Multichannel Cross-Layer Routing for Sensor Networks

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***Abstract*—This paper proposes a new multi-channel tree building protocol for ad-hoc sensor networks. Our protocol alleviates the effect of interference which results in improved network efficiency and stability, link reliability and minimised latency. Our proposal takes into account all available channels to utilise the spectrum. It checks the condition of all the channels before deciding on a channel to switch into. The successful transmission rate of the channels are stored externally from the sensors which can be accessed when require. This information is used to limit the channels to be considered when channel switching is invoked. The channel that is selected is checked for any changes in its condition that might had taken place after it was checked previously before committing to the channel. The results and decisions are informed to the other nodes to update their neighbour table. We use two-hop colouring protocol to avoid collision. Our protocol is inspired by the routing protocol for low power and lossy networks (RPL). Packets will be sent to the destination the same way as a single channel RPL but with less loss. All nodes are battery operated except for the LPBR. This enables a centralised channel switching processes at the LPBR. The channel switching processes take place after the topology is formed to further improve the transmission rate on the best paths. We implement and evaluate our solution using the Contiki framework. Our experimental results demonstrate an increased resilience to interference, significant higher throughput making better use of the total available spectrum and link stability.**

I. INTRODUCTION

Sensor networks have to contend with an increasing number of devices that cause wireless interference. Organising the network topology around this interference becomes an enabler for increasing transmission efficiency at a smaller energy cost. Wireless Sensor Networks (WSN) typically use low power radios such as IEEE 802.15.4, a relatively short range transmission standard radio technology in the 2.4Ghz band. The standard allows transmission to occur on several different channels within this band. Unfortunately, the channels used by this technology often suffer interference, for example, from WiFi and Bluetooth. WSNs need to be able to operate reliably in the presence of such interference.

The IETF standard IPv6 Routing Protocol for Low-Power and Lossy Networks (RPL) is a routing protocol for WSN based on IEEE 802.15.4 that allows nodes to self-organise a communicating network of neighbouring nodes. In its most usual mode of operation, RPL operates with a layer two which uses only a single channel. In this paper, we develop a cross-layer multi-channel protocol which allows a centralised intelligence to determine which channels each node should listen on and ensures that their neighbours send on the correct channel. The protocol also introduces a probing phase that checks whether assigned channels are free of interference. This protocol is tested using a two-hop colouring protocol that ensures nodes located within two hops of each other in the network are listening on different channels (that should reduce interference between physically proximate nodes trying to communicate on the same channel). The system is fail safe in the sense that the WSN functions if the central system which assigns channels fails temporarily or permanently.

Multichannel communication in wireless networks can alleviate the effects of interference which, as a result, can improve the network efficiency and stability, link reliability and minimise latency. It also enables communication between physically proximate nodes to occur simultaneously without the risk of collision if the communicating nodes use different channels. However, not all channels are free from interference, thus, there is a need to hop to another channel when the quality of the channel deteriorates. Two commonly used types of channel hopping [23] are blind channel hopping and whitelisting. In blind channel hopping, nodes choose from all available channels. Whitelisting on the other hand, filters out those channels that may have bad interference properties. Many studies make use of channel whitelisting such as [23] which claimed that channels 11, 15, 25 and 26 are free from Wi-Fi [25]. Chrysso [12] uses channel 11, 14, 20, 22 and 26, and MiCMAC [1] uses channel 15, 20, 25 and 26. It is clear that it is impossible to find a single channel guaranteed free from interference and there is no consensus on the best channel to use. Our work takes into account all available channels to utilise the spectrum and checks the condition of the channels before hopping to avoid those channels with interference.

Several previous studies have developed a multichannel MAC layer but, despite the potential benefits none are yet widely implemented in real world deployments. The usual focus is on MAC layers that operate in an autonomous fashion. This paper focuses instead on a cross-layer multi-channel model where a centralised controller can make and communicate decisions about channels and this decision is implemented by the MAC layer. The protocol provides feedback when a channel is subject to interference using a probing phase. The nodes are given different channels by a centralised controller behind the Low Power Border Router (LPBR). This means that the mechanism for assigning nodes to channels can be aware of the entire topology and can use more advanced algorithms to choose which channels are assigned to which nodes. Nodes are given a listening channel and their neighbours must send to them on that channel. In other words, a node listens on a single channel but sends on many channels. The control messages are sent to the nodes on their usual listening channel as a unicast which eliminates the need for a separate control channel. The changes of channel occur after the RPL topology set up phase. We show that this allows the network to avoid channels with interference and we demonstrate in simulation that this greatly reduces the effects of interference. While our protocol has an overhead in terms of packets sent and in terms of set up time, the number of packets sent is still low overall and during the multi-channel set up phase the system is still capable of sending traffic, thus the network is still fully functional after RPL set up and during our protocol's channel changes.

