Scalable Dynamic Routing Protocol for Cognitive Radio Sensor Networks

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***Abstract*— Wireless sensor networks (WSNs) have been increasingly considered an attractive solution for a plethora of applications. The low cost of sensor nodes provides a mean to deploy large sensor arrays in a variety of applications, such as civilian and environmental monitoring. Most of the WSNs operate in unlicensed spectrum bands, which have become overcrowded. As the number of the nodes that join the network increases, the need for energy-efficient, resource-constrained, and spectrum-efficient protocol also increases. Incorporating cognitive radio capability in sensor networks yields a promising networking paradigm, also known as cognitive radio sensor networks. In this paper, a cognitive networking with opportunistic routing protocol for WSNs is introduced. The objective of the proposed protocol is to improve the network performance after increasing network scalability. The performance of the proposed protocol is evaluated through simulations. An accurate channel model is built to evaluate the signal strength in different areas of a complex indoor environment. Then, a discrete event simulator is applied to examine the performance of the proposed protocol in comparison with two other routing protocols. Simulation results show that when comparing with other common routing protocols, the proposed protocol performs better with respect to throughput, packet delay, and total energy consumption.**

***Index Terms*— Opportunistic routing, wireless sensor networks, scalability, cognitive networking.**

I. Introduction

IN RECENT years, there is a tremendous growth in the applications of Wireless Sensor Networks (WSNs). The rapid convergence of advantages in digital circuitry, wireless transceiver, and microelectro-mechanical systems (MEMS), has made it possible to integrate sensing, data processing, wireless communication and power supply into a low-cost inch scale device. Consequently, the potential of an easily deployed and inexpensive WSN consisting of thousands of these nodes has attracted a great deal of attention. Inch scale sensor devices have been designed to work unattended with limited power requirements, for long periods of time.

One of the looming challenges that threaten successful deployment of WSNs is their energy efficiency with an increase of the network scalability. A number of sensor nodes can join or leave the network at any time while the workload of the network can be extremely high during some time frames. For instance, in monitoring applications and event tracking, when an event occurs the workload can increase dramatically. Moreover, many of the WSNs operate in unlicensed spectrum bands while the worldwide available and commonly used $2.4GHz$ band is shared by other applications such as bluetooth and WiFi. Hence, it is important for WSNs to explore additional capabilities in energy consumption and spectrum access.

Opportunistic routing with cognitive networking can alleviate the problem. In opportunistic routing, the path towards the destination changes dynamically following certain next relay node selection criterion. The selection criterion is crucial in every opportunistic routing protocol and it has high affect on the network performance. The distance from the destination, the node or the link availability are some of the common selection criterion while location information probabilistic forwarding and coding strategies always affect the performance of any opportunistic protocol [1].

Another promising solution is the use of Cognitive Radio (CR) technology along with the wireless sensor nodes. It is possible to apply Dynamic Spectrum Access (DSA) models in WSNs to provide them with access to less congested spectrum. In general, a Cognitive Radio Sensor Network (CRSN) can be defined as a distributed network of wireless cognitive radio sensor nodes, which sense event signals and collaboratively communicate their readings dynamically over available spectrum bands in a multihop manner to ultimately satisfy the application-specific requirements [2]. The combination of these two solutions can deliver promising results. Opportunistic routing principles are easy to be implemented in WSNs while the low-cost of inch scale device design with CR technology makes it a leading technology in the area.

In this work, we investigate the efficiency of an opportunistic routing protocol with cognitive wireless sensor nodes under a CRSN. *Cognitive Networking with Opportunistic Routing (CNOR)* [3], is presented in further details. The system model and the routing principles such as the neighbor discovery process, the packet transmission process and the route maintenance are also described. By the integration of opportunistic routing and DSA, we show how the cognitive networking approach can improve the quality of wireless communications, as compared to simple opportunistic spectrum access protocol, and geographic opportunistic routing protocol. A channel model was built and calibrated for this work. Simulation results are presented with performance evaluations and simulation analysis.

Manuscript received December 18, 2013; revised February 12, 2014; accepted February 12, 2014. Date of publication February 28, 2014; date of current version May 29, 2014. This work was supported in part by the Natural Sciences and Engineering Research Council of Canada and in part by an ORF-RE Grant. The associate editor coordinating the review of this paper and approving it for publication was Prof. Kiseon Kim.

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Digital Object Identifier 10.1109/JSEN.2014.2309138

The contribution of this work is summarized in the introduction of a novel opportunistic routing protocol for CRSN. Moreover a realistic channel model was built with the use of information from measurement campaigns with wireless nodes. Real data were collected with the use of a prototype of a wireless sensor node and used for experiments. The complexity of the proposed protocol is acceptable enough for a WSN network, however the cognitive aspects of the protocol may increase the cost per unit.

The rest of this paper is organized as follows: In Section II, the related works are reviewed. Section III describes the system model. The proposed protocol is presented in Section IV and the channel model is described in Section V. In Section VI, performance evaluation and simulation results are presented. We conclude in Section VII.

II. Related Works

Opportunistic routing has attracted much attention as it is considered a promising direction for improving the performance of wireless ad hoc and sensor networks [1]. Extremely Opportunistic Routing (ExOR) [4], introduces the idea by allowing the routers to use multi-path routes toward the destination according to the Expected Transmission count metric (ETX), which is based on the distance between the receiver and the destination. The shorter the distance the higher the priority. However the simple transmission mechanism might lead to duplicate packets.

