Maximising Throughput and Energy Lifetime in Wireless Sensor Networks

Noradila Nordin, Richard G Clegg, Miguel Rio

Abstract—**Wireless Sensor Networks (WSNs) are ad-hoc networks that consist of sensors that typically use low power radios to connect to the Internet. Unfortunately, the channels used by the sensors often suffer from interference from the other devices sharing the same frequency resulted in retransmissions and higher number of packet losses in addition to higher energy drain rate during the process. This paper presents a two step techniques to optimise multichannel sensor network in term of the throughput and energy lifetime to prolong the network functionality period. A multichannel cross-layer routing protocol is proposed to alleviate the effect of interference to improve the network efficiency, reliability and throughput. The protocol detects and changes the channels that suffer from interference through the channel switching processes. In order to prolong the network lifetime in addition to multichannel, the energy-based tree reconfiguration is proposed to find the optimal energy tree. It improves the overall network lifetime by balancing the sensors to use alternative routes based on the sensors current energy load. It shows an improvement of the sensors lifetime by 6.2 times than the initial. The experimental results demonstrate significant higher throughput that utilise the spectrum and enable the network to remain functional longer.**

Index Terms—**IEEE, IEEEtran, journal, LaTeX, paper, template.**

I. Introduction

Wireless sensor networks (WSNs) are widely used in various kinds of applications to collect data and measurements data from the sensors. The sensors are mainly deployed to track and monitor in different types of environments such as on the land, underground and underwater for continuous sensing, event detection, location sensing and other control over the different components of the sensing device. It is increasingly important to have reliable and energy efficient WSNs that could function for years as sensors are easily deployed in areas that are difficult to reach such as for volcanic monitoring, forest fire detection and flood detection. WSNs could help to enable automated services in smart cities to improve the environment quality, increase the energy saving and improve the lifestyle as WSNs simplify and reduce manual and labour work to automated systems. This is because sensors can be densely deployed, easy to install and require minimal maintenance over a period of time.

N. Nordin is with the Department of Electronic & Electrical Engineering, University College London, London, WC1E 7JE, UK (e-mail: noradila.nordin.12@ucl.ac.uk).

R. G. Clegg is with the School of Electronic Engineering and Computer Science, Queen Mary University, London, E1 4NS, UK (e-mail: richard@richardclegg.org).

M. Rio is with the Department of Electronic & Electrical Engineering, University College London, London, WC1E 7JE, UK (e-mail: miguel.rio@ucl.ac.uk).

Manuscript received April 19, 2005; revised August 26, 2015.

However, sensors suffer from limited hardware resources which only allow limited computational functionalities to be performed. Sensors also suffer from limited energy capacities as they are battery powered and will become faulty and not able to function once the certain threshold of energy level is reached. Sensors also operate in an unreliable radio environment that is noisy and error prone which drain the sensors batteries at a higher rate. These constraints have a major impact on the sensors performance. In order to prolong the sensors lifetime thus, the network lifetime, the sensors need to be able to cope with the limitations and be as energy-efficient as possible to guarantee good overall performance.

Many energy efficient protocols have been proposed in term of the MAC protocols, routing protocols, power control and energy harvesting to overcome the problems of interference to maximise the throughput and the sensors energy to prolong the network lifetime. MAC and routing protocols are the main protocols that control the network energy consumption to allow the network to remain functional for a longer period of time. While the other proposed solutions could increase the sensors residual energy, the energy saving depends on the MAC and routing protocols. There have been many proposals in multichannel MAC protocols that show promising results but none is widely implemented yet. In MAC protocol, the energy consumption can be reduced by adjusting the radio duty cycle to allow the sensors to be in the sleep mode when they are not used and to transmit on channels that have less interference to increase the likeliness of data success.

To further improve the efficiency, routing protocols are responsible to ensure high success rate in data routing from the sender to the intended receiver across the network. The routing protocols are required to manage and maintain the routes to ensure reliable communications between the limited range sensors. The routing protocols in WSNs are different than the traditional routing protocols due to the sensors limitations. Most routing protocols concentrate on the ability for scalability, reliability and adaptability to the network changes without emphasising the importance of residual energy as part of the vital design in a routing protocol.

By considering the overall network in optimising and balancing the routes to the sensors, overloading certain sensors that have higher throughput thus lower residual energy due to energy drain can be avoided. Implementing multichannel MAC protocol that uses a reliable and energy-aware routing protocol enables the overall network lifetime to be prolonged while maintaining high packet reception rate in WSNs.

The contributions of this paper are as follows. First, multichannel cross-layer routing protocol (MCRP)[1] for WSNs that was developed is briefly described for completeness which shows improved energy efficiency as it consumes on average, 6 times less energy during communications. Multichannel helps to increase the overall throughput by using interference free or minimal interference channels, however it does not consider the sensors lifetime during the decision making process. Multichannel routing tree optimisation is introduced which aims to extend the WSN lifetime by switching the routes that use the sensor with the minimum residual energy from their initial paths to other paths which from the experiments show an increase in the lifetime of the network by 6.2 times. The sensors are assumed to be on the good channels. The sensors have different transmission and reception channels.

This paper is organised as follows. Section II presents the related work, Section III defines the problem in WSNs and the approaches for optimisation. Section IV explains the multichannel cross-layer routing protocol and the improvements in comparison to a single and existing multichannel protocols. Section V describes the proposed energy-based tree reconfiguration for WSNs in detail and Section VI evaluates the performance of the proposed optimisation. Finally, Section VII concludes this paper.

II. Related Work

There are various definitions of network lifetime that have been used. These definitions are application-specific as some applications might tolerate a considerable number of loss nodes, while some applications require a higher number of nodes which any loss is considered critical to the network such as in sparsely deployed nodes of an area. The definitions impact the performance differently, depending on the applications. The network lifetime in this paper is defined as the first node to fail in the network.

Network lifetime is strongly related to the remaining energy of all nodes. Typically, sensors that are close to the sink have higher energy drain than the other nodes. Overloading these key sensors would result in a shorter network lifetime. It is important to have energy balance nodes to ensure the nodes consume the same quantity of energy in order to increase the overall network lifetime. Thus, there are two main ways that have been explored in many studies to maximise the network lifetime by introducing multichannel MAC protocol which reduces the energy consumption through interference free channel selection and optimising the routing protocol to consider the residual energy in addition to the routes condition.

The aim of the multichannel routing tree optimisation in WSNs is to extend the network lifetime under the given energy and sensor constraints without jeopardizing reliability and communications efficiency of the network.

A. Multichannel MAC Protocols

Many energy efficient multichannel MAC protocols have been proposed to ensure high reliability for low power networking which also resulted in better network lifetime such as MC-LMAC [2], Y-MAC [3], Orchestra [4] and MiCMAC [5]. The main causes of energy consumption are nodes collision, overhearing and idle listening [6].

In idle listening, the node keeps its radio on while listening to the channel for potential packets. The node does not know when it will be the receiver of the packet. Considerable amounts of energy are wasted as the node keeps its radio on for a longer period listening to an idle channel when it does not receive or transmit packets. Thus, it is important to reduce the radio usage to conserve the nodes energy. Overhearing happens when a node receives irrelevant packets or signals that are not intended for the node. As the radio uses nearly the same energy for all operations, this drains the node energy unnecessarily.

Collision happens when nodes that are within each others' transmission range transmit simultaneously. The energy used in the collided transmissions is wasted as none of the nodes would receive the transmitted packet. Collision also happens with external interference especially with Wi-Fi interference as it can potentially collide with four 802.15.4 channels. There are only a few channels that do not overlap with Wi-Fi. However, avoiding all channels with Wi-Fi would overload the limited available channels. Thus, the overlapping frequencies can be used by introducing other means to improve the technologies coexistence.

Multichannel has many benefits for a WSN. By using multichannel, the internal and external interference can be reduced. As the effect, the latency is decreased while the reception rate and throughput are increased.

B. Routing Protocols

Various energy efficient routing protocols for WSNs have been proposed and developed to ensure efficient packet delivery to the destination. A major issue in WSNs routing protocol is in finding and maintaining the optimal routes that are energy efficient. This is due to the energy constraints and unexpected changes in node status such as node failure or a node being unreachable. This causes the topology to be altered frequently to adapt to the changes. Rapid topology modification is important to avoid the network from being disconnected which leads to higher rate of packet loss at the involved nodes as the routes are not updated.

RPL is a routing protocol that builds the topology based on the Objective Function (OF) that is application dependent that specifies the routing metrics and constraints for path calculation. This allows new metrics and constraints to be defined to fulfil the specific application and network optimisation criteria. There are many studies that were looking into improving RPL by including the energy as the metric in selecting a next hop neighbour [7], [8], [9], [10], [11], [12], [13]. There are also studies that instead of concentrating on the energy directly, increased the network lifetime by distributing the communication load in the network such as in [14], [15] rather than overusing certain nodes that are either closer to the sink or selected as the best route to get to the sink. In load balanced routing, the workload is distributed in the network which as a result, distributes the energy consumption across the nodes.

The studies in ELT [9], neigbourhood metrics routing [15], LB-RPL [14] take into account the packets transmission that is overloading the best path by helping to move the workload from overusing individual nodes which as a result, balanced the energy on the nodes. Unbalanced workload distribution could lead to shorter network lifetime as the nodes energy is depleted quicker for certain nodes. Load balancing effects the energy consumption of the nodes by distributing the load thus energy consumption in the network.