The rest of the paper is organised as follows: Section II presents related work to multichannel protocols. Section III describes the key idea of our proposed protocol and the high-level design and the implementation of the protocol in Contiki. We describe and evaluate the experimental results in Section IV. Finally, we conclude in Section V.

II. Related Work

Radio duty cycling mechanisms can be classified into two categories; synchronous and asynchronous systems. A synchronous system is a system that requires a tight time synchronisation between the nodes. It uses time-scheduled communication where the network clock needs to be periodically synchronised in order for the nodes not to drift in time. Asynchronous systems on the other hand, do not require synchronisation but instead is a sender or receiver initiated communication. In asynchronous systems the nodes are able to self-configure without time synchronisation and this can have advantages. There are many studies done in multichannel for both categories. Multichannel synchronous protocols include MC-LMAC [11] which uses a time slot to transmit on a particular channel and Y-MAC [13], EM-MAC [17] and TSCH that depend on the neighbouring nodes to synchronise with each other. Multichannel asynchronous protocols such as MuChMAC [4], Chrysso [12], MiCMAC [1] and our protocol are independent of time slot and synchronisation.

ContikiMAC [6] radio duty cycling mechanism is the default radio duty cycling protocol in Contiki that is responsible for the node wake-ups period. ContikiMAC is a power-saving radio duty cycling protocol. It was proved to be efficient in a single channel [1], [7]. ContikiMAC uses periodical wake-ups to listen to the neighbours transmission packet. It has a phase-lock mechanism to learn the neighbours wake-up phase to enable efficient transmissions and a fast sleep optimisation in case of spurious radio interference. The sender uses the knowledge of the wake-up phase of the receiver to optimise its transmission. When a packet is successfully received, the receiver sends a link layer acknowledgement. The sender repeatedly sends its packet until it receives a link layer acknowledgement from the receiver. ContikiMAC relies on retransmissions for reliable transmissions. A Carrier Sense Multiple Access, CSMA is a MAC protocol that performs retransmissions when the underlying MAC layer has problems with collisions. When the sender does not receive the link layer acknowledgement, ContikiMAC with CSMA will retransmit the packets three times before dropping it from the buffer queue.

MiCMAC [1] is a ContikiMAC [6] channel hopping variant. On every wakeup cycle, the channel is periodically switched according to a pseudo-random sequence. MiCMAC introduces channel lock for the channel reception at the sender. There is a dedicated broadcast channel for a duration at every wake up period. Chrysso [12] is a multichannel protocol for data collection applications. The nodes are organised into parent-children groups where each parent-children uses two channels for transmitting and receiving packets. Our work also uses two separate channels as in Chrysso. Both parent and children nodes can hop to another channel when interference is detected based on the channel switching policies. If a node loses connectivity, Chrysso calls the scan mode to enable neighbour discovery over multiple channels. Chrysso functionality comprises a set of channel switching policies that interface to both the MAC layer and the network layer.

In order to maximise the use of multichannel in improving packet delivery, routing topology plays a big role in providing an optimised routing tree to the network that is scalable and energy efficient. There are many studies that were done on routing protocol such as LEACH [2], PEGASIS [15], CTP [9] and RPL which is designed largely based on CTP. Recent multichannel protocols such as MiCMAC uses RPL as the routing protocol. Chrysso uses Contiki collect which is a CTP-like data collection protocol in Contiki. We choose to use RPL as it is the standard for IPv6 routing in low power and lossy networks.