In [5], a Geographic Random Forwarding (GeRaF) technique was introduced. In GeRaF, each packet carries the location of the sender and the destination, in order for the transmitter to prioritize the candidates nodes based on their location information. Similarly in [6] the nodes use location information to prioritize their relay nodes. These techniques are simple to be implemented but they require location information for all the nodes in the network. Hybrid ARQ-Based Intercluster Geographic Relaying (HARBINGER) [7], is a combination of GeRaF with hybrid Automatic Repeat request (ARQ). In GeRaF, when there is no forwarder within the range of the sender node, everything must start over again while in HARBINGER hybrid ARQ is used for a receiver to combine the information accumulated over multiple transmission from the same sender. Coding-Aware Opportunistic Routing Mechanism (CORE) [8], is an integration of localized interflow network coding and opportunistic routing. By integrating localized network coding and opportunistic forwarding, CORE enables a packet holder to forward a packet to the next hop that leads to the most coding changes among its forwarder set. In [9], a distributed adaptive opportunistic routing scheme for multihop wireless ad hoc networks is proposed. D-AdaptOR performance is shown to be optimal with zero knowledge regarding network topology and channel statistics. In [10], an Energy Aware Opportunistic Routing (EAOR) was examined. These approaches make use of opportunistic routing for wireless network, without integrating cognitive networking concepts. Apart from the distance between the communicate nodes, in the literature other works focus on parameters such as shadow fading [11]–[13].

In cognitive networking, a spectrum aware routing is proposed in [14]. Spectrum Aware Mesh Routing (SAMER), opportunistically routes traffic across paths with higher spectrum availability and quality. SAMER tries to balance between long-term route stability and short-term opportunistic performance. In [15], a Spectrum Aware Opportunistic Routing (SAOR) algorithm is introduced. SAOR uses an Opportunistic Link Transmission (OLT) metric, which is a combination of transmission delay, packet queueing delay and link access delay. By introducing channel access probability to characterize the opportunistic CR link, Multi-channel Spectrum Aware Opportunistic Routing (MSAOR) [16], improves the performance of SAOR. In [17], a novel opportunity-heterogeneous Cognitive Sensor Network (CSN) model is presented and redened the problem of spectrum sensing in CSNs from a joint spatio-temporal two-dimensional detection perspective.

In this work, we try to fill the gap between opportunistic routing and cognitive networking for WSNs. We propose an opportunistic routing protocol with opportunistic spectrum access for WSNs. A selection criterion is introduced, that has been designed by taking into consideration the limited computational capabilities and the limited energy resources of the wireless sensor nodes. The proposed network address mechanism is simple. A packet reception rate has been assigned to each communication link. A realistic channel model is used to evaluate the performance of the proposed protocol while the network scalability is changed. Although considering only the transmission distance may lead to inaccurate models [18], in this work a comparison between the calibrated and real results have show very similar and accurate performance.

III. System Model

In this section the basic functionality of the system model is presented. The network address mechanism is described, followed by the radio implementation of the wireless sensor nodes. The link model is also discussed.

A. Network Address Mechanism

The network address of each sensor node in the network is subjected to a delivery criterion and is related to the distance from the destination node. Given the address of a node i, and the address of the destination node dst, the delivery criterion $c_{i,dst}$ should be locally obtained. Usually, in WSNs this delivery criterion is correlated with the distance between two nodes.

In the proposed protocol, the destination node broadcasts identity advertisement packets toward every sensor node in the network. This packet has the delivery criterion field $c_{dst,dst}$ equals to zero. On the reception of this packet, every sensor node i, updates the delivery criterion field according to its distance from the destination $c_{i,dst}$. When all the nodes have broadcasted all the packets, every node in the network knows its delivery criterion. As the network scalability changes, the nodes can update their delivery criterion locally. When a new node joins the network, it can estimate its logic address by acquiring the logic address of its neighbor nodes. When a node leaves the network or there is a different source node, the network addresses of all the nodes remain the same. Only if the destination node changes this network address mechanism should take place again.

After this, each node will advertise identity packets periodically, depending on the application. For instance, in a monitoring application, the time the identity packets are sent is related with the event occur probability. If a node is no longer available in the network, this node will not participate in any future transmission. In order to have a unique network address this address is also related to a hardware product number. Hence, any node that joins the network can not use any network address from a previous node.

B. Radio Implementation

Cognitive radio is an ideal-omnipotent radio for user centric communications because it takes into consideration all the available parameters. In [19], two propositions were further suggested for large-scale wireless networks:

i) Collision avoidance with other simultaneous on-going transmissions can be achieved when the radio can sense the spectrum resource, opportunistically, before any transmission.

ii) Useful information for local cooperation can be extracted by opportunistically polling one or more proximity radios onto the selected spectrum.

With the above proportions, the concept of cognitive radio can be extended to the area of cognitive network, which implements both dynamic spectrum and radio access. The proposed protocol is based on these propositions and the radio nodes that are used for simulation implement these two ideas.

C. Link Model

There are three major factors that can affect the successful transmission of a packet between any two nodes: *channel availability*, *channel access priority* and *packet reception ratio*.

1) Channel Availability: In a link between two neighbor nodes there is a number of available channels N_{ch}. When a node has a packet to transmit, it will search for the available channel between all these N_{ch} channels. If all the channels are occupied, the node has to wait for the next available channel. The number of the channels N_{ch} should be carefully selected. A large number of channels may not be useful while it can lead the nodes to spend time and energy on sensing all the channels. On the other hand, a small value in N_{ch} will not take full advantage of the cognitive radio concept.

2) Channel Access Priority: When a channel Ch_i, is free, a number of nodes that have packets to transmit will compete for this channel. When a node is transmitting over a channel, none of the nodes in its transmission range can use this channel. As a consequence, the priority criterion is crucial. In this work, the distance from the destination was used as a priority criterion. The node which is closer to the destination, according to its network address, will have the highest priority to access the next available channel.

3) Packet Reception Ratio: When a node sends a packet to a neighbor node over a channel Ch_i, there is a Packet Reception Ratio (PRR) for this channel. To simulate a realistic channel model for lossy WSNs with Binary Phase-Shift Keying (BPSK) without channel coding, the log-normal shadowing path loss model derived in [20], was used:

$$PRR(L_f, d_{i,j}) = (1 - \frac{1}{2}\exp^{-\frac{\gamma(d_{i,j})}{2\times 0.64}})^{8\rho L_f} \tag{1}$$

where L_f is the length of the frame, $d_{i,j}$ is the distance between the transmitter node i and the receiver node j, $\gamma(d)$ is the Signal to Noise Ratio (SNR) and ρ is the encoding ratio. The Received Signal Strength Indicator (RSSI) measurements can be used to determine the SNR, as in [20]. RSSI measurement campaigns were conducted and will be described in Section V-D. The main goal of these campaigns is a more realistic calculation of *PRR*, following Eq.1.