All of the studies used several metrics in order to optimise both the residual energy and packet transmissions with most of the studies use expected number of transmissions (ETX) until a link-layer acknowledgement is received in addition to another metric which usually is the residual energy level. Other metrics such as the location and resource oriented were also considered to increase the efficiency of the nodes.

The studies have different objectives in their path selection. ELT [9] aims to maximise the minimum nodes lifetime while [7] and ROEE [11] aim to minimise the maximum residual energy. Neighbourhood metrics routing [15], energy-oriented routing [14], ELT [9], L^2AM [12], [10] aim to have a network whose nodes deplete at similar speed. Despite the differences, the main goal is to consider the nodes remaining energy or workload thus energy consumption, in deciding the routes to increase the overall network lifetime.

It can be concluded that the energy consumption and workload need to be balanced in the network in order to increase the overall network lifetime while ensuring high throughput.

III. General Approach: A Two Step Optimisation

In WSNs, sensors often suffer from unreliable radio environment that is noisy and error prone which results in higher energy drain rate. WSNs require reliable communication to ensure important data to be transmitted and received as intended. The network also has to be fully functional for the maximum period possible especially in the case where only certain nodes could reach the sink node. In order to fulfil these requirements, a two step optimisation approaches were used where the main goals are to; (i) reduce interference through multichannel and (ii) maximise the network lifetime by reconfiguring the topology. These approaches are briefly described in the next section.

A. Reduce Interference

In single channel MAC protocols, nodes are configured to use a single channel throughout the nodes lifetimes. Multichannel has the advantage of an increase in robustness against external and intra nodes interference which as a result, improves the network traffic flow which reduces packet loss and maximise the overall throughput. Multichannel is a preferable solution to improve resilience against interference and maintain reliable communications. However, not all channels are free from interference; thus, there is a gain to hop to another channel when the quality of the channel deteriorates. The authors in [16] found that the channel reliability changes over time in non cyclic manner, thus no specific channels could achieve a long term reliability.

Multichannel Cross-Layer Routing Protocol (MCRP) [1] is introduced with extension results from the previously published paper where the protocol assigns and thoroughly checks for channels that are free or have low interference for nodes channel allocation. All available channels are considered and the channels reliability are checked during run time for precision to ensure infrequent channel hopping processes to be invoked which could have an effect on the network connectivity. MCRP is briefly explained in Section IV for completeness to relate to the further improvement done to the topology.

B. Maximise Lifetime

The network lifetime depends on various factors such as the network architecture and protocols, channel characteristics, energy consumption model and the network lifetime definition. In order to increase the network lifetime, these information regarding the channel and residual energy of the sensors should be exploited. Multichannel protocol not only could reduce the end to end delay, it also helps to ensure minimal packet retransmissions thus consume less energy during communications as the effect from multichannel. However, it is not for certain that the topology has the energy optimal routes as the channels would have different effect on the nodes. While the node uses a better channel than previously, another path from the node on the new channel might gives a better result. Multichannel helps to maximise the throughput but it does not maximise the network lifetime. MCRP consumes less energy than in other cases as the effect from multichannel.

In order to increase the energy efficiency thus network lifetime, MCRP needs to reconstruct the topology based on the available energy of the nodes and the link conditions gradually to avoid breaking any current connectivity. The energy-based tree reconfiguration is describes in Section V and the results show prolonged lifetime by 6.2 times more when the optimal tree is found in the 500 nodes network.

IV. Initial Tree Construction Process

A. Details of MCRP

WSNs often suffer from frequent occurrences of external interference such as Wi-Fi and Bluetooth. Multichannel communications in wireless networks can alleviate the effects of interference to enable WSNs to operate reliably in the presence of such interference. As a result, multichannel solution can improve the network efficiency of spectrum usage, network stability, link reliability, minimise latency and minimise the number of packet loss, hence, retransmission.

Multichannel Cross-Layer Routing Protocol (MCRP) [1] is a decentralised cross-layer protocol with a centralised controller. The cross layer multichannel protocol focuses on the network and application layers. This allows channel assignment decisions to be made thoroughly without being limited by the low layer complexity. The system has two parts: a central algorithm which is typically run by the LPBR for nodes channel allocation; 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. MCRP concentrates on finding channels for the nodes that are free from or have low

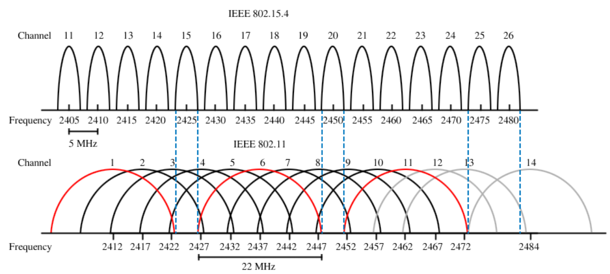


Fig. 1. IEEE 802.15.4 and IEEE 802.11 frequency channels in the 2.4 GHz ISM band

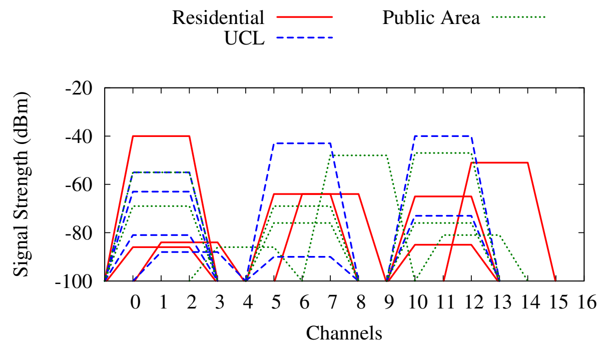


Fig. 2. Interference level on the channels at different locations

external interference to maximise the packet reception rate. It also allows the allocation of these channels to avoid cross interference between different pairs of nodes.

1) Initialisation: Upon start up, all nodes are initialised to channel 26. Channel 15, 20, 25 and 26 do not overlap with Wi-Fi as shown in Figure 1. However, channel 26 is the selected clear channel based on the channels occupancy tested in three different locations; residential, public area and university (UCL) environments shown in Figure 2. The environment condition and the network could be different depending on the location, time and channel occupancy. This shows that it is extremely difficult to find a good interference free channel and it varies from one location to another.

The nodes will only be on the same channel (channel 26) once during the initial setup. This enables the node to detect and find nearby neighbours that are in range to allow RPL set up mechanism to form the initial optimised topology before channel assignments can take place which improves the tree. The initial channel should not be used as the transmission channel throughout the runs unless MCRP fails or could not find a better channel in order to not overload the initial channel. It could lead to interference between the nodes competing for transmissions opportunity which is the problem in a single channel network.

2) Channel Selection Strategy: One main advantage of the proposed system is generality. Any algorithm can be used at the LPBR to assign channels. MCRP uses a two-hop colouring algorithm to select a channel to be assigned to a node. The two-hop colouring algorithm attempts to ensure that nearby nodes do not communicate on the same channel and risk interfering with each other. This enables simultaneous transmissions and allows fair load balancing on the channels. The protocol is inspired by the graph colouring problems [17]. The core idea is that no node should use the same listening channel as a neighbour or a neighbour of a neighbour (two hops).

In the two-hop colouring algorithm, the LPBR chooses a node N to which it will assign a new channel D to listen on. Instead of checking all or several channels, MCRP chooses a random channel and learns the channel condition from the current run. The authors in [18] proposed a spectrum sensing algorithm to decide on the number of channels to be sensed before the channel is selected for transmissions. While it was found that sensing more channels increase the likeliness to find the best channel with less or no interference, it requires higher energy consumption and longer time delay during each check.

MCRP only considers two channels at a time, whether the new channel D has better reception rate than the current channel C. By doing so, the channel selection is more spread out (random and fulfil two-hops rule) rather than all nodes trying to use the same best channel. The protocol checks the node N neighbours and neighbours of neighbours to see if any of those are currently listening on the selected channel D. If any are, a new channel D is randomly chosen from the remaining list of available channels. If no channel D can be found meeting these conditions, the current channel C 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 D and for the node N to finalise the channel to be used before another node attempts 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 D or announcing a reversion to the old channel C. Until one or other of these happens, no new channel change will be made to ensure that the neighbours are transmitting on the correct channel.

3) Channel Switching: As explained in the previous section, a choice of a new channel by the channel selection protocol causes the change channel message to be sent to the appropriate node. Upon receiving the channel change message, the 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. Node N informs its neighbours of the decision. The neighbours will update their neighbour table to transmit on channel C. If all channel quality checks succeed, the node N will listens on channel D. Node N does not send a confirmation message to the neighbours as it would be redundant since the neighbours already know the node N listening channel.

4) Channel Quality Checking: 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. The probe packets 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.

Probing is only done between the node N and the tree neighbours. Tree neighbours are the nodes that a node does transmit to through the topology formed by the RPL protocol. The tree neighbour node is selected from the list of available neighbours based on the ability to transmit to the next hop towards the LPBR depending on the RPL. By default, it is decided by using the least expected number of transmission from the node to LPBR. Node neighbours are all nodes that a given node knows it could transmit to. The nodes are within the transmission range of each other. 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.

