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. Low power radios such as IEEE 802.15.4 are a relatively short range transmission standard radio technology in the 2.4Ghz band. Unfortunately, the frequency band is shared with WiFi and Bluetooth which cause problem for Wireless Sensor Networks that require minimal packet loss, interference and delay. 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. By basing our protocol in routing protocol for low power and lossy networks (RPL), packets can 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).

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. However, not all channels are free from interference, thus, the 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 [2] 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. 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 which also 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 mechanism can be classified into two categories; synchronous and asynchronous system. A synchronous system is a system that requires a tight synchronisation between the nodes. It uses a tight time-scheduled communication where the network clock needs to be periodically synchronise in order for the nodes not to drift in time. Asynchronous multichannel on the other hand, does not require synchronisation but instead, is a sender or receiver initiated communication. It requires simple set up and the nodes are able to self-configure without tight synchronisation which is more appealing. There are many studies done in multichannel for both categories. Multichannel synchronous protocols such as MC-LMAC [11] which uses 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 [5], Chrysso [12], MiCMAC [2] and our protocol are independent of time slot and synchronisation.

ContikiMAC [7] 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 [2][8]. 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 [2] is a ContikiMAC [7] 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 channel. Chryssos 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 which allow the nodes to self configure and change to another channel when interference happen. The channels that the protocols can used are fixed to several channels that were decided beforehand. Our protocol is centralised where most of the processes in channel assignment decisions are done by the LPBR. LPBR, which is the central point, is fully powered and does not have a limited memory. 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.

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 [3], PEGASIS [15], CTP [10] 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 [9].

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. Cross-Layer Multi-Channel Protocol

Cross-layer multi-channel protocol concentrates on finding the best channels for nodes to listen and transmit on, given policies that need to be complied.

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 opted. 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. We assume that no new nodes should join the topology after the initial setup.

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 once the topology tree has been formed by LPBR and stabilise.

B. Channel Selection Strategy

LPBR uses a two-hop colouring protocol to select a channel to be assigned to a node. This allows fair load balancing on the channels and reduces congestion on the channel that could occur when several nearby nodes start transmitting at similar time. A sensor node integrated an onboard antenna that covers a transmission range of 50 metres indoor and 125 metres outdoors between the sensors. Two hops from the node would cover some ranges between the nodes to reduce transmission interference to a minimum. This allows transmission to happen at the same time without the risk of packet loss due to collision.

However, at initialisation, all nodes are initialised to channel 26 by default. The nodes need to be on the same channel for neighbour discovery and enable RPL 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 the initial channel as it usually does not overlap with WiFi and is relatively in a cleaner frequency than the other channels. The studies in [12][2][23] use several channels in their experiments and have channel 26 in common.

In two-hop colouring protocol, LPBR chooses a random channel from channel 11 to 26 for a node unless LPBR has full knowledge of the channels condition. If LPBR has knowledge of all the channels, LPBR can limit the channels range to consider only channels that the node has used in the past that gives good transmission results. LPBR keeps the information of each node neighbours and channels in a table. Before LPBR sends a channel change message to the node, it runs the two-hop colouring protocol. It first checks if the node is LPBR neighbours. If it is, LPBR checks if the new channel value is the same as LPBR channel. If it is not, LPBR checks if the node is a neighbour of the other nodes. The new channel is compared with the current channel of the other node. If the channels are the same, the first hop of the two hop strategy has failed. LPBR will try going through the same steps with another new channel.

If the first hop succeeds, LPBR will check the nodes that are two hops away from the node the new channel is for. If the node is LPBR neighbour, LPBR checks the new channel value with all LPBR neighbours channels. Otherwise, the node neighbours neighbours channels are checked. If the channel values are not the same, LPBR will send the new channel value to the node to proceed with channel quality checking. If the two hops failed, LPBR retries with a new channel value. The steps from the first hop is repeated. LPBR tries to find the channel that is two hops free within four tries. If a two hops free channel is not found, the default channel 26 is used.