IV. CNOR: Cognitive Networking With Opportunistic Routing Protocol

The proposed Cognitive Networking with Opportunistic Routing (CNOR) protocol for scalable WSNs, tries to combine the advantages of opportunistic routing and opportunistic spectrum access (traditional cognitive radio). It is a *reactive* routing protocol since it discovers routes only when desired. An explicit route discovery process takes place only when it is needed. In CNOR, that process is *destination-initiated*. The destination node of the network begins the route discovery process and this process ends when a routing path has been established while a maintenance procedure preserves it until the path is no longer available or desired. As the network scalability is increased, CNOR tends to discover more paths leading to the increase of the network performance.

In CNOR, multiple paths between the source and the destination are maintained. Packets can follow any of those paths, according to the dynamically changing network conditions, such as interference, channel and relay node availability. As the scalability of the network is increased, the number of the relay nodes also increases. Then, CNOR tries to discover more efficient paths towards the destination and increase the total network performance. Moreover, due to the probabilistic choice of the relay nodes, the protocol is able to evaluate different routing paths continuously and choose them according to the condition in every time slot.

A. Neighbor Discovery Process

Every sensor node i in the network knows its relative location, hence it can categorize the nodes around it into *neighbor node set* A_i, and *candidate node set* K_i.

Neighbor node set A_i of node i, is a set of all the nodes in the transmission range R of node i:

$$A_i = \{j \in S \mid d_{i,j} \leq R\},\ i \neq j \tag{2}$$

where S is the set of all the nodes in the network, $d_{i,j}$ is the distance between node i and node j and R is the transmission range of the node.

Candidate node set K_i of node i, is a set of those nodes that are in A_i and they are closer to the destination node dst than the transmitting node i. Candidate node set is a subset of neighbor node set, i.e. $K_i \leq A_i$ and can be defined as:

$$K_i = \{j \in A_i \mid d_{j,dst} \leq d_{i,dst}\}, i \neq j \tag{3}$$

The destination node initiates the neighbor discovery process by flooding a small packet to its neighbor node set. Every node forwards the packet to its neighbor node set and updates the delivery criterion field. In this way, the packet moves from the destination towards every sensor node in the network, with each node counting the delivery cost to the destination.

During this process, each node also creates a metric with the number of the neighbor nodes around it, A_i. When a node receives the same packet from different neighbor nodes, then it can count the number of the neighbor nodes. When all the sensor nodes in the network have transmitted the packet, the neighbor discovery process is over. After the end of the whole process, each sensor node in the network has all the necessary information to start data transmission.

B. Packet Transmission Process

After the neighbor discovery process, the packet transmission process from any node towards the destination can take place. There are four types of packets: *DATA*, *Acknowledgement (ACK)*, *Request To Send (RTS)* and *Clear To Send (CTS)*. Every packet transmission is subjected to the PRR, as in Eq.1.

When a node i has a packet to transmit toward the destination node dst, there is a *RTS/CTS* handshake between the transmitter node i and the nodes at its candidate set K_i. The transmitter search for an available channel Ch_i, floods a *RTS* packet over one available channel and waits for time T_{RTS} or till the first response. Since the transmitter floods the *RTS* packet to every neighbor node in its A_i set, it might get a response from a node that belongs in A_i but not in K_i. In this case, the transmitter will ignore the response and will accept response only from nodes in its candidate set K_i. The transmitter will wait for the response at the same channel Ch_i. Depending on the network conditions and the distance between the transmitter and each neighbor node, some of the nodes in the neighbor set will receive the *RTS* packet. Before the node i retransmits the data, it has to wait for time:

$$T_{RTS} = \left(\frac{RTS_{size} + CTS_{size}}{T_{tr}} + (2 \times T_{pd}) \right) \times \exp(A_i) \times C_0 + SIFS \tag{4}$$

where RTS_{size}/CTS_{size} is the size of *RTS/CTS* packet, T_{tr} is the transmission rate, T_{pd} is the propagation delay needed to reach a node placed at the limit of the transmission range R of the transmitter and $SIFS$ is the *Short Interframe Space*, the small time interval between the *RTS* and *CTS* transmission.

After time T_{RTS} the transmitter assumes that the *RTS* packet was lost and it retransmits it. In CNOR protocol, as the number of the neighbor nodes A_i is increased, T_{RTS} also increases so the transmitter will wait longer for a response. This way, there is enough time for all the neighbor nodes to reply to the *RTS* before the transmitter assumes the *RTS* packet has been lost. Hence, energy is saved since avoid retransmissions.

On the reception of a *RTS* packet, neighbor node k will respond with a *CTS* packet to node i, if it is available for immediate packet transmission and there are no other packets waiting to be transmitted. Before the transmission of the *CTS* packet, neighbor node k will wait for time:

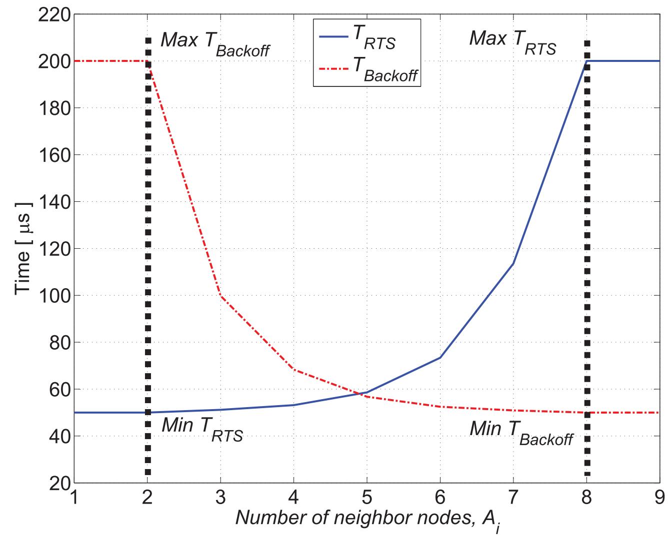


Fig. 1. T_{RTS} and $T_{Backoff}$ when the communicating nodes are in 10m distance. Maximum value in this configuration is $200\mu s$ and minimum $50\mu s$.

$$T_{Backoff} = \frac{C_1}{(d_{i,dst} - d_{k,dst}) \times \exp(A_i)} + SIFS \tag{5}$$

where $d_{i,dst}$ is the distance between the transmitter node i and the destination node dst, $d_{k,dst}$ is the distance between the neighbor node k and the destination node dst and C_1 is a constant. In order for a node to reply with a *CTS* packet before the transmitter broadcasts the same *RTS* packet, from Eq.4, C_1 should be smaller than *SIFS*, i.e. $C_1 \ll SIFS$. Moreover, as the number of the neighbor nodes increases, the $T_{Backoff}$ decreases. There are more available neighbor nodes, hence the backoff time for each of them should be smaller, so they can reply to the transmitter node on time, before the end of T_{RTS}.