The channel quality checking is invoked each time a node N changes channel after receiving a message from the LPBR. 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 tree 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. The authors in [16] observed that a short period of time is sufficient to give an overview of the channel condition as increasing the period shows minimal benefit. The condition of the channel D is further investigated through the number of retransmissions and packet collisions of the probing packets for accuracy of the channel condition.

If the probing process times out (because of some communication failure) or the number of probe packets received is above a threshold (currently set to 16, including retransmissions and collisions) then node N immediately exits *Probe Wait* state and reverts to channel C its previous channel. All neighbours are informed of the change back to channel C. If, on the other hand, all channel quality checks succeed, the change to channel D becomes permanent for node N. In both cases, the LPBR is informed of the results with a summary of all probes received and the channel.

5) Reconnection Strategy: RPL routing protocol functionality remains the same. RPL control messages are adjusted to support multichannel. The nodes can still change the parents as usual as all neighbours are informed of any channel changes. This enables the topology to be optimised when communication fails and further improved through MCRP as the nodes have knowledge of the listening channels of all other nodes within the range. If a new node tries to join the topology, it sends a RPL control message through all channels as the listening nodes are unlikely to be on the initial channel. The new nodes will start on channel 26. The listening nodes send a broadcast on the default channel to discover new nodes and send RPL messages through unicast when the neighbours are known to reduce unnecessary transmissions in broadcast on all available channels. New nodes and nodes which fall off the network can now rejoin on many potential channels.

B. Simulation Performance Evaluation

MCRP is evaluated in the Cooja simulated environment. The network consists of 31 nodes which are used to run the simulation where one node is used as the border router node, 16 interference nodes, and 14 duty cycled nodes that act as UDP clients to send packets to LPBR spanning over 20-30 metres between each node. 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. The border router also acts as the root of the tree.

In Cooja simulation, an interference model is used as simulation to allow full control over the test environment and the experiments are repeatable. Although the interference model does not fully mimic the behaviour of the real world interference, it enables MCRP performance to be tested in various conditions when the channel performance is degraded and to have a better understanding of the performance.

The controlled interference node generates semi-periodic bursty interference is simulated to resemble a simplified Wi-Fi or Bluetooth transmitter on several channels at random. The interference model proposed in [19] is used in the simulation to generate similar packet loss rate to the theoretical and real nodes values given in [20]. The interference has two states, a clear state (C) and an interference state (I). 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 (ir). Multiple channels interference is used in the simulation to show the hypothesis that MCRP can help avoid interference. The scenario that is considered is where ContikiMAC with 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.

The protocol performance in loss over time in the presence of interference is observed. The level of interference used in term of the *clear_time* is 100% for no interference, 75% for mild, 50% for moderate and 25% for extreme interference. The percentage represents the ratio of the time the channel is clear for transmission. Two multiple channels interference scenarios are considered; (i) extreme and no interference rate on 8 channels each and (ii) extreme, moderate, mild and no interference rate on 4 channels each.

The interference channels are randomly chosen 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, the interference rates are fixed to extreme and no interference to observe the effect it has on the channel changing decisions. In scenario 2, the interference rates are vary to observe how MCRP copes in deciding a channel when there is more interference than scenario 1 but with less interference intensity.

The simulation runs for a duration of 45-60 minutes to send 210-560 packets. When the nodes are switched on for the first time, all nodes are initialised to channel 26, the default channel for Contiki MAC layer. RPL is allowed five minutes to set up (which is ample time). RPL topology is formed in a minute. The simulation waits for another five minutes to allow trickle timer to double the interval length so that RPL control messages are not being sent frequently. The multichannel protocol is then runs for 25 minutes. In the 15 nodes simulation, the protocol takes 20-25 minutes to run the channel change set up. Another 5 minutes wait time is allowed if retransmissions 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 form 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. It is proven that the protocol tries to avoid changing to the interference channel through time out and probing failures. After 30 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 performance of MCRP is compared against the standard ContikiMAC with RPL and Orchestra to demonstrates MCRP abilities in dealing with external and intra interferences. Orchestra does not support RPL downwards routing due to limited memory in TelosB. It however, support the upwards traffic which is require in the experiments as all traffics are directed upwards towards the LPBR. MCRP is analysed using an end-to-end packet delivery performance metric, setup overhead, channel switching and reconnection delay in MCRP. The transmission success rate is calculated from the sender to the receiver over multiple hops. The simulations are repeated ten times. In all plots, the mean value of the ten simulations is plotted with error bars corresponding to one standard deviation in either deviation to give a measure of repeatability. 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.

1) Packet Loss Rates: Figure 3 shows the results in simulation for ContikiMAC with 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.

In the single channel, the node does not have enough time to recover from the interference to retransmit and drops all packets. In the extreme interference case, it shows that there are more packets drop over time and it stops receiving packets as it doesn't have enough buffer to store the incoming packet and the channel becomes congested. However, as the interference rate increases (less interference), the single channel performance improves as it has more time to recover.

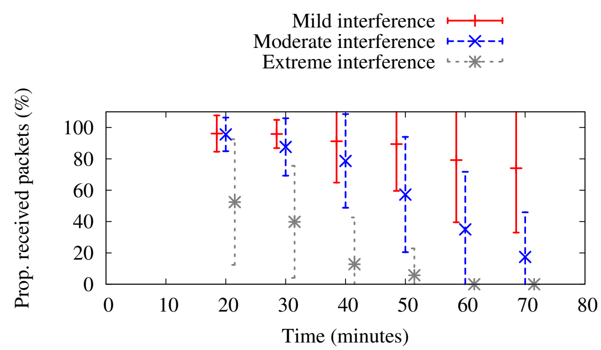


Fig. 3. Level of packet loss for mild, moderate and extreme interference levels using single channel

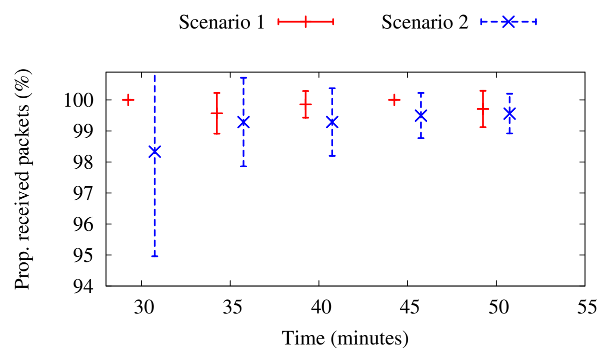


Fig. 4. Level of packet loss for scenario 1 and scenario 2 using multichannel

To evaluate MCRP capabilities to cope with interference from many sources, thus channels, and to compare to a single channel, two interference scenarios are considered. 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 original channel) have no interference, four have mild, four moderate and four extreme interference. Figure 4 shows multichannel 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 similar results as in scenario 1. The protocol does well at reducing the effects of interference and could detect moderate and mild interference. MCRP avoids the interference channel which as a result, resulted in less loss than in a single channel case.

In scenario 2 where there are mild interference channels, most of the probing messages on those channels are received. This means that the channels can be used for transmission. This is also the case with a single channel. The interference does not affect the transmissions as the interference is not frequent enough. The node has enough time to recover from the interference through retransmissions. However, the interference would slightly effect the packet transmission over time.

To prove that MCRP also performs better than not only single channel protocol, MCRP is compared against Orchestra. In the experiment, Orchesta uses channel hopping on all 16

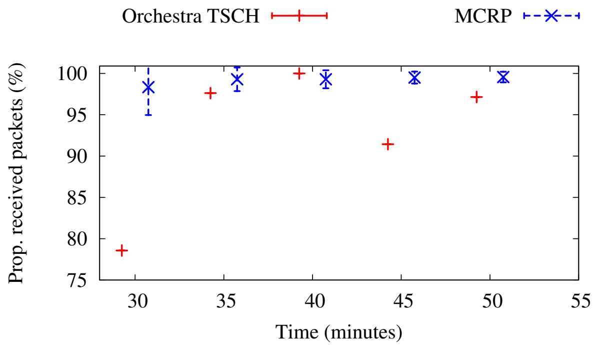
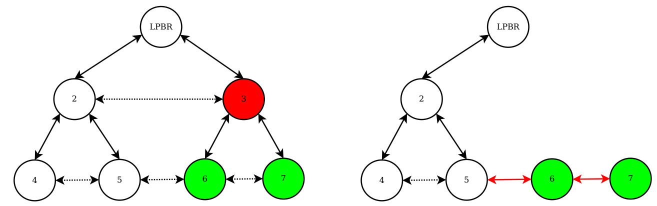


Fig. 5. Level of packet loss on testbed for MCRP and Orchestra



(a) Initial tree

(b) Reconstructed tree when node 3 is undetected

Fig. 6. A simple simulation layout to test the tree reconnection

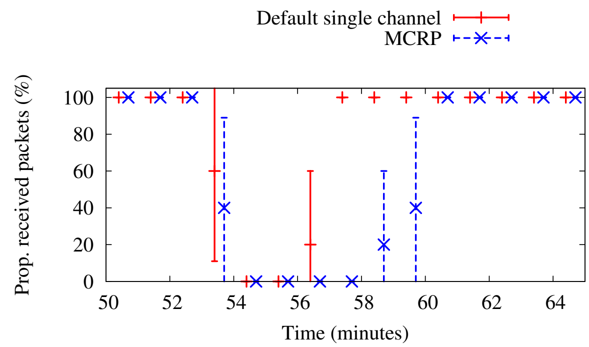


Fig. 7. Reconnection time taken for MCRP and single channel

channels. Figure 5 shows the result from scenario 2 on both MCRP and Orchestra. Orchestra has a low packet loss showing around 90-100% received packet as it hops on all channels which includes the channels that have higher interference. In comparison, MCRP selects certain channels to change into after checking the channels condition which gives MCRP nearly zero packet loss. Orchestra shows good result as it hops to another channel in the next iteration which allows it to move from the interference channel faster to be able to keep the loss rate to a minimum. While Orchestra has high proportion of received packets, MCRP shows near 100% packet reception. Orchestra shows no deviation as the channel values are fixed for each iteration thus giving the same results each time unlike MCRP where the channels are selected at random before it is used.