C. Channel Quality Checking

The channel quality checking is invoke each time the node receives the channel change message from LPBR. The node informs all the tree neighbours in turn, of the new channel it will be listening on. The tree neighbours will update their neighbour table to hold the new channel value as the node current channel for transmission. The node sends a message to the tree neighbour to send probes and switches to the listening channel ready to receive any incoming messages. The node's tree neighbour starts sending the probe messages to the node and the node collects the information on the success or failure rate of the channel. These information is then, sent to LPBR to updates LPBR's knowledge on the channel condition for the specific node and its neighbours. The node uses the results from probing to decide if the new channel is better than the current channel. All the neighbours and LPBR are informed of the decision and update the node's channel.

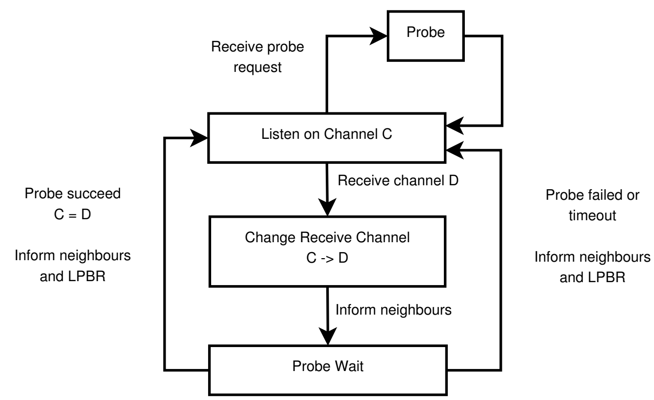


Fig. 1. Channel switching processes

A channel is not chosen as a good channel to change into either if it timed out or the probing messages received are below a threshold. The node will revert to the previous channel as it is better than the new channel selected. The interference channel might be used by some nodes if during the probing, all probing messages are received. The channel change will be invoked again in this case.

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.

D. Channel Switching

Figure 1 shows the states in channel switching. As explained in the previous sections, LPBR chooses a channel based on the two-hop colouring protocol and sends the change channel message to the node. The node saves it's current and new channel separately to allow the channel to be restored if require. The node contacts its tree neighbours and starts the channel quality checking. The channel that is decided on is informed to the neighbours and LPBR, and waits for acknowledgement. If the acknowledgement does not arrive after the timeout, the change channel confirmation message is retransmitted. The neighbour's node is ignored if the retransmissions has timed out.

IV. Evaluation

The results of our multichannel RPL protocol is compared against a single-channel tree protocol.

A. Experimental Setup

We evaluate the protocol in 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 16 nodes are used to run the simulation where we have 1 border router node, 1 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.

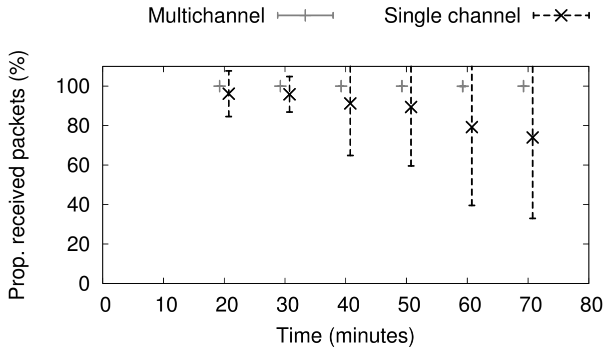
We simulated a controlled interference node that generates semi-periodic bursty interference to resemble a simplified WiFi or Bluetooth transmitter on channel 22. The interference model that we use is described in [4]. The interference has two states, clear state and interference state. In clear state where it does not do anything, the process stays in the state for a time that is uniformly distributed between $9/16$ seconds and $15/16$ seconds. In interference state, the interference node generates packets for a time that is uniformly distributed between $3/4{*}clear\_time$ and $5/4{*}clear\_time$ where *clear_time* refers to the rate of interference. We use a single channel interference in our simulation to show our hypothesis that multiple channels can help avoid interference where we consider a scenario where an RPL system is subject to interference on its channel after set up has successfully completed.

We evaluate multichannel RPL variant using 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 protocols react to interference and set up overhead.

