Multichannel Cross-Layer Routing for Sensor Networks

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Abstract—This paper proposes a new centralised 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 and aims to use the spectrum efficiently by transmitting on several channels. The protocol detects which channels suffer interference and changes away from those channels. We use two-hop colouring protocol to avoid collision. In order to maintain a link when a node changes its channel, all neighbours must be informed of the change. All nodes are battery operated except for the low power border router (LPBR). This enables a centralised channel switching process at the LPBR. Our protocol is inspired by the routing protocol for low power and lossy networks (RPL). In its initial phase, the protocol uses RPL's standard topology formation to create an initial working topology and then seeks to improve this topology by switching channels. We implement and evaluate our solution using the Contiki framework. Our experimental results demonstrate an increased resilience to interference, and significant higher throughput making better use of the total available spectrum and link stability.

I. Introduction

Wireless Sensor Network (WSN) is an ad-hoc network that consists of sensor nodes that typically use low power radios such as IEEE 802.15.4, a relatively short range transmission standard radio technology in the 2.4 GHz band. The standard allows transmission to occur on several different channels within this band [1]. Unfortunately, the channels used by this technology often suffer interference [4], [18], for example, from Wi-Fi [11], [29] and Bluetooth. Sensor networks have to contend with an increasing number of devices that cause this wireless interference. Organising the network topology around this interference becomes an enabler for increasing transmission efficiency at a smaller energy cost. WSNs need to be able to operate reliably in the presence of such interference.

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 [27]. It also enables communication between physically proximate nodes to occur simultaneously without the risk of collision when 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 [27] are blind channel hopping

and whitelisting. In blind channel hopping, nodes choose from all available channels. Whitelisting, on the other hand, gives a set list of 'good' channels that avoids those that are known to commonly suffer interference. Many studies make use of channel whitelisting such as in Chrysso [13] and MiCMAC [2]. However, they used different channels with channel 26 in common in their respective experiments.

It is notable that Chrysso and MiCMAC can use all available channels without whitelisting. However, they do not have a mechanism to check the channel condition before using it for packet transmission. MiCMAC sees its performance degraded when using more than 4 channels, thus the decision on specifying 4 channels to be included in their experiment. MICMAC uses a different channel chosen at random each time it wakes up ////CHECK AT RANDOM? OR IN TURN? ////TO CHANGE SENTENCE However, it might try to send on bad channels for a while before it finds a good channel to deliver the packet. Chrysso on the other hand, switches the affected nodes to a new set of channels upon detecting interference. It would require frequent channel switching if all channels are to be considered.

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. A possible explanation for this is that the existing solutions are too complex to implement and use, and require transmissions scheduling or synchronisation. The usual focus in a multi-channel communication is on MAC layers that operate in an autonomous fashion.

This paper focuses on a Multichannel Cross-Layer Routing Protocol (MCRP) which allows a centralised intelligence to make and communicate decisions about channels and this decision is implemented by the MAC layer. MCRP provides feedback when a channel is subject to interference using a probing phase. The protocol is tested using a two-hop colouring protocol to reduce interference between physically proximate nodes trying to communicate on the same channel. The system is failed safe in the sense that the WSN functions if the central system which assigns channels fails temporarily

or permanently.

We implement MCRP in Contiki and evaluate the protocol in Cooja simulated environment and in 26-nodes testbed FlockLab [16]. We demonstrate that MCRP avoids channels with interference which greatly reduces the effects of interference on the network.

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 [12], Y-MAC [14], and TSCH [22]. Multichannel asynchronous protocols such as EM-MAC [20], MuChMAC [5], Chrysso [13], MiCMAC [2] and our protocol are independent of time slot and synchronisation.

MiCMAC [2] is a ContikiMAC [7] channel hopping variant. ContikiMAC was proved to be efficient in a single channel [2], [8] which was the reason for MiCMAC to be based on it. In MiCMAC, on every wakeup cycle, the channel is periodically switched according to a pseudo-random sequence. Chrysso [13] 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. MCRP also uses two separate channels as in Chrysso. In Chrysso, both parent and children nodes can hop to another channel when interference is detected based on the channel switching policies. Chrysso functionality comprises a set of channel switching policies that interface to both the MAC layer and the network layer.

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. MiCMAC and Chrysso could use all channels, however, they do not have a mechanism for channel quality checking before a channel is chosen. It would be time consuming before it could find the interference free channel. This contrasts with our protocol where we are able to produce real time channel selection decisions by considering all available channels to be used in transmissions without blacklisting any of them.

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 have been many studies on routing protocol such as LEACH [3], PEGASIS [17], CTP [10], and RPL. Recent multichannel protocols such as MiCMAC is compatible with RPL as the routing protocol. Chrysso uses Contiki collect which is a CTP-like data collection protocol in Contiki. Chrysso is restricted to only data collection networks. We choose to use RPL as it is the standard for IPv6 routing in low power and lossy networks.

RPL [28] is a gradient based routing protocol forming any-to-any routing for low power IPv6 networks. The topology is set up based on the routing metric [26] such as hop count and expected transmission count (ETX) metrics to calculate the distance of the nodes to the low power border router (LPBR). RPL is a rooted topology where any-to-any traffic is directed towards the root unless the common ancestor is found in which case 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. By default, RPL uses ETX metric to find 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 [9]. Our protocol makes use of RPL topology formation and improves on the channels of the nodes in the topology.