2) 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. MCRP, the 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, the protocol begins to change channels only when the RPL set up process is complete (or at least stabilises). The set up time is 1154 seconds beyond the RPL set up time of 286 seconds. However, it should be noted that, in fact, the system remains fully functional and capable of sending packets during the set up so this set up overhead does not matter to data transmission. Therefore it can be concluded that data sending costs (extra packets) of set up are negligible in the context of a deployment that will last more than a day. The extra set up time is also negligible within this context and furthermore does not degrade performance of the network during this set up phase.

3) Channel Switching Delay: Each node has different listening and transmitting channels. When the node is awake, it waits for incoming packets on its listening channel. If the node has a packet to send, it will switch to the next hop listening channel based on the channel information from the neighbour table. The channel switching takes at most 100μ to switch to the transmission channel. This delay is negligible in the low packet rate WSN. MCRP ContikiMAC uses a transmission phase-lock where the transmission node knows the receiver wake up phase. The node starts transmitting just before the receiver is expected to be awake. The channel switching happens shortly before the receiver is ready to receive the packets, thus the time taken in channel switching does not affect the packet reception. The node goes back to sleep once the transmission has succeeded or reached the maximum number of retransmissions (packet loss). In the next iteration, the node is reset and wakes up on its listening channel.

The channel reset is done in these cases: (i) the queue buffer is empty, (ii) before sending the next packet from the queue buffer, and (iii) the last packet in the queue buffer has been sent. This reset is done to avoid any delay in packet reception that could happen when the node is awake.

4) MCRP Reconnection: Figure 6 shows the experimental setup to test MCRP reconnection in term of the time taken to detect and adjust the routes when a node fails (run out of battery or cannot be detected). There is no external interference introduced to ensure an accurate convergence time of the topology. The dotted lines represent potential paths and the solid lines are the selected paths. The result from MCRP is compared to a single case scenario with the same setup. In the figure, node 3 is disabled after 53-54 minutes (25 packets are sent and received). Node 6 and 7 route through node 3 to the LPBR. When node 3 is dropped, node 6 and 7 have to find another route which is through node 5 and 2 to get to the LPBR. The time taken for the nodes to reconfigure the routes and the number of packet loss are showed in Figure 7.

In MCRP, it took between 5-7 minutes before node 6 and 7 discover and reconnect with the tree to proceed with the transmission. Single channel however, was slightly quicker, taken 3-5 minutes. The reason for this is MCRP control packets are sent on several channels, thus it would take slightly longer to be able to reach all nearby nodes that might be on different listening channels. A single channel on the other hand, could send a broadcast to the nodes which help to reduce the time taken during the topology reconnection. The reconnection time in MCRP is acceptable as MCRP shows high packet reception once the route is discovered in interference cases.

Comparing to Orchestra, Orchestra is a synchronous protocol. It has a dedicated slot and periodic schedule for RPL signalling which means it detects the failed node quicker unlike in MCRP and default single channel asynchronous protocols. The results from the Orchestra simulation shows that as Orchestra has a slot checking the nodes every minute, it is able to reconnect the nodes without having any packet loss. The disadvantages of Orchestra are, the nodes are listening on the same channel during the broadcast which the known channel is prone to attack. Also, even though Orchestra introduces priority to the traffic, RPL traffic is sent frequently at every period if there is no other higher priority traffic. Trickle timer that is used by the default RPL has the advantage of reducing the number of redundant control packets by doubling the waiting time for the control packets. Orchestra detects failed node quicker at the cost of frequent control packets that are redundant in a stable topology which increases the use of bandwidth and nodes energy consumption.

C. Hardware Performance Evaluation

The real hardware experiments provide the ability to validate MCRP performance in the real wireless channel environments unlike simulation. However, the network's behaviours are complicated to examine as the experiments are not repeatable. The environment condition and the network could be different at each iteration depending on the location, time and channels occupancy. The authors in [16] compared the channel occupancy in the office and home environments which potentially can have distinct channel usage. This affects the results differently as the channel conditions could have drastic changes during the run time in the residential environments than in the office environments.

The experiments of MCRP were taken place in both residential and university environments with the same experimental setup. The results are compared to the single channel case to analyse the MCRP performance in various environments. A small number of nodes are used in order to confirm that MCRP is working. The network consists of 7 nodes; 1 border router and 6 duty cycled nodes. The nodes are placed within at least 1 node's range (approximately 15-80 cm); at the power level of 2 which should have nearly 100% packet reception given that there is no interference at the range of around 20 cm. It is done to have a smaller scale of network where all nodes would have the same interference source that affects the nodes. Also, to ensure that the nodes would have at least one hop to the sink to fulfil MCRP criteria in changing channel processes. This experiment can be duplicated to cover a larger scale as the radio has the range that could span over 20-30 metres.

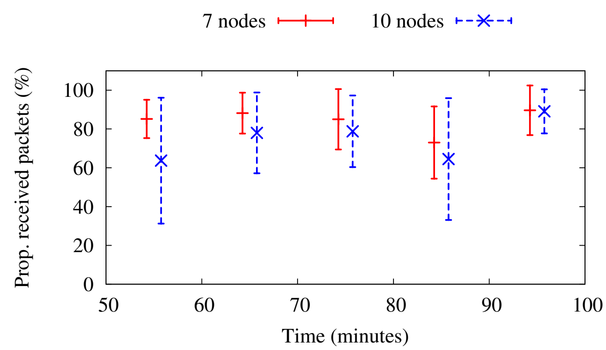


Fig. 8. Level of packet loss for MCRP in real world environment

The MCRP experiment is run for a duration of 2 hours to send 300 packets, which is 50 packets per node, sending 1 packet per minute. As the nodes are switched on at nearly the same time, RPL is allowed five minutes to set up. MCRP is run for 45 minutes for the channel changes processes. The nodes wait for the MCRP process timer to time out before the nodes can send normal packets. The experiment is then repeated with 11 nodes (1 LPBR, 10 duty cycled nodes) to study the effect that MCRP has with the increased number of nodes. The experiments are repeated ten times each.

Similar to the simulation, the end-to-end packet delivery is used as the performance metric. The interference could occupy and affect the channels differently at each run. Unlike in the simulation, the RPL tree formation set up is affected by the interference during initialisation. The network could be formed differently at each iteration.

As the nodes are at a close range to the LPBR, some of the nodes could not run the MCRP processes as MCRP requires at least one hop to be able to check the channel condition. However, several nodes were able to run MCRP processes. The tree topology formed differently each time depending on the radio coverage and interference level which affect the RPL ETX value for next hop selection. By increasing the number of nodes, it increases the chances that the nodes would have routes to or from which enables MCRP to be executed.

Figure 8 shows the result from the experiment. It can be seen that the number of received packets vary from approximately 50% to nearly 100% with better results when using a smaller number of nodes; 7 nodes than 10 nodes. However, in both results, the number of packets loss decreases over time except for at minute 85 before it stabilises again. The reason for this is, the control packets are being sent at the same time (due to trickle timer which enables control packets not to be sent frequently) which resulted in many normal packets to be dropped and lost.

Figure 9 shows the result of MCRP compared to a single

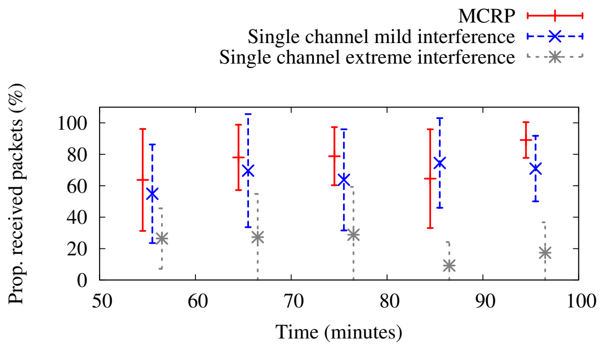


Fig. 9. Level of packet loss for MCRP and single channel

channel in mild to moderate and extreme interference. The single channel with mild interference has the signal strength approximately $-65dBm$ while the extreme interference is $-40dBm$. These channels are used for communications to see the effect of the interference channels towards the transmissions. Referring to the interference graph in Figure 2, it can be seen that most channels are occupied except for channel 26 (labelled as 16) which means, MCRP hardly could find a clear channel for transmissions thus the proportion of received packets to be around 50% to 100% unlike the simulation results that show high reception values. In the single channel case, it can be seen that the results are acceptable in mild to moderate interference case. However, it shows low packet reception rate in the extreme interference case. This shows that MCRP has more advantage than a single channel in extreme interference. The results are fairly acceptable due to the unpredicted interference occupancy in the 2.4 Ghz frequency band.