RPL is a gradient based routing protocol forming any-to-any routing for low power IPv6 networks. RPL topology is a Destination-Oriented Directed Acyclic Graph (DODAG), rooted at LPBR with no cycles. The root has the overall view of the network. The other nodes however, only has knowledge of its neighbours and default router. RPL is a rooted topology which any-to-any traffic is directed towards the root unless the common ancestor is found which the traffic is then routed downwards towards the destination. This strategy is used in order to scale large networks by reducing the routing overhead at the cost of increased hop count through common ancestor. In RPL terminology, the node distance to the root and other nodes is defined as the node's rank. RPL finds the path with the minimum number of transmissions that a node expect to successfully deliver a packet to the destination and switches only if it is less than the current rank to prevent frequent changes [8].

MiCMAC and Chrysso are fully distributed and allow the nodes to self configure and change to another channel when interference happens. The channels that the protocols can use are fixed to a subset of whitelisted channels. This contrasts with our protocol where the control decisions as to channel assignment happen behind the Low Power Border Router (LPBR). The LPBR, which is the point where a WSN connects to other networks, is fully powered and does not have the limited memory of low power nodes. In standard RPL this point in the system also has knowledge of the network topology that can be used in the decision making process. We are able to produce real time channel selection decisions where we can consider all available channels to be used in transmissions without blacklisting any of them.

Our proposed protocol takes into account RPL topology formation scheme and the control messages exchange between nodes that take place periodically to maintain the quality of the tree. We enable the RPL control messages to be sent through unicast in order to reduce unnecessary transmitting in broadcast. Our work makes use of RPL topology formation and improves on the channels of the nodes in the topology. Our protocol is a cross-layer protocol with a centralised coordinator that enables us to make real time decisions without being constraint by the layer capabilities. Our centralised LPBR has the intelligence in choosing the channel for the node as it has the full overview of the network. We also do not blacklist any channel as we do channel checking each time a channel change occur in order to have the update on the channel condition.

III. Multichannel Cross-Layer Routing Protocol

Multichannel Cross-Layer Routing Protocol (MCRP) concentrates on finding channels for nodes that are free from or have low interference. It allows the allocation of these channels in a way likely to minimise the chances of nodes which are physically near communicating on the same channel and hence reduce cross interference between different pairs of nodes.

A. Overview

The design of the multichannel protocol is based on several crucial observations:

- Channel assignment - Sensors have limited memory and battery capabilities. In order to maximise the sensors lifetime, a centralised LPBR that has larger memory and fully powered is used for decision making. LPBR has a complete knowledge of the topology which enables it to make good channel assignment decisions based on the criteria that are explained in the next section.
- Interference - External interference cannot be predicted, thus channels cannot be allocated beforehand as it varies over time and locations. It is impossible to determine a single channel that is free from interference at any location. Our protocol checks the channel condition each time before deciding on a channel change to reduce interference and maximise throughput.
- Frequency diversity - RPL is typically used with ContikiMAC which is a single channel protocol. By using multichannel, we increase the robustness of the network towards interference. However, applying multichannel to the existing RPL may hinder neighbour detection and RPL processes to maintain the network topology as it does not switch to the correct channel. We overcome this problem by enabling unicast in neighbour detection and RPL control messages.

Our cross-layer multi-channel protocol focuses on the network and application layer of the protocol. This allows channel assignment decisions to be made thoroughly without being limited by the low layer complexity. The channel assignment processes take place only after the topology tree has been formed by RPL and stabilised. The system has two parts: a central algorithm which can be collocated with the LPBR and selects which channel each node should listen on; and a protocol which allows the network to communicate the channel change decision, probe the new channel and either communicate the success of the change or fall back to the previous channel.

B. Channel Selection Strategy

The system we propose is general and any algorithm can be used at the LPBR to assign channels. In this paper we use a two-hop colouring protocol to select a channel to be assigned to a node. Channels are chosen in a way that ensures no nodes within two hops of each other on the network are listening on the same channel. This allows fair load balancing on the channels and reduces channel interference that could occur when two nearby nodes transmit together on the same channel. The nodes used in this paper have a transmission range of approximately 50 metres indoors and 125 metres outdoors. It could be the case, therefore, that many nodes in a sensor network are in the transmission range of each other and potentially interfered with.

As in standard RPL all nodes are initialised to channel 26 by default. The usual RPL set up mechanism is used to exchange control messages that are required to form an optimised topology before channel assignments can take place. The nodes will only be on the same channel once during the initial setup. Channel 26 is chosen as this is the usual RPL default initial channel since it often has fewer interference problems with WiFi and other sources. The studies in [12], [1], [23] use several channels in their experiments and have channel 26 in common.