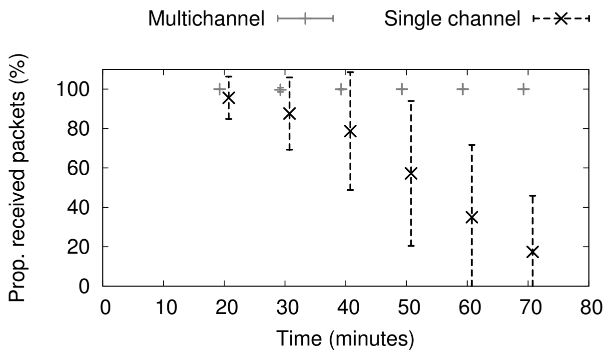
We run the simulation for a duration of 60-70 minutes to send 700 packets; 50 packets for each node. When the nodes are switched on for the first time, all nodes are initialised to channel 26 by default. RPL runs the initial network set up for a few minutes before it is stable. We set the RPL set up time to be 5 minutes. 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. Effect of Multi-channel

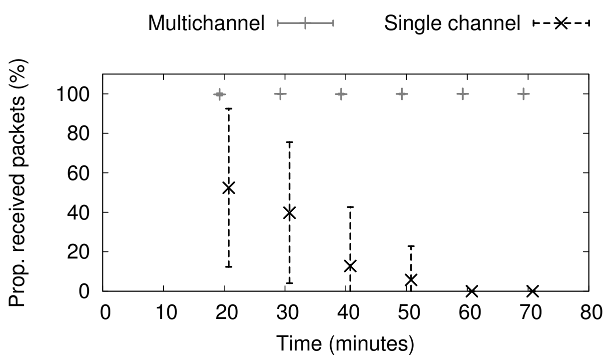
We vary the interference rate, which is referred to as *clear_time* in [4] to 100% (no interference), 75% (mild), 50%



(a) Mild Interference



(b) Moderate Interference



(c) Extreme Interference

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

(moderate) and 25% (extreme) where the percentage is the ratio of the time the channel is cleared from interference. The test is done to evaluate our protocol behaviour in different interference rate and to compare the result with a single channel case. Figure 2 shows the mean results from ten simulation runs in each scenario and the error bars represent the standard deviation. We observed that during high interference and moderate interference, when the LPBR generates a random two hop channel for a node to change into, the receiving node will probe on the channel. It will either time out or the probing messages received are less than a threshold that allows for the node to change it's listening channel to the new channel. This is as expected as our protocol checks the channel each time before deciding on the new channel to avoid interference channel. By doing this, we can be sure that the node listening channel is a good channel. This enables us to use all available channels without blacklisting any channel until we are sure it is a bad channel through our probing process. The channel quality table is built at the LPBR that over time, can be used to learn good and bad channels based on several probing processes.

In the mild interference case, all probing messages are received even though there are interference in that channel. This is because, the probing gives good result which means that the channel can be used. As the interference rate is mild, all packets are received. This is also the case with a single channel. The interference does not affect the transmissions as the interference is not frequent enough that enables the node to recover. However, the interference would slightly effect the packet transmission over time. We plan to run channel change processes periodically to avoid this from happening.

In the single channel, the system cannot cope with the interference and as time goes on the RPL topology cannot continue to function sending and receiving packets. Figure 2 shows that the rate of packet loss increases over time and when the interference is sufficient then packet reception will entirely stop sometimes within the first twenty minutes of the interference starting. Figure 2(a) shows that the single channel model can cope but has degraded performance when the interference is mild, but when the interference becomes moderate then more than half the packets are lost towards the end of the simulation period. When the interference is extreme, the packet loss increases to 100% in all cases.

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 281 packets. Our multi-channel protocol completed its set up in 844 packets, that is an overhead of 563 packets on top of RPL. 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 multichannel RPL, a centralised cross-layer protocol as an extension to the existing RPL with ContikiMAC. Our protocol mitigates the effect of interference by avoiding the affected channel through probing when deciding a new channel. The results from the simulation showed that our protocol avoided the interfered channel to maintain a high throughput over time.

We are continuing with the work to further develop this 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. We plan to replicate the interference model to closely represent the real world where interference happens at many channels. We also plan to test our implementation on real hardware and to allow continual updates on packet loss for each node so that the channels can be changed dynamically when interference occurs.

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