D. Energy Improvement from MCRP

Multichannel protocol not only could reduce the end to end delay, it also helps to improve the nodes energy efficiency by ensuring minimal packet retransmissions thus energy consumption. MCRP implements Contiki's existing energy module, Powertrace. Powertrace uses the software based online energy estimation mechanism [21] to estimate the node's current energy consumption in real time. The energy estimation module uses time measurements that can be directly obtained from the microprocessor on-chip timer when the component is switched on to produce a time stamp. The time difference from when the component was on and when it later is switched off is computed. The current draw of the component listed in the TelosB data sheet is used to compute the total energy consumption estimation.

$$E = (I_m t_m + I_l t_l + I_{tx} t_{tx} + I_r t_r + \sum_i I_{c_i} t_{c_i}) \times \frac{V}{32768} \quad (1)$$

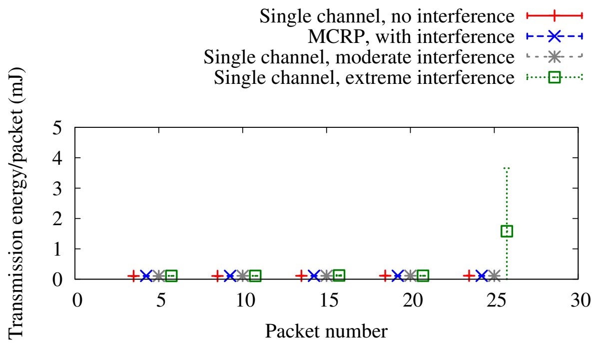
Equation 1 shows the energy consumption model given in [21], E in mJ where V is the supply voltage, I the current draw and t the active time computed in Powertrace for m the microprocessor, l the microprocessor in low power mode, tx the communication device in transmit mode, r the communication device in receive mode and c_i for other components such as sensors and LEDs. The values of I_m, I_l, I_{tx} and I_r are device dependent. In this paper, I_m is $1.8mA$, I_l is $0.0545mA$, I_{tx} is $19.5mA$ and Ir is $21.8mA$. The on-chip timer has the value of $32768Hz$.

Powertrace is used to compute the energy consumption estimation of the network. However, the nodes do not have enough capability to compute their individual energy consumption. In order to estimate the energy taken from the sender to the receiver, each node sends their $energest$ values to LPBR regularly as MCRP has a centralised controller. This enables LPBR to predict the energy drain if the routes have high interference or packet losses. LPBR is able to compute the end to end energy consumption on each routes and estimate the nodes battery level based on the $energest$ values. Each node sends the $energest$ value of its packet transmission, packet forwarding and total time value that the radio has been on from the beginning to LPBR for energy consumption computation. By doing that, the nodes knowledge of its energy level is kept at minimum.

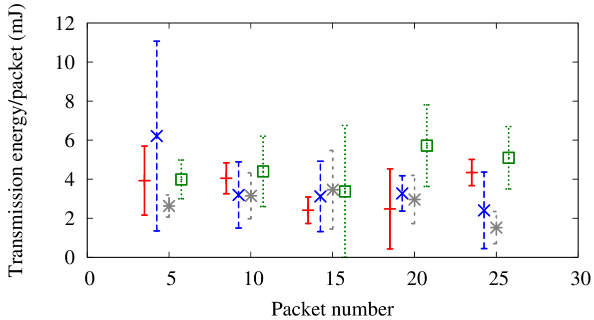
In order to calculate accurate energy consumption for specific packet transmission, the unicast packet type is separated into normal unicast and control messages unicast. The unicast packet from the application layer (normal unicast) is set as *unicastMsg = 1*, which the value is 0 by default to represents other unicast packets. This allows the energy of the transmission packet to be calculated separately without including other control messages that could be sent right after or before the normal packet transmission. This is done to avoid inaccurate energy spent as control messages are only being sent periodically unlike the normal packet that are sent frequently. It also enables retransmit packets to be included as the current transmission packet energy. This will alert the LPBR on the current condition of the node with much higher energy consumption than the usual energy per packet because of the retransmissions. The $unicastMsg$ value is reset when the link layer acknowledgement is received or the maximum number of retransmission is reached.

E. Energy Performance Evaluation

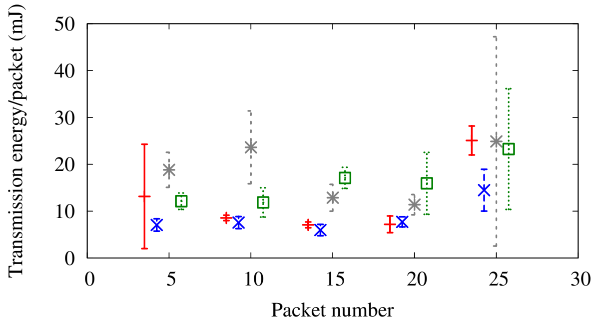
Using the simulation layout as shown in Figure **??**, the energy consumption in MCRP in term of transmission per packet, forwarding packets energy and total energy used are computed to prove that multichannel helps to prolong the network lifetime by using the energy more efficiently than in a single channel network. Each node sends one packet per minute, 350 packets in total throughout the simulation period. Equation 1 is used to calculate the nodes energy consumption. The energy consumption of each node is computed by the LPBR based on the information contained in the transmitted packet. Node 2, 5 and 15 energy usage are selected for comparisons as other nodes show similar result. Node 2 is one hop to LPBR while node 5 is 2 hops and node 15 is 3 hops away. The maximum number of hops in the simulation is 3 hops. The results of a single channel with no interference is used as the base case as it is the ideal energy consumption value. The results are also compared to the energy of a single



(a) Node 2 energy consumption



(b) Node 5 energy consumption



(c) Node 15 energy consumption

Fig. 10. Comparison of energy consumption per packet for node 2, 5 and 15

channel with moderate and extreme interference, and MCRP for multi channels.

1) Energy Per Packet Performance: Figure 10 shows the transmission energy per packet for node 2, 5 and 15. From the figure, it can be concluded that less transmission energy is used when there is less number of hops. However, in a large scale network, the number of hops cannot be reduced as not all nodes would be in the range or directly connected to the destination node. Thus, the node's next hop should be selected carefully to avoid nodes that have higher interference rate.

Node 2 energy consumption in Figure 10(a) for the 5th, 10th, 15th, 20th and 25th packet consumed approximately similar energy in all cases. As node 2 is one hop to the destination (LPBR), it was not affected by the interference except for a slight variation in the single channel with extreme interference case for packet 25. Node 3 gives similar result to node 2 as it is also one hop to the LPBR.

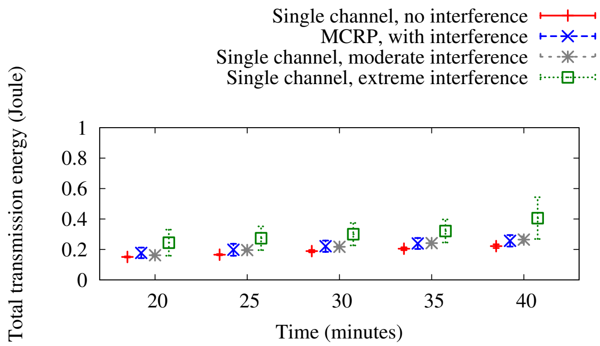
Figure 10(b) and Figure 10(c) show higher values of energy that a packet requires from the sender (node 5 and 15) to LPBR through 2 and 3 hops. This is because of the interference near to the nodes. The nodes are unable to detect the exact wake-up time for the nodes thus, the nodes have to transmit in a longer period to ensure the packet gets transmitted. In the one hop graph, the energy can be kept at minimum because the LPBR is always awake to accept packet as it is fully powered unlike the other nodes that have to switch the radio off when there are no transmissions and receptions taking place to save the energy.

In both graphs, MCRP shows approximately similar transmission energy consumption to the base case. The transmission energy for a single channel with moderate and extreme interference is slightly higher compared to MCRP in 2 hops. In 3 hops, the energy per packet in the single channel with moderate and extreme interference are much higher than the energy used by the base case and MCRP. This shows that the energy per packet depends on the number of hops and the interference that affect the routes. Multichannel helps to mitigate the effect of interference, thus reducing the transmission energy taken to send a packet.

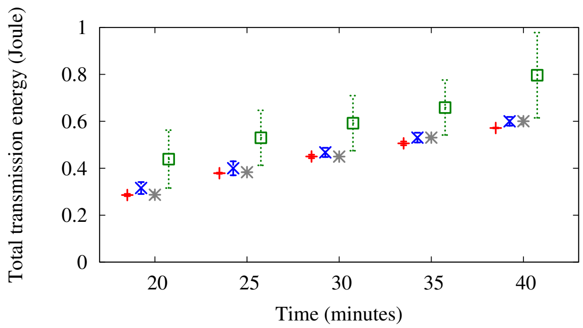
2) Energy Over Time Performance: Figure 11 shows the graphs of the three nodes total energy consumption that the nodes took to send 25 packets (approximately 40 minutes) including retransmissions and control packets energy. Figure 11(a) shows node 2 energy consumption where it can be seen that in all cases, the total energy taken are approximately similar with a small increase over time. The single channel with extreme interference case however, requires more energy consumption than in other cases. Figure 11(b) shows higher increase in energy usage over time in all cases. The reason for this is because node 5 has 2 other nodes that are using it as a forwarder. Node 5 (2 hops) uses higher energy when forwarding packet to LPBR compared to node 2 (1 hop). Figure 11(c) shows lower energy consumption for node 15 compared to node 5 because node 15 does not act as a forwarder.

