay of the messages received by the sink. Radio-mode 2 has the highest delay, followed by radio-mode 0 and radio-mode 1. The delays for the radio-modes 0 and 1 are comparable, and they are much smaller than the delay of radio-mode 2. The higher delay of radio-mode 2 with the data rate of 1 Mbps is due to the high queuing delays. The delivery ratio measurements in Figure 4c is consistent with the throughput results, showing a higher delivery ratio for radio-mode 0, followed by radio-modes 1 and 2.

For each mode, $p = 100$ has a higher throughput initially, but as the network becomes overloaded, $p = 30\%$ produces a higher throughput. The end-to-end delays are higher for $p = 100\%$ since the queuing delays are higher. The delivery ratio is higher for $p = 30\%$ since fewer packets are being dropped.

In the second experiment in Figure 5 we compare the four algorithms when we vary the message size $MsgSize$ = 100, 250, 500, 750, 1000, 1250, 1500, 1750, 2000 bytes. The number of sensors is $n = 1323$, $p = 100\%$, and the data generation interval is 1 sec. The aggregate network load on the x-axis is computed as $MsgSize * 8 * n/(interval * 10^6)$ Mbps.

Figure 5a shows the data throughput at the sink. RMA obtains the highest throughput since data are collected simultaneously on three radio-modes. The maximum throughput is obtained when the aggregate load is about 16Mbps, that is when the maximum network capacity given by the three radio-modes is achieved. This is followed by radio-modes 0, 1, and 2, which have the data rate in decreasing order.

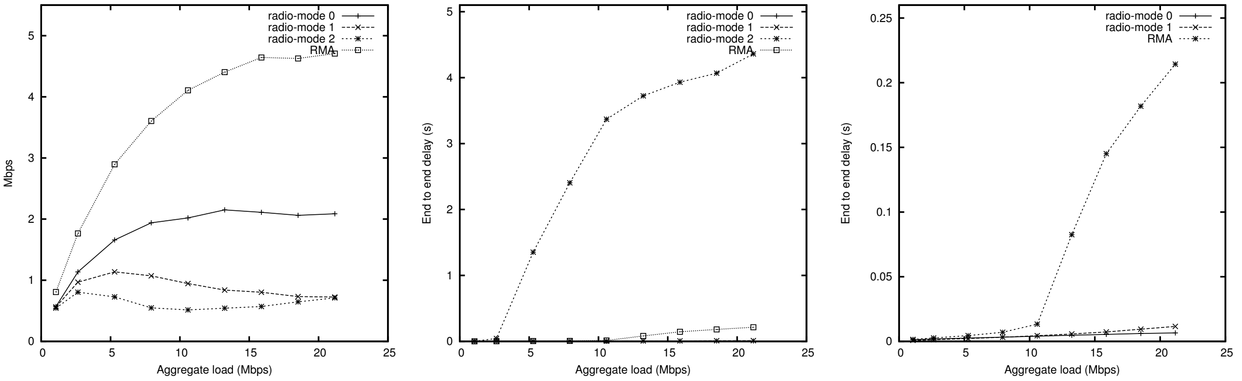


(a)

(b)

(c)

Fig. 4. Comparison of the algorithms when aggregate network load varies. (a)Data throughput. (b)End-to-end delay. (c)Delivery ratio.