From Eq.4 and Eq.5, it can be inferred that for a specific distance from the transmitter and as the network scalability changes, there is an optimal number of neighbor nodes that can minimize the total time spent on T_{RTS} and $T_{Backoff}$. Fig. 1 shows an example for a specific configuration. There are maximum and minimum values of T_{RTS} and $T_{Backoff}$. Maximum value of T_{RTS} is to ensure that a node will not wait after an upper bound limit for a *CTS* packet, even under a high network density. This value is the same with the maximum $T_{Backoff}$ of a network with low density. The minimum value of $T_{Backoff}$ is to ensure that there is enough time for the node to process the packet before it replies with a *CTS* packet. This value is the same with the minimum T_{RTS} which is the minimum time needed only for one node located in the limits of the transmission range to reply with a *CTS* packet. *CNOR* tends to be as close as possible to that number under different network densities by taking into account the average number of the neighbor nodes when each node calculates those times.

After that time, neighbor node k will check if the channel Ch_i is available, in order to respond with a *CTS* packet over the same channel as the *RTS* packet. If the channel is unavailable, it will wait. Since the *CTS* packet transmission is also subjected to the PRR, some packets might be lost.

On successful reception of a *CTS* packet, the transmitter will forward the *DATA* packet to the node that replied first with a *CTS* packet and will ignore any consequent *CTS* packets for the same *DATA* packet. However, it can use all the *CTS* packets for the same *DATA* packet to update the A_i metric for future transmissions. The *DATA* packet transmission will take place again over the same channel as the *RTS/CTS* handshake and the transmitter will wait for an *ACK* for this *DATA* packet.

When a node transmits a packet, it will store a copy in its buffer and will wait for the *ACK*. The time that the node will wait for an *ACK* can be determined as:

$$T_{ACK} = \frac{DATA_{size} + ACK_{size}}{T_{tr}} + (2 \times T_{pd}) + SIFS \quad (6)$$

where $DATA_{size}/ACK_{size}$ is the size of the *DATA/ACK* packet. If there is no *ACK* after T_{ACK}, following Eq.6, the node will transmit the *DATA* packet again. Each intermediate node follows the same packet transmission process. Consequent packet transmissions might use different paths and different channels. This process continues till all the packets reach the destination node.

In Eq.5, $T_{Backoff}$ is inverse proportional to the difference $d_{i,dst} - d_{k,dst}$. Thus, the neighbor node that is closer to the destination will have the smallest $T_{Backoff}$ and will try to reply first with a *CTS* packet. Any *CTS* packet that will arrive to the transmitter after the first one, will be ignored. Any neighbor node that is still during its $T_{Backoff}$ and senses a *DATA* packet transmission, will drop the *CTS* packet for this *DATA* packet and go back to sleep mode. Moreover, $T_{Backoff}$ considers the number of the neighbor nodes. When the network density is high, the node should spend less time on waiting before replying with a *CTS* packet, as in Eq.5. On the other hand, the transmitter should wait longer for a *CTS* packet before retransmitting the data, as in Eq.4.

The selection criterion of CNOR is the distance between the node and the destination, enhanced with information about the network density. This selection criterion is easy to be implemented in WSNs which have limited capabilities. Each sensor node needs to know its own network address and the destination node network address to calculate the distance. The neighbor node metric can be obtained during the neighbor discovery process and is updated with the *CTS* packet responses without any extra overhead. If a sensor node joins or leaves the network the neighbor nodes will notice it immediately without the need of a neighbor discover process. Moreover, the opportunistic spectrum access increases the performance of the opportunistic routing. Before every packet transmission, the nodes sense for the best available channel. Packet transmissions can take place simultaneously while the number of the collisions is decreased. A flowchart of the CNOR protocol can be seen in Fig. 2.

C. Route Maintenance

Localized flooding is performed infrequently to keep all the information about the different routing paths updated. Sensor nodes, that are not participating in any transmission at a time slot, help collect maintenance information. This process also helps to check if any new node joins the network or any other node runs out of energy and stops operating. The nodes can then update their neighbor node metric.

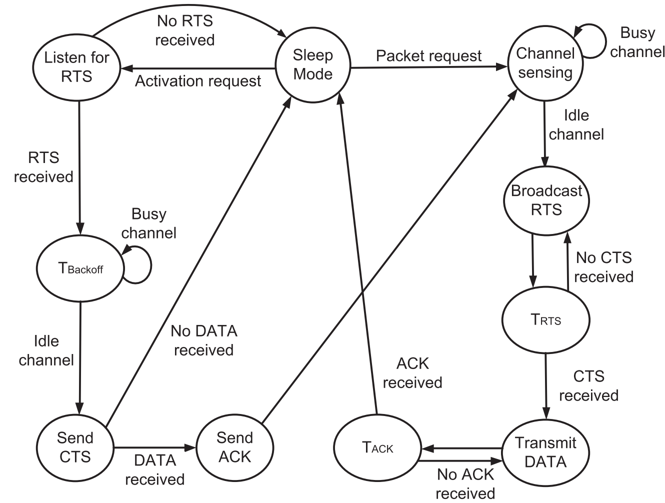


Fig. 2. Flowchart of the CNOR protocol.