In the two-hop colouring protocol, the LPBR chooses a node to which it will assign a channel to listen on. This selection is random from channels 11 to 26 (the full range available). The protocol checks neighbours and neighbours of neighbours to see if any of those are listening on this channel already. If any are, a new channel is picked from the remaining list of available channels. If the LPBR has knowledge of existing bad channels then those channels can be blacklisted. Knowledge of channel interference (gained by probing, see later description) can be used to decide that a channel should not be used. If a channel is found then the channel switching protocol is used (see section III-C). If no channel can be found meeting these conditions the current channel is kept.

The node selection algorithm must only attempt one channel change at a time. The protocol ensures that the channel change attempt will always result in a message returned to the LPBR either confirming the new channel or announcing a reversion to the old channel. Until one or other of these happens no new channel change will be made.

C. Channel Switching

Figure 1 shows the state machine for the channel switching protocol. As explained in the previous section, a choice of a new channel by the channel selection protocol causes a change channel message to be sent to the appropriate node. On receiving a channel change message a node N stores its current channel C and communicates to all its neighbours the new channel D it wishes to change to. Those neighbours will update their neighbour tables to ensure that they now send to node N on channel D. The node N now begins the channel quality checking process (see section III-D) with each neighbour in turn by sending them a probe request. If

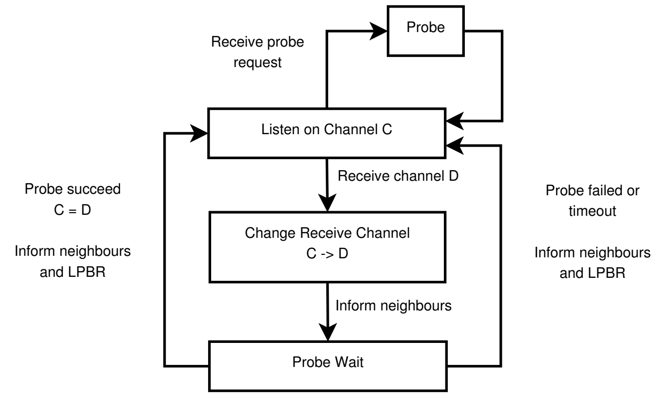

Fig. 1. Channel switching processes

this process fails for any neighbour then the node reverts to channel C. Node N informs its neighbours of this reversion to channel C and informs the LPBR of the channel checking results and its reversion to listening on channel C. If all channel quality checks succeed the node N. It is important to emphasise that the network remains fully functional and connected at all stages of this protocol (however, the channel checking process uses probe packets that might interfere with other transmissions temporarily).

D. Channel Quality Checking

In describing the channel quality checking process it is worth emphasising the RPL distinction between neighbours and tree neighbours. In RPL, node neighbours are all nodes that a given node knows it could transmit to. Tree neighbours are the nodes that a node does transmit to through the topology formed by the RPL protocol.

The channel quality checking is invoked each time a node changes channel after receiving a message from the LPBR. A node N changing to channel D informs all neighbours in turn, of the new channel D it will be listening on as described in the previous section. It then enters the Probe Wait state and begins channel quality checking with each tree neighbour in turn.

In the Probe Wait state node N sends a Probe message to each neighbour in turn. That neighbour will respond to the message by sending eight packets to N on the new channel D. If this process times out (because of some communication failure) or the number of probe packets received is below a threshold (currently set to seven) then node N immediately exits Probe Wait and reverts to channel C its previous channel. All neighbours are informed of the change back to channel C and the LPBR is informed of the quality check failure with a summary of all probes received. If, on the other hand, all channel quality checks succeed the change to channel D becomes permanent for node N and it informs the LPBR of the results of the probing (numbers of packets received) and the channel change.

Probing is an important part in making the channel change decision. It gives a quick overview of the channel condition based on the number of probing messages received. It is worth noting that probing is only done between the node and the tree neighbours. Neighbours that are not tree neighbours will not use the node as a route during their transmission thus, there is no need for probing to take place with those neighbours. However, the neighbours still need to know the channel value as RPL control messages are sent to neighbours directly without using the routes.

IV. Evaluation

The performance of MCRP is compared against the standard RPL with ContikiMAC on multiple channels.