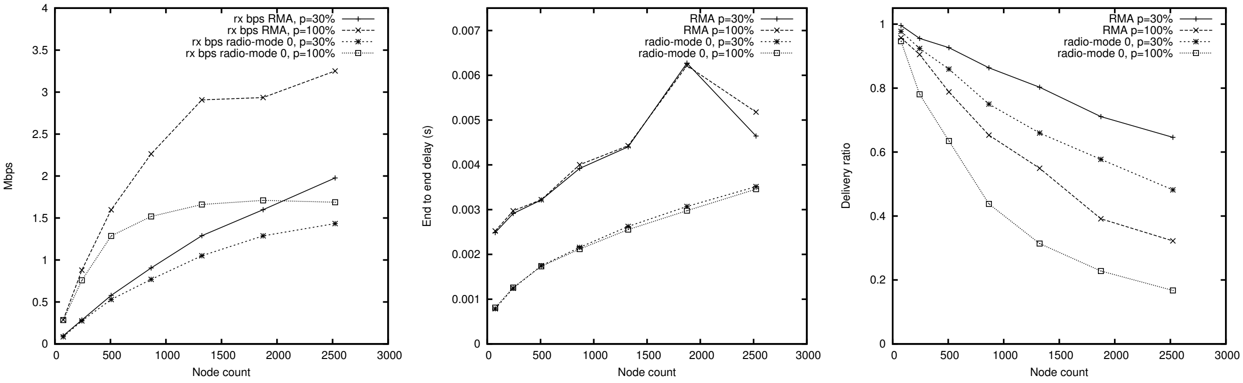


(a)

(b)

(c)

Fig. 5. Comparison of the algorithms when aggregate network load varies. (a)Data throughput. (b)End-to-end delay. (c)End-to-end delay.



(a)

(b)

(c)

Fig. 6. Comparisons between the RMA and radio-mode 0 algorithms. (a)Data throughput. (b)End-to-end delay. (c)Delivery ratio.

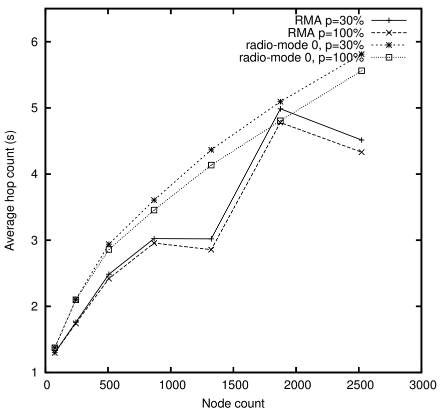


Fig. 7. Comparisons between the RMA and radio-mode 0 algorithms, average hop count.

Figures 5b and 5c show the average end-to-end delay of the messages received by the sink. Radio-mode 2 is excluded from Figure 5c in order to observe better the delay of the three other algorithms. The radio-mode 2 with the smallest data rate of 1Mbps has the largest delay. The network becomes overloaded and large queues in the nodes trigger a large delay. Next is the RMA algorithm, which has a much smaller delay than radio-mode 2 algorithm, but larger than the two other algorithms. This is due to the fact that RMA is a combination of the three algorithms.

Radio-mode 0 algorithm has a better performance than radio-mode 1 and radio-mode 2 algorithms when network has high traffic. In Figure 6 we compare RMA and radio-mode 0 algorithms when message size is 500 bytes. Figure 6a shows data throughput at the sink. RMA algorithm performs better than radio-mode 0, achieving a higher delivery rate. RMA achieves a better throughput since data is collected by the sink simultaneously on multiple radios operating on different radio-modes. $p = 100\%$ achieves better throughput than $p = 30\%$ since more packets are generated by the network.

In Figure 6b we observe that RMA has larger delay than radio-mode 0 which is consistent with the previous experiment. The case $p = 30\%$ has comparable delays with $p = 100\%$, and in general it depends on where the nodes generating the traffic are located.

Figure 6c shows the packet delivery ratio at the sink. The result is consistent with the data throughput measurements, showing a higher delivery ratio by the RMA algorithm. Figure 7 illustrates the average number of hops traversed by the packets received by the sink. RMA has a smaller hop count than radio-mode 0 since some of the sensors are working on radio-modes 1 and 2 with larger transmission range, thus a smaller hop count.

In summary, the simulations show the benefit of using the RAM algorithm compared to the case when only one radio-mode is used by the whole network. Current technologies allow the sink to use multiple radios and sensor nodes to use reconfigurable radios. Designing algorithms that collect sensor data simultaneously on multiple radio-modes reduce interference and increase throughput at the sink.

V. Conclusions

In this paper we propose a distributed algorithm that can be used by sensor nodes to assign radio-modes to their reconfigurable radios such that the resulting topology is connected to the sink. On top of this topology, data are gathered along the shortest-paths. Simulation results show that this framework produces a higher throughput and a higher delivery ratio compared to traditional WSNs.

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