V. Channel Model

The channel model was built in OMNeT$_{++}$ [21]. Inside a complex indoor environment similar to [22], multiple contributions between radio nodes are constructed by reflections, transmissions and diffractions on the building structures. In order to build an accurate channel model for a complex indoor environment, the initial channel model was calibrated with real time data. For the collection of the real time data, 24 radio nodes were used during three measurement campaigns.

The procedure can be divided into three phases: In the first phase, the dimension of the simulation area and of the different obstacles is measured. Then, the simulation area is built in OMNeT$_{++}$ and a simple channel model is implemented. In the second phase, nodes are distributed in a fraction of the simulation area. The nodes collect useful data for the available channels in different locations of the area, under different communication scenarios. In the third phase of the channel model procedure, the collected data are used to calibrate the simple channel model which was built during the first phase, for the specific environment.

A. Simulation Environment

The studied area is the 4^{th} floor of the Bahen Centre for Information Technology (BCIT) building located at the University of Toronto. The examined floor is a good example of a complex indoor environment and presents a lot of scatterers and obstacles such as walls, pillars, wooden doors, etc. These are of great influence when the radio links in such areas are examined. The channel modeling has to take into consideration those objects to correctly predict the communication link availability in the area.

A $3D$ Digital Building Model (DBM) of the simulation environment was built. It accurately represents every part of the building, including, floors, walls, doors, windows, etc.

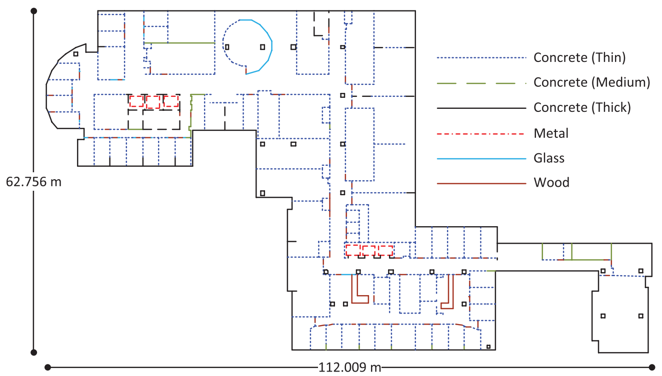


Fig. 3. Simulation Environment, the 4^{th} floor of *BCIT* building at the University of Toronto. It is a complex indoor environment with a number of classrooms, offices and open areas. The materials have been categorized into six types: Thin, medium and thick concrete, metal, glass and wood. Each material has a different effect on the wireless signals.

Each entity is described by its size – on the order of a few centimeters – and its material, the latter being used to calculate transmission, reflection and diffraction coefficients. The location of these partitions, their width and the material characteristics are obtained from architect plans and were further corrected using recent pictures taken in the field. The $3D$ DBM are available either on paper or in Computer-Aided Design (CAD) files. The location and width of all partitions are generally given with high accuracy, on the order of a few centimeters. The $3D$ DBM was used in order to design an accurate representation of the building in OMNeT_{++}. Fig. 3 shows the simulation environment with the different materials that will affect any wireless communication in the area.

B. Simple Channel Model

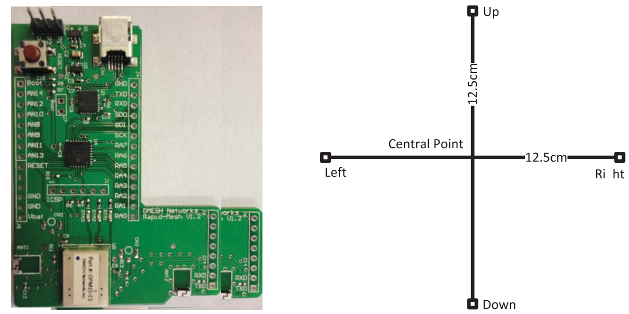
An initial channel model was built in OMNeT_{++} with the use of the DBM model. The simple obstacle model was used for the different wall materials. The simulation environment was described with the use of concrete walls, glass windows and wooden doors. This is the simplest description of a complex indoor environment, hence it was used as a simple channel model.

Since the simulation took place in a real environment, it was essential to make sure that the digital simulations accurately reproduce the real propagation of electromagnetic waves. To this aim, a measurement campaign with radio nodes has been realized, leading to the calibration of the initial channel model.

C. Cognitive Radio Nodes

OPM15 radio nodes from OMESH Networks [23], shown in Fig. 4(a), were used during the data collection. The OPM15 radio is based on IEEE 802.15.4 standard to realize OPM (Opportunistic Mesh) dynamic networking with multi-frequency. The communication rate is 250*kbps* and the frequency band is 2.4*GHz*.

A node could serve either as *stationary* or as *mobile* node. A *stationary* node frequently broadcasts data packets during the campaign. A *mobile* node moves around the stationary nodes and collects these packets. The collected data packets include the *RSSI* value from the different stationary nodes. The data were stored in a file with the *ID* of the stationary node, along with a timestamp of the measurement.



(a) (b)

Fig. 4. Measurement campaign equipment and orientation. (a) OPM15 radio node. (b) Five different positions.

D. Measurement Campaigns

Three measurement campaigns were contacted, simulating different communication scenarios. The novelty of the measurement campaigns is the use of the RSSI information from 2.4*GHz* wireless nodes to calibrate the channel model, as in Eq.1, instead of expensive Continuous Wave (CW) equipment. This approach may lack accuracy, but remains good enough for the purpose of this work. The different campaigns took place at the 4^{th} floor of the BCIT building, to study numerous effects along the corridors and the complex propagation situation.

Scenario 1*: Line-of-Sight path campaign.* For the *Line-of-Sight (LOS)* path measurement campaign, two radio nodes were used. One node served as stationary and the other as mobile. The mobile node kept recording data from different locations while the stationary node kept on broadcasting packets with RSSI data.

The stationary node was located at the one end of the central corridor of the floor. The initial distance between the two nodes was 1m. Ten different pairs of source and destination nodes were chosen. The distance between them was from 1m up to 10m, increased by 1m in every pair. A spatial averaging configuration was followed: for each distance, 5 locations were measured – central, left, right, up and down – for a more accurate measurement and better calibration. At 2.4*GHz*, the wavelength (lambda) is 12.5cm, hence each location is 12.5cm from the central. Fig. 4(b), shows the different positions of the mobile node at one location. For each location, the measurement lasts approximately 30 sec and an average number of 240 RSSI values were collected. Fig. 5, shows the variation of the RSSI values of the *LOS* path campaign for 5 distances between the communicating nodes.