A. Experimental Setup

We evaluate the protocol in the Cooja simulated environment with emulation of TMote sky nodes that feature the CC2420 transceiver, a 802.15.4 radio. The nodes run on IPv6, using UDP with standard RPL and 6LoWPAN protocols. The network consists of 31 nodes are used to run the simulation where we have 1 border router node, 16 interference node, and 14 duty cycled nodes that act as UDP clients to send packets to LPBR. RPL border router is used as LPBR in order to move most processing decisions on a PC as it has more RAM and better processing capabilities than a sensor. TelosB has limited RAM and ROM of 10K bytes and 48K bytes of flash memory. By using a border router, this allows channel changing to be decided in real time without draining the memory and battery on a sensor. The border router also acts as the root of the tree.

We simulated a controlled interference node that generates semi-periodic bursty interference to resemble a simplified WiFi or Bluetooth transmitter on several channels at random (see later). The interference model that we use is described in [3]. The interference has two states, a clear state and an interference state. In the interference state, the interference node generates packets for a time that is uniformly distributed between $9/16$ seconds and $15/16$ seconds. In the clear state the interferer produces no packets and stays in this state for between $3/4{*}$*clear_time* and $5/4{*}$*clear_time* where *clear_time* refers to the rate of interference (see later). We use multiple channels interference in our simulation to show our hypothesis that our multichannel protocol can help avoid interference. We consider the scenario where an RPL system is subject to interference on its channel after set up has successfully completed so the RPL set up is allowed to complete before interference begins.

We evaluate MCRP using an end-to-end packet delivery performance metric. The transmission success rate is calculated from the sender to the receiver over multiple hops. We also look at the loss over time to observe the protocol performance in the presence of interference. We considered two multiple channels interference scenarios; (1) extreme and no interference rate on 8 channels each and (2) extreme, moderate, mild and no interference rate on 4 channels each. The interference channels are chosen by random from the available 16 channels and the same interference channels and rates are used throughout the experiments. However, channel 26 is kept clear from interference in order to ensure RPL set up is unaffected. In scenario 1, we fixed the interference rate to extreme and no interference to observe the effect it has on channel changing decisions. In scenario 2, we vary the interference rate to observe how MCRP copes in deciding a channel when there are more interference than scenario 1 but with less interference intensity.

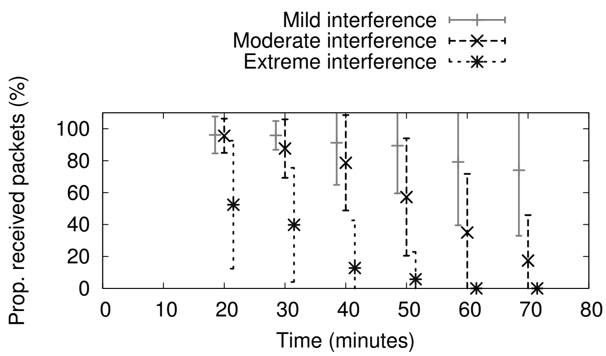

Fig. 2. Level of packet loss for mild, moderate and extreme interference levels using single channel

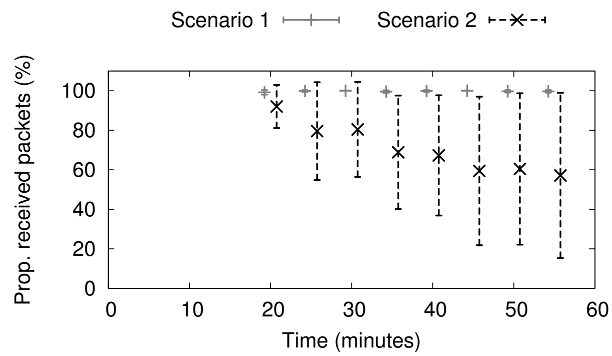

Fig. 3. Level of packet loss for scenario 1 and scenario 2 using multi channel

We run the simulation for a duration of 60 minutes to send 560 packets. When the nodes are switched on for the first time, all nodes are initialised to channel 26 by default. RPL is allowed five minutes to set up (which is ample time). RPL topology is formed in a minute. We wait for another 4 minutes to allow trickle timer to doubles the interval length so that RPL control messages are less frequently invoke. We then let our multichannel protocol runs for 10 minutes. In our 15 nodes simulation, our protocol takes 7-8 minutes to run the channel change set up. We allow another 2 minutes wait time if channel changes retransmission happen. In a single channel simulation, all the nodes are changed to channel 22 after 5 minutes of RPL set up time. This allows RPL to have enough time to discover all nodes to form an optimised topology. The topology formation does not formed completely if the interference node interferes from the beginning. The interference node starts sending packets to interfere after 3 minutes the system is switched on so that the interference channel is involve in the channel changes decision. We proved that our protocol tries to avoid from changing to the interference channel through time out and probing failures. After 15 minutes, the client nodes will send a normal packet periodically every 30-60 seconds to LPBR. This is done in order to avoid collision of the nodes sending at the same time. The simulation is repeated 10 times.