Figure 12 shows the total energy consumption for all nodes in the simulation. Node 2 and node 3 are one hop to LPBR, nodes 4-7 are 2 hops, and other nodes are 3 hops away. For most nodes, the energy consumption is slightly improved when using MCRP than a single channel with interference. This improvement can be clearly seen in the 2 hops nodes as these nodes use more energy during interference for retransmissions. If the retransmissions fail, the packet is dropped and the energy used during the retransmissions is wasted. The total energy consumption graph shows all energy from the packet transmission including failed packet energy.

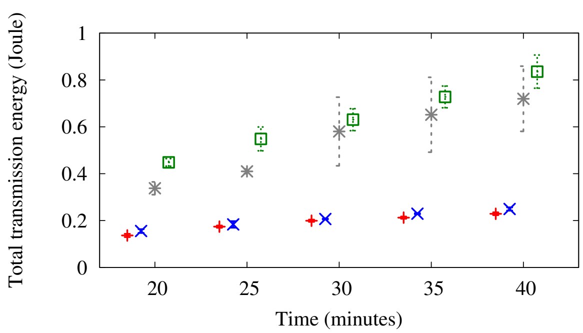
3) Forwarding Energy Analysis: Figure 13 shows the energy used in forwarding packets for nodes 2-7. The other nodes in the simulation do not forward packets. Node 2 and 3 use less energy than nodes 4-7 as the nodes only need to check if the channel is being use by the other node before it can forward to the LPBR. LPBR waits for incoming packet thus the nodes could send the packet with less waiting time as LPBR radio is always on. Based on the simulation layout in Figure **??**, node 4 and 5 forward packets to node 2 while node 6 and 7 to node 3 as their next hop. Node 4-7 use higher energy than node 2 and



(a) Node 2 energy consumption



(b) Node 5 energy consumption



(c) Node 15 energy consumption

Fig. 11. Comparison of total energy consumption for node 2, 5 and 15

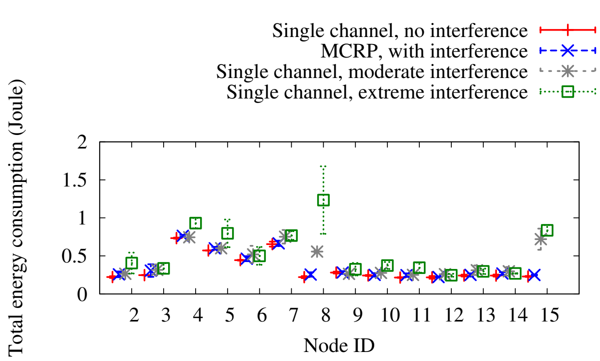


Fig. 12. Simulation nodes total energy

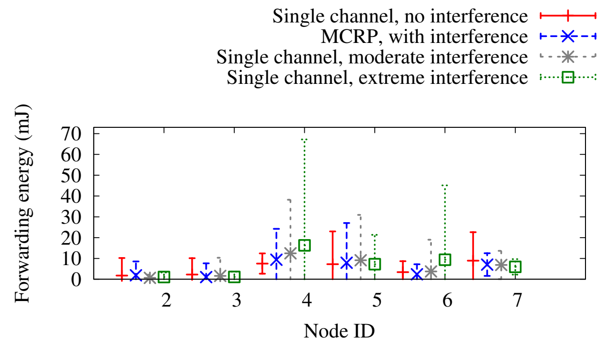


Fig. 13. Simulation nodes forwarding energy

3 in forwarding packets as the nodes have more packets (from the children) to be forwarded. In order to be able to forward the packets, the nodes have to be awake for longer time and ensure the next hop is also awake and ready to accept the packets. Thus forwarding takes more energy consumption than an end to end packet transmission. By increasing the number of nodes thus children, the nodes will use more energy in order to forward the packets. The forwarding energy consumption contributes to the most energy used by the nodes. MCRP helps to reduce the energy consumption which can be seen in node 4 and 6 results than in a single channel. In the base case, the energy consumption varies as the nodes are interfering with each other even without external interference during transmissions.

The simulation results showed that MCRP consumes less energy than in other cases when there is interference as the effect of multichannel. In order to increase the energy efficiency thus network lifetime, MCRP needs to reconstruct the topology based on the energy consumption, residual energy of the nodes and the link conditions gradually to avoid breaking any current connectivity.

V. Energy-based Tree Reconfiguration

RPL uses ETX which is the expected number of transmissions to reflect the link reliability and the expected latency on the channel. The ETX value is calculated by the node in selecting the next hop route. In order to find the optimal tree, it is assumed that RPL has selected the best routes and MCRP further improved the selected paths by switching to better channels for the transmissions. However, the current best paths do not take into account the nodes residual energy. This could drain the battery of certain nodes quicker than other nodes. RPL can reconstruct the tree as the result of MCRP. The routes might have better reliability in the new channel than it was previously.

A. Details of Optimal Tree Reconfiguration

In order to maximise the network lifetime, MCRP has to consider swapping the paths. The optimal tree swapping has to take into account the number of children and descendants to balance the energy consumption in the network based on the residual energy of the nodes. The proposal aims to find the tree that could maximise the node with the minimum lifetime.

There are three possible solutions that are considered; (a) swap the parent of node i, (b) swap the children of node i, and (c) swap the descendants of node i that are not the children. However, swapping the parent of the minimum lifetime node does not improve the node lifetime as the number of children and descendants remain same. Thus, only option (b) and (c) are further investigated.

$$l_i = \frac{e_i}{(d_i+1)t_{ip(i)} + \sum_{j \in c(i)}(d_j+1)t_{ji}} \quad (2)$$

Equation 2 shows MCRP optimal tree calculation where l_i is the node i current lifetime based on the node's remaining energy e_i (in percentage), d_i is the number of descendants, t_{ij} represents the number of transmissions on average from node i to node j, $p(i)$ refers to the parent of i and $c(i)$ is node i set of children.

Algorithm 1 Pseudo-code for MCRP optimal tree algorithm

```
Notations
l_i is the node lifetime
c_i is the number of node i children
d_i is the number of node i descendants
Pseudo-code
Form tree based on MCRP
Update battery level for all nodes
Update all nodes l_i, c_i, d_i
minimum ← 0
previousSwapNode ← 0
while node ≠ previousSwapNode do
    Find node with minimum l_i
    List all potential c_i and d_i swap
    if c_i and d_i swap l_i > minimum then
        Recalculate all nodes l_i
        if all new nodes l_i > minimum then
            Update tree
            New tree is optimal
        else
            Revert to previous optimal tree
        end if
        previousSwapNode ← node
    else
        Current tree is optimal
    end if
end while
```

Algorithm 1 describes the swapping processes based on the nodes lifetime calculated from Equation 2. It considers all available paths between the nodes and shows all potential topologies before deciding on the optimal tree. It is assumed that all nodes residual energy and the paths are known. Both the nodes battery and the link conditions can deteriorate over time. However, it is assumed that the current selected paths are the favourable routes selected by the MCRP, thus, only the battery level of the nodes is the variable. The topology is changed accordingly where the nodes that have the minimum value is selected to balance the network in term of the battery, link conditions and the number of children and descendants. The network is considered as balanced in term of the lifetime which means, the number of nodes and descendants connected might not be fairly distributed as the battery level vary in each node.

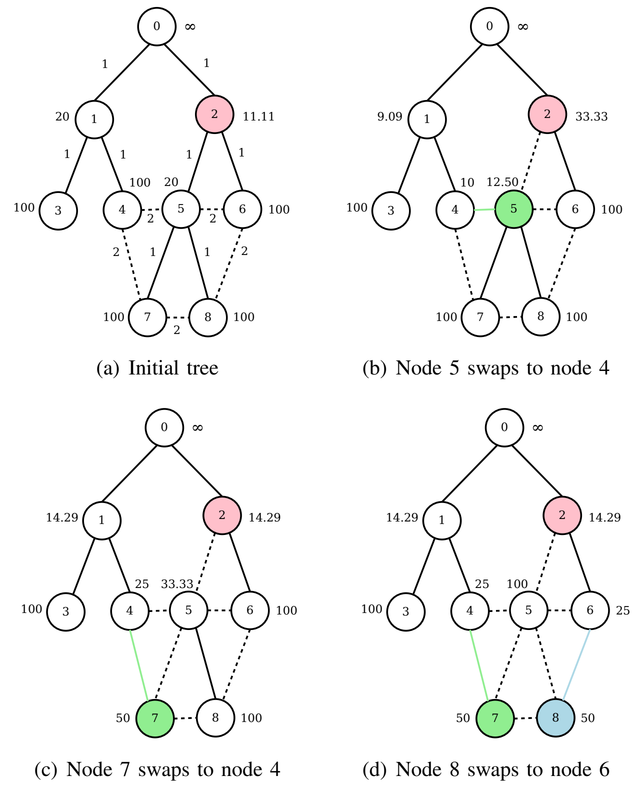
B. Illustrative Example

Figure 14 is an illustrative example to explain the algorithm proposed. Assumed that the tree formed in Figure 14(a) is the current optimal tree after running MCRP processes. Each node is labelled with the battery level, represented in percentage for simplicity. It can also be represented in volts or Joules. The lines between the nodes represent routes in different channels where dotted lines are the potential routes and the solid lines are the current routes. The values represent the link conditions in terms of the number of successful expected transmission between the two nodes. The values of the links are the expected transmission taken only for the upwards route as the links downwards could have different values due to the different transmission and reception channels on each node thus different link quality. The transmission and reception channels of a node cannot be the same to avoid interference with nearby nodes.