Scenario 2*: Non-Line-of-Sight path campaign.* For the *Non-Line-of-Sight (NLOS)* path measurement campaign, 2 radio nodes were used. The communication between the radio nodes was corrupted by four types of obstacles. In the first case, the obstacle was a wooden door of the simulation environment. In the second case, the nodes were placed in

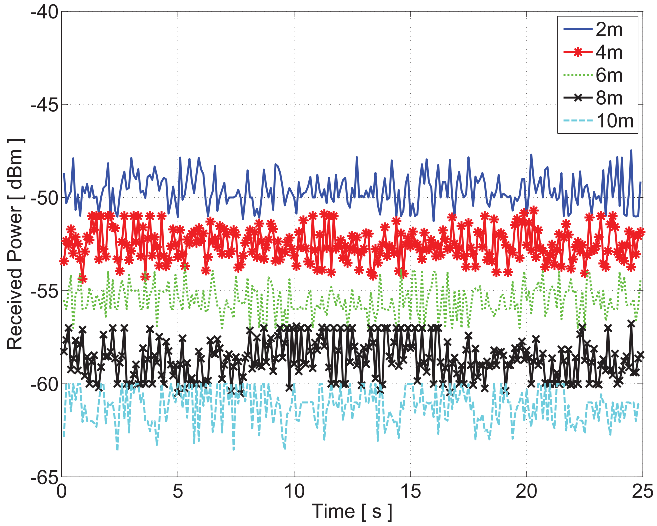


Fig. 5. Variation of the received power in time for a node located at the central point of the orientation in five different distances between the stationary and the mobile node during the *LOS* measurement campaign.

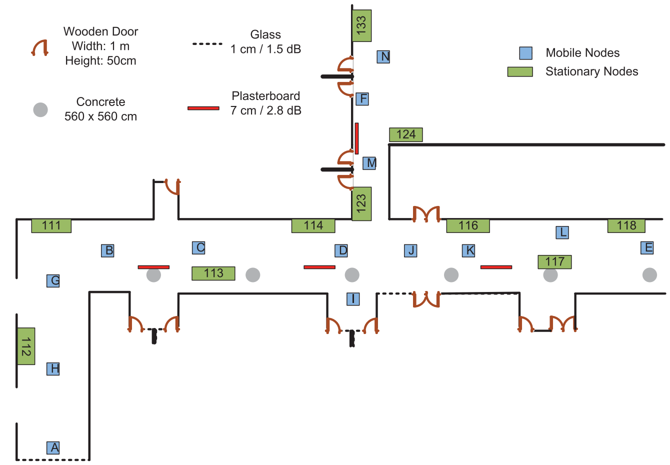


Fig. 6. The fraction of the building in which the building campaign took place. There are four different materials: wood and glass along with their size as well as concrete and plasterboard along with their attenuation values. There are also 10 stationary and 14 mobile nodes.

the opposite sites of a glass window while in the third case, a plasterboard was between the communicating node. In the forth case, the nodes were trying to communicate behind a concrete wall of the simulation environment.

In this campaign, one of the nodes was broadcasting packets and the other was recording the data. For each material, the distance between the nodes was increased till there was no communication between them. The initial distance between them was 1m and kept increasing by 20 on each site of the obstacle. In each location, the nodes remain for 1 minute and an average of 410 RSSI values were collected.

Scenario 3*: Building campaign.* This measurement campaign covered a large part of the central corridor of the floor. For the network data collection, 24 nodes were used and the communication between them includes *LOS* as well as *NLOS* paths. During the measurements, 10 of those nodes were used as stationary nodes. Those nodes continuously broadcast during the whole measurement. The remaining 14 nodes were mobile nodes. These nodes were moving around the stationary nodes and were collecting data. Each node collected data from any stationary node that it could listen to. The topology of the stationary nodes and the collecting nodes can be seen in Fig. 6. In contrast with the previous two campaigns, in this campaign many transmission were taking place simultaneously from the stationary nodes towards all the mobile nodes. The stationary nodes were scanning for the best available channel before any transmission while the mobile nodes were listening periodically to the different channels and recording the data.

The measurement time was 2 minutes for each location. RSSI information was collected from the mobile nodes and used to build the channel model. Between each communicating pair of stationary and mobile node, an average of 630 RSSI values were collected.

E. Calibration

The calibration is the connection between real measured data and simulated data. It is an essential step to produce realistic information through digital simulations. The main goal is to optimize the simulator to predict a specific metric, such as the received power, as close as possible to the measured data. The exact reproduction of the measured data from the simulated model is difficult because of the discrepancies between the real indoor environment and its digital representation, and because of the fluctuations of a time-variant channel. To measure the degree of exactitude of a model, the standard deviation of the metric difference for the various scenarios was calculated.

In the simple channel model, the description of the different materials and their impact on the communication links between the nodes is generic. After the measurement campaign and the collection of the real measured data, a more accurate description of the material and their impact on the radio was built. For example, it was found that the description of the concrete wall in the simple obstacle model in OMNeT$_{++}$ is not accurate enough to describe the material of the walls of the simulation environment. This description was tuned in order to provide results close to the collected data.

Another very important aspect of the calibration procedure is the readjustment of the floor map data. The best results would be obtained by drawing accurately every piece of furniture on the map. However, a trade-off has to be found between the computation time and the complexity of the map. During the calibration procedure, the points where the real and the simulated data had great difference, more than 5 *dBm*, were built again in the simulated floor map. The main reason for great differences was usually factors that affected the signals, such as electric panels inside rooms, which can not be predicted. The measurement campaign followed by the calibration procedure helped to tune the model in those points.