B. Packet loss rates with single channel RPL versus multi-channel

As described previously, levels of interference used (referred to as *clear_time* in [3]) vary between 100% (no interference), 75% (mild), 50% (moderate) and 25% (extreme) where the percentage is the ratio of the time the channel is clear for transmission. All our tests have a common format: the RPL procedure is allowed to set up without interference in order not to bias subsequent tests. Then the intereferers begin to operate with a constant level (none, mild, moderate or extreme). In the single channel case only that channel is used for interference. In the multi-channel case, different channels have different interference levels. All experiments are repeated ten times and the mean is plotted with error bars corresponding to one standard deviation in either deviation. The plots are of the proportion of received packets (from 0% to 100%) against time where the loss is measured over the previous time period. The x-value is shifted slightly left and right to prevent error bars overlapping

Figure 2 shows the results for the original RPL protocol. It can be seen that the level of packet loss varies considerably between experiments (the error bars are always large). It can also be seen that even for mild interference there is considerable loss and this gets worse as time proceeds. In the extreme interference case the loss always goes up until no packets are received. For mild interference the system evolves until it is losing around 20% of packets but this can increase.

For our new multiple channel protocol we consider two interference scenarios. In scenario 1 half the channels (including the original channel) have no interference at all and half the channels have extreme interference. In scenario 2, four channels (including the orginal channel) have no interference, four have mild, four moderate and four extreme interference. Figure 3 shows multi channel results for these two scenarios. In scenario 1 the protocol performs extremely well, the packet loss is near zero and the protocol successfully detects channels with interference. Scenario 2 has worse results but the protocol still does well at reducing the effects of interference. In this case the final result is somewhere between the mild and the moderate interference level of the single channel case showing that the protocol has picked some of the channels with the least interference. The variance in the results is, as with the single channel case, high. The worst results happen when nodes near the LPBR choose channels with higher interference levels (as those nodes carry the most traffic).

C. Setup Overhead

Obviously the system of changing channels and probing to see if a channel is free of interference introduces a certain amount of overhead into the protocol. This takes the form of (a) extra messages passed and (b) extra time taken to set up. Default RPL on ContikiMAC for the topology considered in these experiments completed its set up using 276 packets. Our multi-channel protocol completed its set up in 716 packets, that is an overhead of 440 packets on top of RPL. This overhead comes from the channel changing messages to nodes and neighbours, probing messages, channel confirmation messages and acknowledgement packets which are required to ensure a thorough channel change decision. However, it is worth mentioning that this is a one-off cost. This represents (in this experimental set up) approximately one hour of extra packets in the situation of a deployment that is meant to work for weeks or months. In terms of set up time, our protocol begins to change channels only when the RPL set up process is complete (or at least stablises). The set up time is 435 seconds beyond the RPL set up time of 286 seconds. However, it should be noted that, in fact, our system remains fully functional and capable of sending packets during the set up so this set up overhead does not matter to data transmission.

V. Conclusion

We presented MCRP, a centralised cross-layer protocol that mitigates the effect of interference by avoiding affected channels and allows better spectrum usage by trying to move nearby nodes to listen on different channel. The interference avoidance is through probing when moving to a new channel. The results from the simulation showed that our protocol avoids channels with interference and hence avoids packet loss. We also showed that this system works best when trying to avoid extreme interference

Future work is ongoing to develop the protocol. The next stages that we plan to pursue is to improve the interference model that we used in testing to cover multiple interference channels replicating the real world environment. The protocol will be tested against competing multi-channel protocols such as MiCMAC. We also plan to test our implementation on real hardware. Finally we will allow nodes to update the LPBR on packet loss experienced in order that changes to interference patterns in the network can be reacted to.

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