The figure shows that node 2 has the most descendants which consequently reduce the node lifetime as it has to forward more packets than any other nodes. Initially, the topology is formed based on the least value on the paths. In order to optimise the tree, the overall network lifetime is considered where paths that are not the minimum could be chosen as the route as it prolongs the overall functionality of the network. In this example, node 2 has the minimum lifetime. It can be maximised through swaps.

There are several potential swaps to improve node 2 lifetime that includes both the children which are node 5 and 6, and the children of children, node 7 and 8. Figure 14(b) shows node 5 swaps to node 4 instead of its initial node 2 and the network lifetime is calculated. Node 2 lifetime is improved, however, node 1 has a lower lifetime than the initial minimum value as the result of swapping. Node 1 now has 5 descendants while node 2 only has one when it initially had 4. In order to reduce the number of unnecessary swap, once the maximum minimum lifetime is found, all nodes lifetime values are checked to ensure that they have higher lifetime than the initial minimum lifetime regardless of the maximising the minimum node to avoid endless cycle of swaps. While the swap done by node 5 improves node 2 lifetime, node 1 lifetime deteriorates to a value lower than the minimum. The network reverts to the previous topology that is better than the new swap. Node 5 tries and swaps to node 6, then node 6 swaps to node 8. However, the potential topology is not improved. Node 2 then swaps its descendants node 7 and 8.

When node 7 is swaps to node 4 instead of node 5, the tree is improved. It can be seen in Figure 14(c) that the tree is more balanced and node 2 lifetime is prolonged. As the result of swapping, node 4 lifetime is reduced as the path from node 7 to node 4 is not the smallest path value. The tree is updated as the current optimal tree. It is not yet the final optimal tree because node 8, which is another node 2 descendant has not been checked. If node 8 swap does not



(a) Initial tree (b) Node 5 swaps to node 4

(c) Node 7 swaps to node 4 (d) Node 8 swaps to node 6

Fig. 14. Graph of the bidirectional paths in a WSN

improve the tree, the swap from node 7 is chosen as the final optimal tree. Another potential swap is shown in Figure 14(d) where node 8 is connected to node 6 instead of node 5. In both cases, node 2 lifetime is maximised and all nodes lifetime are above the minimum value. The tree in Figure 14(c) is selected as the final optimal tree in maximising node 2 lifetime. Further investigations are required in order to decide the criteria on an optimal tree when there are several good topologies to be selected.

Node 1 is then selected as the minimum lifetime as node 2 cannot be selected again to avoid unnecessary repetition. Optimal tree from the potential swaps for node 1 is not found thus the tree is said to be optimal. In the algorithm, the same node cannot swap again right after its previous swap. This is done to avoid oscillation which would produce similar result. The node however, could swaps in the next round as the other node swap would have changed the topology.

The swaps are assumed to happen once until the network stops functioning, thus the overheads are negligible. The swapping calculations and decisions are made by the LPBR due to sensors limitations and constraints. LPBR informs the specific nodes of the final swapping if it needs to take place. In term of energy cost, the cost is negligible as the swaps are infrequent and being controlled by the LPBR.

VI. Performance Evaluation

This section describes the evaluation of the following performance metrics: (a) the average number of switches to form the optimal tree and (b) the impact of swapping on the network lifetime.

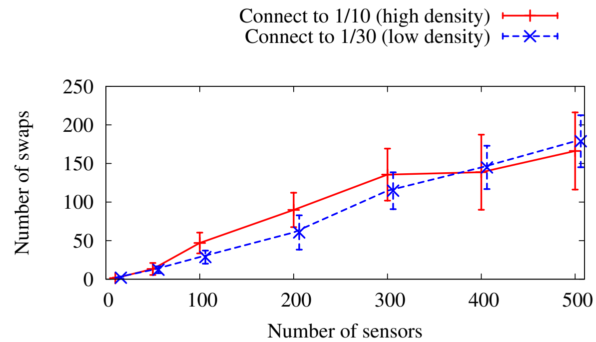


Fig. 15. Average number of swaps

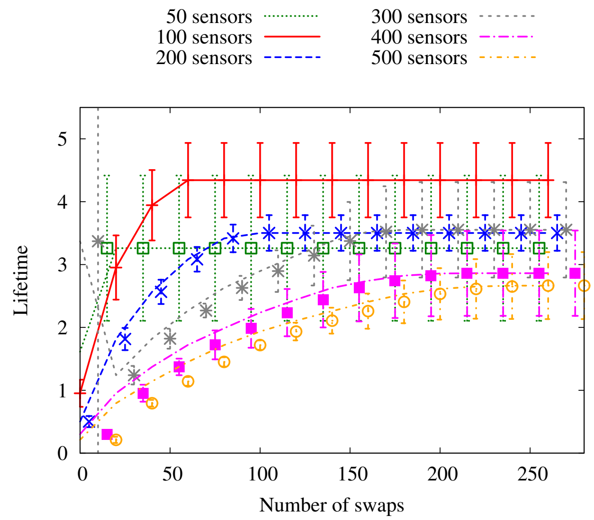
A. Simulation Setup

The optimal tree algorithm is simulated in C. The number of sensors considered is between 10 to 500 and each node is randomly assigned an initial energy between 50% to 100%. The link conditions are also randomly assigned the value between 1 to 10 where smaller number indicates better link condition as it requires smaller number of retransmissions. In this setup, the channels are fixed, assuming that the current channels that the nodes are listening and transmitting on, are the best selected channels from the previous MCRP processes. RPL builds the initial tree based on the ETX value which is then further improved by MCRP. In order to avoid all the nodes from directly connecting to the LPBR, each node could route to a minimum of $1/10$ and $1/30$ of the total number of nodes. This allows the node to have alternative parents (thus paths) for the swapping processes and hops to reach the LPBR. The node is not necessarily connected to all $1/10$ and $1/30$ nodes. The paths between the nodes are selected based on the RPL and MCRP processes. These values are selected in the case where (a) the nodes are closely together ($1/10$), and (b) the nodes are spread out with minimum connections to the other nodes available ($1/30$).

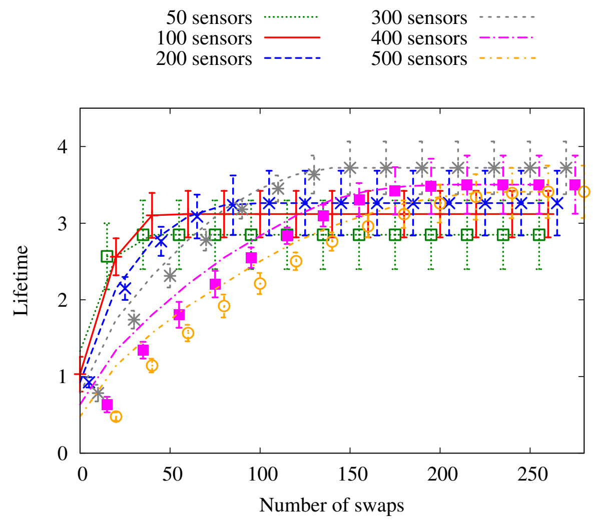
B. Simulation Results

1) Average Number of Switches: Figure 15 shows the standard deviation and average number of swaps using MCRP optimal tree algorithm. The standard deviation on the x axis is slightly shifted to avoid overlapping. It can be observed that there are more swaps on average when there are more sensors in the network in both connection cases. However, nodes that could route to $1/10$ of the total sensors showed slightly higher number of swaps than in the $1/30$ connection. The reason for this is because in $1/10$ connection, it has more neighbours, hence many potential parents to select.

In a smaller network, the sensors are limited by the number of potential parents. This prevents the nodes from swapping as the potential parents might not have any improvement. This can be seen from the number of swaps in a 50 sensors network where the average number of swaps is less than 10. This is because each node has 5 (in $1/10$) and 2 (in $1/30$) potential parents to select from unlike in the 500 sensors network which each has 50 and 17 potential parents. However, as there are



(a) Connect to 1/10 of total sensors



(b) Connect to 1/30 of total sensors

Fig. 16. Comparison of the number of swaps and lifetime in different network scale

more sensors, it takes longer to find the best parents as the swaps will consider all nodes that are within the range.

This experiment does not reflect the condition in the real world where the sensors could be scattered with more or less available range to the other nodes depending on the application; which means more nodes can directly be connected to the LPBR without hops in between. This however, represents a reasonable connection between the nodes to allow swapping and alternative nodes if the current forwarding nodes values are at a minimum for the experiment.