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 to communicate 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 a two-hop colouring protocol.
- 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 - Multichannel increases 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 both broadcast on a default channel, and unicast, in neighbour detection and RPL control messages.
- RPL - In multichannel, sending a broadcast on every channels would waste the bandwidth. RPL messages are instead sent through unicast when the neighbours are known and broadcast in the default Contiki channel 26 in order to reduce unnecessary transmitting in broadcast. By sending a broadcast on only one channel on which the new neighbours are going to start, the nodes can be discovered and the channel change processes can be performed.
- Topology - The topology could change according to the routing metric the way the usual RPL would work. The nodes can still change the parents as usual as all neighbours know each other new channels. The neighbours that are not part of the route do not probe the parent when making the channel decision. However, the neighbours are informed of any channel changes.

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

One main advantage of the system we propose is it 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 20-30 metres indoors and 75-100 metres outdoors [21]. 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.

All nodes are initialised to channel 26 by default in Contiki since it often has fewer interference problems with Wi-Fi and other sources. The studies in [13], [2], [27] use whitelisted channels in their experiments and have channel 26 in common.
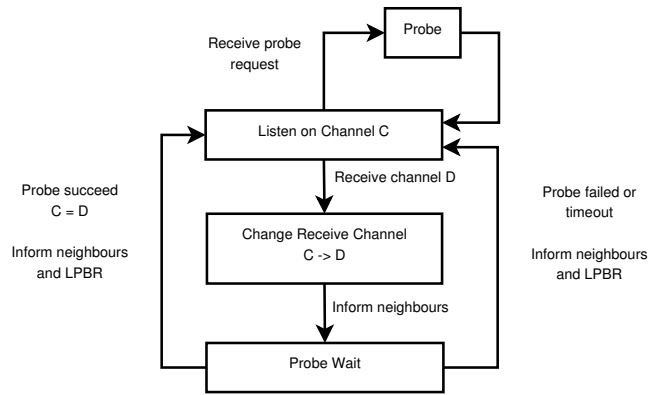

Fig. 1. Channel switching processes

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.

In the two-hop colouring protocol, the LPBR chooses a node to which it will assign a channel to listen on. The selection is random (from channels 11 to 26) based on the full range available [1]. 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 which is gained by probing can be used to decide that a channel should not be used. If a channel is found then the channel switching protocol is triggered. 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 to ensure probing is done on the correct new channel and for the node to finalise the channel to be used before another node tries to attempt a channel change. The protocol ascertains 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 to enable the neighbours transmitting on the correct channel.

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. Upon receiving a channel change message, a node N stores its current channel C and communicates to all its neighbours the new channel D that 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 begins the channel quality checking process with each neighbour in turn by sending them a probe request. If this process fails for any

neighbour then the node reverts to channel C. If all channel quality checks succeed, the node N will listens on channel D. In both cases, node N informs its neighbours of the decision to channel C or D and informs the LPBR of the channel checking results. The channel checking process uses probe packets that might interfere with other transmissions temporarily. However, it is important to emphasise that the network remains fully functional and connected at all stages of this protocol.

D. Channel Quality Checking

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 describing the channel quality checking process, it is worth emphasising the distinction between neighbours and tree neighbours. 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.

In the Probe Wait state, node N sends a Probe message to each neighbour in turn. The neighbours respond to the message by sending eight packets to N on the new channel D. The buffer can accommodate eight packets at a time. As the packets might not be sent immediately due to wakes up and collisions, sending more packets would have the risk of being dropped. Increasing the buffer size is not ideal as the sensor has limited memory capability. However, as the numbers of probing packets are small, the estimate value might not be accurate as the representation of the channel condition. The condition of the channel is further investigated through the number of retransmissions and packet collisions of the probing packets.

If the probing process times out (because of some communication failure) or the number of probe packets received is below a threshold (currently set to 16) then node N immediately exits Probe Wait and reverts to channel C its previous channel.

The threshold is set to be 16 (including retransmissions and collisions) to ensure that interference channels are avoided. If the threshold is not met, none of the node would change the channel as it performs better in its current 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 essential to make 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 given that 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 nodes, 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 [4]. 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.

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 [4]) 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
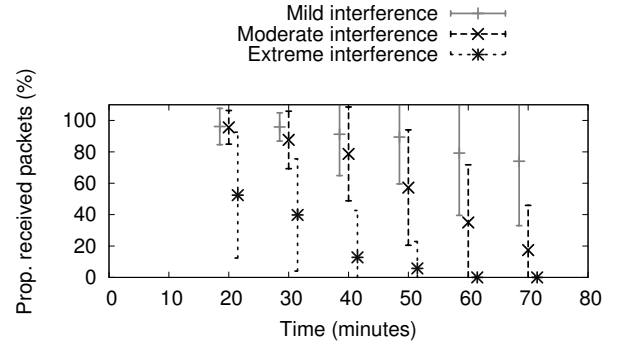

Fig. 2. Level of packet loss for mild, moderate and extreme interference levels using single channel
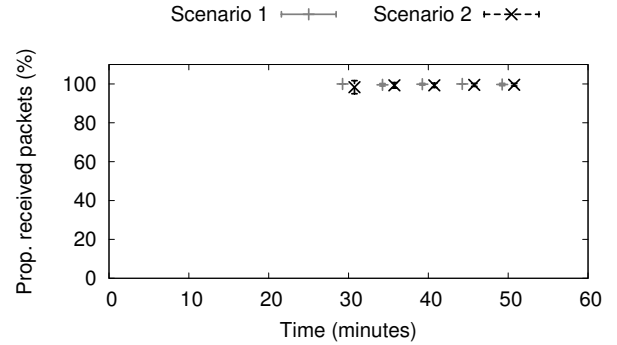

Fig. 3. Level of packet loss for scenario 1 and scenario 2 using multi channel

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

conclusion

Acknowledgments

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