Fig. 7, shows a comparison among the data from the simple model, the mean value of the data from the LOS measurement campaign and the data from the calibrated channel model. In the LOS measurement campaign, the data points of the simple model follows Eq.1. Fig. 8, shows similar data for the building campaign. After calibration the standard deviation between the measured received power and the simulated

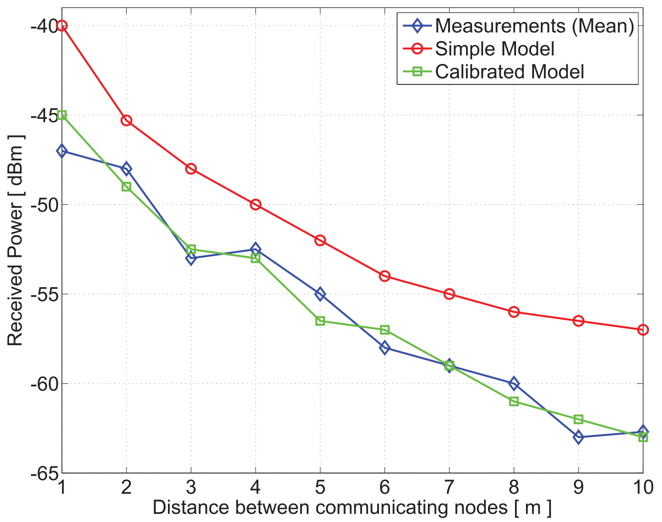


Fig. 7. Comparison of the LOS measurement campaign data with data from the simple model and the calibrated model that was built based on the mean of the measurement data. The standard deviation between the measured received power and the simulated received power is $\sigma = 1.26$.

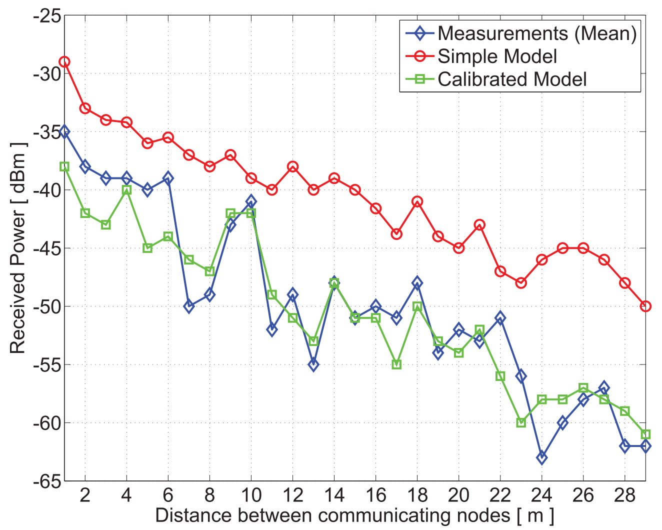


Fig. 8. Comparison of the building measurement campaign data with data from the simple model and the calibrated model that was built based on the mean of the measurement data. The standard deviation between the measured received power and the simulated received power is $\sigma = 2.85$.

received power for the LOS and the building campaign is $\sigma = 1.26$ and $\sigma = 2.85$ respectively. The low standard deviation indicates that the simulated points tend to be very close to the mean of the measured points, hence the calibrated channel is accurate enough for the purpose of the simulation. A RSSI measurement campaign leads to an accurate calibration of the initial simple channel model, for an indoor complex environment. With the calibrated model obtained, realistic simulations performed in the entire described area.

VI. Performance Evaluation and Simulation Results

In this section, we compare the proposed protocol with geographic opportunistic routing and simple opportunistic spectrum access routing in terms of throughput, packet delay and total energy consumption. Geographic opportunistic routing (GEOR), follows a similar approach with GeRaF [5], while every packet transmission is subjected to the PRR. GEOR uses only one channel. Simple Opportunistic Spectrum Access (s-OSA) tries to use multiple channels for packet transmission while it forwards the packet only over reliable links, i.e. links with PRR > 0.8. Identity packets were sent every 100 DATA packet transmissions.

TABLE I

Simulation Parameters

Parameter	Unit	Value
$DATA\ size$	*bit*	100×8
$RTS/CTS\ size$	*bit*	8×8
$ACK\ size$	*bit*	8×8
$SIFS$	μs	10
$TransmittingPower$	*mW*	15
$ReceivingPower$	*mW*	10
$TransmissionRate(T_{tr})$	*kbps*	250
C_0		10^5
C_1		10^{-6}

Indoor air quality data are used in the simulation. The data were collected with a wireless sensor node prototype, as described in [24].

The calibrated channel model was used as the wireless channel model. The destination node is located on the very east side of the floor map, Fig. 3. Every sensor node in the network can be a source node that collects and transmits data. The sensor nodes were randomly distributed over simulation environment, inside the classrooms and the offices as well as at the open areas. For every configuration, ten different source–destination pairs were simulated and below are the average simulation results. The communication parameters were chosen based on IEEE 802.15.4. All the simulation parameters are listed in Table I.

A. Throughput

Throughput is the number of bits divided by the time needed to transport the bits. From each of the 10 different source nodes 1000 packets were transmitted towards the destination. The network density was increased from 50 to 400 nodes leading to an average of 3 to 8 neighbor nodes. As the network density increases, the number of the active nodes that can transmit data increases. Fig. 9 shows the results.

The s-OSA routing protocol follows the most reliable links over multiple channels. As the network density increases, there are more reliable links for that approach. GEOR performs better than s-OSA because it tries to take advantage of the non-reliable links in the network as well. However, the use of one channel, makes that approach worse than CNOR. CNOR can achieve the highest throughput in comparison with the other two approaches because it combines the advantages of the other two. As the number of the nodes in the network increases, the number of the relay active nodes also increases, leading to more paths toward the destination. CNOR tries to follow the best available paths in every time slot, and it also uses multiple channels for the packets transmissions.