2) Impact On The Network Lifetime: Figure 16 shows the improvement in the node thus network lifetime by maximising the minimum and the number of swaps required in 10 runs in 6 networks with 50, 100, 200, 300, 400 and 500 sensors with different degree of connection. The standard deviation on the x axis is slightly shifted to prevent the error bars from overlapping. It is observed that the node lifetime decreases with an increase in the number of sensors in the network. The reason for this is in a larger network, there are a higher number

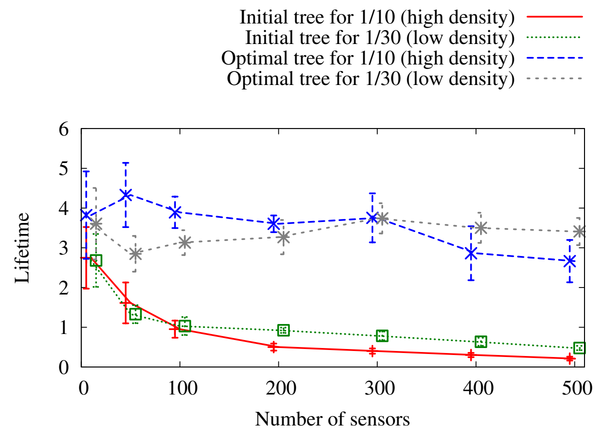


Fig. 17. Lifetime of MCRP optimal tree

of descendants and each connection has its own path values. By taking into account these variables, the number of nodes affect the whole network lifetime. While a higher number of nodes allow more alternative routes, it also consumes more energy as there are more connected nodes. Smaller network however, has limited number of possible swaps which does not improve the network lifetime.

Figure 16(a) shows the number of swaps and the lifetime when the nodes are connected to $1/10$ of the total nodes in the network. In the 50 nodes network, the number of swaps is less than 10 before it reaches the maximum lifetime for the whole network. As the number of sensors in the network increase, it takes more swaps before the tree is optimal. In the 200 nodes network, the number of swaps is around 100 swaps and the lifetime is improved from the minimum of 0.5% to 3.1%. In 500 nodes network, it takes more swaps, around 200 swaps for the lifetime to be maximised from 0.3% to 2.5%.

Figure 16(b) shows similar improvement in the $1/30$ connection case. However, it can be seen that the maximum lifetime values in the figure for 100 sensors network is slightly less than in Figure 16(a). This is because the networks have lesser potential parents and paths to select from. The tree is limited by the number of connections. The other large networks have similar maximum lifetime values in both figures.

Figure 17 shows the comparison between the initial and optimal tree in both cases. The standard deviation on the x axis is slightly shifted to the left and right to prevent the error bars from overlapping. MCRP swapping prolongs the network lifetime which shows an increase from the initial lifetime. Smaller networks have high initial lifetime values compared to larger networks. However, larger networks have better lifetime improvement than the slight improvement in smaller networks.

In the initial trees, it can be seen that when there are more sensors in the network, the lifetime values are decreasing. This shows the importance of finding the optimal tree as the results showed that the lifetime can be improved by approximately 3% when initially, in all networks, the minimum sensors have less than 1% lifetime. The increase enables the network to remain functional slightly longer than initially.

VII. Conclusion

In this paper, a two step optimisation approaches were presented that reduce the effect of interference by implementing MCRP, a multichannel cross-layer routing protocol, and maximise the network lifetime by reconfiguring the topology to find the optimal tree. MCRP shows high packet reception rate in simulations and hardware results. In addition, MCRP reduces the energy consumption by an average of 6 times during communications as the effect of multichannel. The energy-based tree reconfiguration is proposed to further improve the multichannel network by considering the energy level of each sensor. It is aimed to enable the network to be fully functional for a longer period of time by maximising the minimum sensor energy level and enable the sensors to have similar lifetime. The results showed an increase in the network lifetime by 6.2 times more for the optimal tree compared to the initial tree in a 500 nodes system.

Acknowledgment

The authors would like to thank...

References

[1] N. Nordin, R. G. Clegg, and M. Rio, "Multichannel cross-layer routing for sensor networks," in *2016 23rd International Conference on Telecommunications (ICT)*, May 2016, pp. 1–6.

[2] O. D. Incel, L. van Hoesel, P. Jansen, and P. Havinga, "MC-LMAC: A multi-channel MAC protocol for wireless sensor networks," *Ad Hoc Netw.*, vol. 9, no. 1, pp. 73–94, Jan. 2011. [Online]. Available: http://dx.doi.org/10.1016/j.adhoc.2010.05.003

[3] Y. Kim, H. Shin, and H. Cha, "Y-MAC: An energy-efficient multi-channel MAC protocol for dense wireless sensor networks," in *Information Processing in Sensor Networks, 2008. IPSN '08. International Conference on*, April 2008, pp. 53–63.

[4] S. Duquennoy, B. Al Nahas, O. Landsiedel, and T. Watteyne, "Orchestra: Robust mesh networks through autonomously scheduled TSCH," in *Proceedings of the 13th ACM Conference on Embedded Networked Sensor Systems*, ser. SenSys '15. New York, NY, USA: ACM, 2015, pp. 337–350. [Online]. Available: http://doi.acm.org/10.1145/2809695.2809714

[5] B. Al Nahas, S. Duquennoy, V. Iyer, and T. Voigt, "Low-power listening goes multi-channel," in *2014 IEEE International Conference on Distributed Computing in Sensor Systems (DCOSS)*, May 2014, pp. 2–9.

[6] A. Bachir, M. Dohler, T. Watteyne, and K. Leung, "MAC essentials for wireless sensor networks," *Communications Surveys Tutorials, IEEE*, vol. 12, no. 2, pp. 222–248, Second 2010.

[7] P. O. Kamgueu, E. Nataf, T. Djotio, and O. Festor, "Energy-based metric for the routing protocol in low-power and lossy network." in *SENSORNETS*, 2013, pp. 145–148.

[8] L. H. Chang, T. H. Lee, S. J. Chen, and C. Y. Liao, "Energy-efficient oriented routing algorithm in wireless sensor networks," in *2013 IEEE International Conference on Systems, Man, and Cybernetics*, Oct 2013, pp. 3813–3818.

[9] O. Iova, F. Theoleyre, and T. Noel, "Improving the network lifetime with energy-balancing routing: Application to RPL," in *Wireless and Mobile Networking Conference (WMNC), 2014 7th IFIP*, May 2014, pp. 1–8.

[10] D. Todol-Ferrandis, S. Santonja-Climent, V. Sempere-Pay, and J. Silvestre-Blanes, "RPL routing in a real life scenario with an energy efficient objective function," in *Telecommunications Forum Telfor (TELFOR), 2015 23rd*, Nov 2015, pp. 285–288.

[11] A. Barbato, M. Barrano, A. Capone, and N. Figiani, "Resource oriented and energy efficient routing protocol for IPv6 wireless sensor networks," in *Online Conference on Green Communications (GreenCom), 2013 IEEE*, Oct 2013, pp. 163–168.

[12] S. Capone, R. Brama, N. Accettura, D. Striccoli, and G. Boggia, "An energy efficient and reliable composite metric for RPL organized networks," in *Embedded and Ubiquitous Computing (EUC), 2014 12th IEEE International Conference on*, Aug 2014, pp. 178–184.

[13] B. Sharkawy, A. Khattab, and K. M. F. Elsayed, "Fault-tolerant RPL through context awareness," in *Internet of Things (WF-IoT), 2014 IEEE World Forum on*, March 2014, pp. 437–441.

[14] X. Liu, J. Guo, G. Bhatti, P. Orlik, and K. Parsons, "Load balanced routing for low power and lossy networks," in *2013 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2013, pp. 2238–2243.

[15] D. T. Delaney, L. Xu, and G. M. P. O'Hare, "Spreading the load in a tree type routing structure," in *2013 22nd International Conference on Computer Communication and Networks (ICCCN)*, July 2013, pp. 1–7.

[16] M. Sha, G. Hackmann, and C. Lu, "Real-world empirical studies on multi-channel reliability and spectrum usage for home-area sensor networks," *IEEE Transactions on Network and Service Management*, vol. 10, no. 1, pp. 56–69, March 2013.

[17] T. Jensen and B. Toft, *Graph Coloring Problems*, ser. Wiley Series in Discrete Mathematics and Optimization. Wiley, 2011. [Online]. Available: https://books.google.co.uk/books?id=leL0Y5N0bFoC

[18] L. Stabellini, "Energy-aware channel selection for cognitive wireless sensor networks," in *Wireless Communication Systems (ISWCS), 2010 7th International Symposium on*, Sept 2010, pp. 892–896.

[19] C. A. Boano, T. Voigt, N. Tsiftes, L. Mottola, K. Römer, and M. A. Zúñiga, "Making sensornet mac protocols robust against interference," in *Proceedings of the 7th European Conference on Wireless Sensor Networks*, ser. EWSN'10. Berlin, Heidelberg: Springer-Verlag, 2010, pp. 272–288.

[20] C. A. Boano, Z. He, Y. Li, T. Voigt, M. Zniga, and A. Willig, "Controllable radio interference for experimental and testing purposes in wireless sensor networks," in *2009 IEEE 34th Conference on Local Computer Networks*, Oct 2009, pp. 865–872.

[21] A. Dunkels, F. Osterlind, N. Tsiftes, and Z. He, "Software-based on-line energy estimation for sensor nodes," in *Proceedings of the 4th workshop on Embedded networked sensors*. ACM, 2007, pp. 28–32.

PLACE PHOTO HERE

Michael Shell Biography text here.

John Doe Biography text here.

Jane Doe Biography text here.