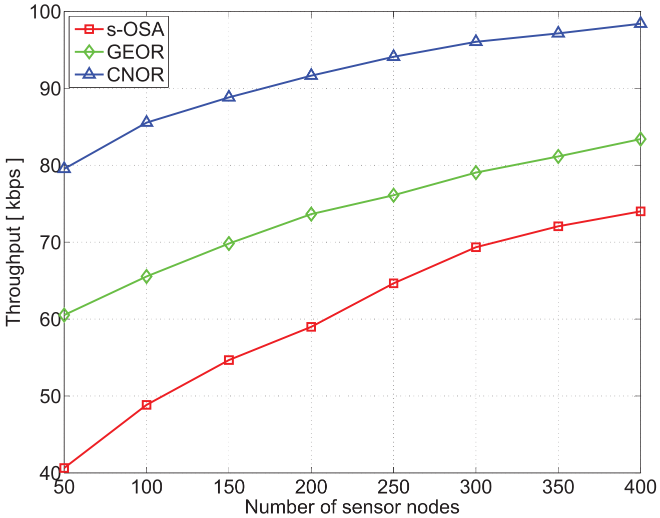


Fig. 9. Throughput under different network density.

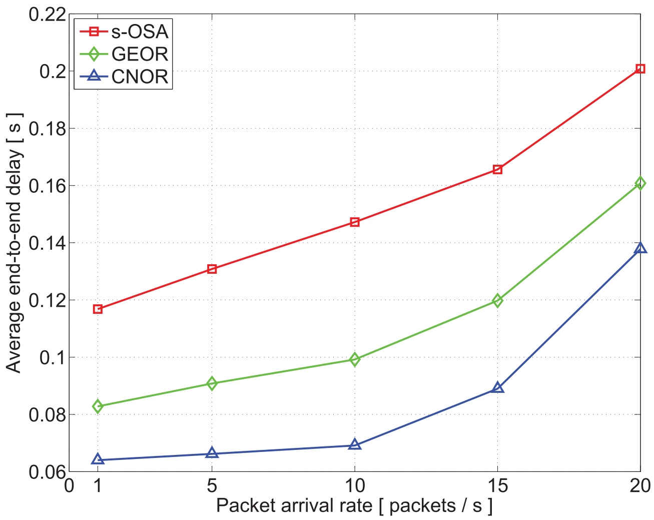


Fig. 10. Average end-to-end delay under different packet arrival rates.

B. Packet End-to-End Delay

End-to-end delay of a packet in the network is the time it takes the packet to reach the destination after leaving the source. Each of the 10 different source nodes sends 1000 packets toward the destination, in a network with 200 randomly distributed nodes and with 5 average neighbor nodes and a transmission time of $6.4ms$. Each node can store up to 5 packets in its buffer while if the buffer of a node is full, it can not participate in any packet transmission. The average end-to-end delay of the packets under different packet arrival rates is shown in Fig. 10.

When the packet rate is higher than the buffer size, the average end-to-end delay in all the three approaches is increased. The buffer of many nodes tends to be full, decreasing the number of the available relay nodes. The s-OSA uses only the most reliable channels for similar relay nodes while GEOR uses different available relay nodes at the same channel. The introduced CNOR protocol has the best performance in terms of average end-to-end delay. As the number of the packets per second increases, this approach tends to find multiple paths toward the destination and over multiple channels, in order to keep the delay low. It tries to use all the available nodes and all the available channels. This approach uses nodes with available slots in their buffer while nodes with full buffer are trying to forward their packets through multiple channels to a number of neighbor nodes.

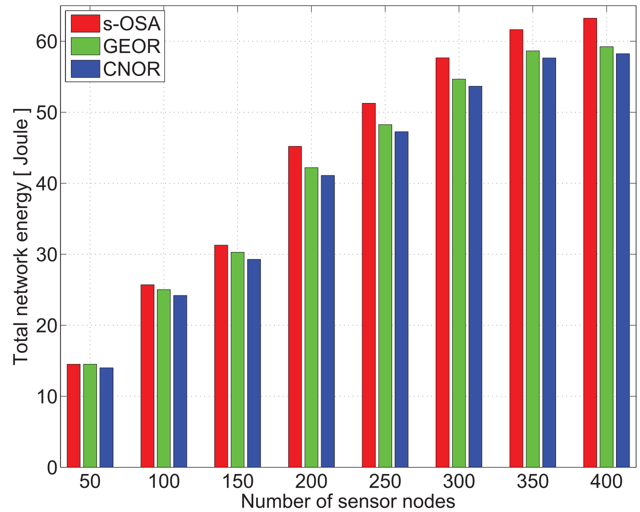


Fig. 11. Total energy consumption under different network density.

C. Network Energy Consumption

Network energy consumption is the amount of energy consumed from all the nodes in the network. Every source node sends 100 packets towards the destination while the network density was increased from 50 to 400 nodes. Let the node power consumption in transmitting and receiving/idle modes be denoted by P_{trans} and P_r/i respectively. The sleeping mode power consumption is practically 1000 times smaller than P_{trans} and P_r/i, which is negligible [10]. Let $P_{trans} = 15$mW and $P_r/i = 10$mW. For each distance, there are 4 different destination nodes. The energy consumption during the identity packets transmission is also considered, but it is negligible compared with the total energy. Fig. 11 shows the results.

As the number of the nodes in the network is increased the total energy consumption is increased. The s-OSA protocol keeps using the same relay nodes and the number of the collisions is increased. As a consequence, the number of the retransmissions is also increased leading to a high total energy consumption. The GEOR protocol performs better than s-OSA because it uses different relay nodes. The number of the necessary retransmissions is decreased and the total energy consumption is lower than s-OSA. The CNOR protocol performs slightly better than GEOR. In this approach, when a node is active and has a number of packets to transmit, it can forward them over multiple channels without the need to go back to sleep mode if the channel is occupied, as in GEOR. Although in CNOR the nodes spend some energy on scanning the different channels, the total energy consumption is lower than the other two approaches, as it is shown in Fig. 11.

VII. Conclusion

In this paper, a cognitive networking with opportunistic routing for WSNs is introduced. The protocol dynamically changes the paths and the channels that are used for transmission, to quickly adopt to any changes of the network scalability. The performance of the proposed protocol is compared with a simple opportunistic spectrum access protocol and a geographic opportunistic routing protocol. An accurate channel model, calibrated with real collected data, is built to evaluate the signal strength in different areas of the environment. The introduced protocol is shown to be the most efficient in terms of throughput, packet delay and energy consumption in a complex indoor environment. The introduced protocol can quickly adopt to any change in the network scalability while keeping the complexity and the implementation acceptable enough for WSNs.

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