# Abstract

(1 page)

This report presents the current state of research work that has been carried out in the context of the PhD. (describe why do it). The PhD work proposes a new decentralised multi-channel tree building protocol with a centralised controller for ad-hoc sensor networks. The protocol alleviates the effect of interference which results in improved network efficiency and stability, and link reliability. The proposed protocol takes into account all available channels to utilise the spectrum and aims to use the spectrum efficiently by transmitting on several channels. The protocol detects which channels suffer interference and changes away from those channels. The algorithm for channel selection is a two-hop colouring protocol that reduces the chances of nearby nodes to transmit on the same channel. All nodes are battery operated except for the low power border router (LPBR). This enables a centralised channel switching process at the LPBR. The protocol is built based on the routing protocol for low power and lossy networks (RPL). In its initial phase, the protocol uses RPL's standard topology formation to create an initial working topology and then seeks to improve this topology by switching channels. The report discusses the main engineering and research challenges raised by the protocol, and describes and explains the principles and mechanisms used to support the proposed protocol. It then presents an extensive evaluation of the protocol and other other approaches. The implementation and evaluation of the protocol is performed using the Contiki framework. The report then describes the future main research issues that will be investigated in the context of this PhD.

In this report,

The proposed approach

The report discusses

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# Introduction

(2-3 pages)

## Context and Motivation

Wireless Sensor Networks (WSN) are ad-hoc networks that consist of sensor nodes that typically use low power radios such as IEEE 802.15.4, a relatively short range transmission standard radio technology in the 2.4 GHz band. The standard allows transmission to occur on several different channels within this band \cite{ieee802.15.4}. Unfortunately, the channels used by this technology often suffer interference \cite{Boano:2010:MSM:2127940.2127963, ieeeCompare}, for example, from Wi-Fi \cite{ieee\_2012, wu} and Bluetooth. Sensor networks have to contend with an increasing number of devices that cause this wireless interference. Organising the network topology around this interference becomes an enabler for increasing transmission efficiency at a smaller energy cost. WSNs need to be able to operate reliably in the presence of such interference. It is important to minimise energy costs in these networks since deployments can be for weeks, months or longer.

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 \cite{watteyne}. It also enables communication between physically proximate nodes to occur simultaneously without the risk of collision when the communicating nodes use different channels. However, not all channels are free from interference; thus, there is a gain to hop to another channel when the quality of the channel deteriorates. Two commonly used types of channel hopping \cite{watteyne} are blind channel hopping and whitelisting. In blind channel hopping, nodes choose from all available channels.

Whitelisting, on the other hand, gives a set list of channels that avoids those that are known to commonly suffer interference.

Many studies make use of channel whitelisting such as in Chrysso \cite{chrysso} and MiCMAC \cite{micmac}.

Note that potentially Chrysso and MiCMAC could use all available channels.

However, they do not have a mechanism to check the channel condition before using it for packet transmission. MiCMAC sees its performance degraded when using more than 4 channels, thus the decision on specifying 4 channels to be included in their experiment.

MiCMAC uses a different channel chosen at random each time it wakes up.

It might require several wake up periods which is time consuming, before a clear channel is found from the 16 channels, to deliver the packet.

Chrysso on the other hand, switches the affected nodes to a new set of channels upon detecting interference which entails frequent channel switching if all channels are to be considered.

## Problem Statement

It is clear that it is impossible to find a single channel guaranteed free from interference and there is no consensus on the best channel to use. Our work takes into account all available channels to utilise the spectrum and checks the condition of the channels before hopping to avoid those channels with interference. Several previous studies have developed a multichannel MAC layer but, despite the potential benefits none are yet widely implemented in real world deployments.

## Contribution

Important aspects of this work will be investigating lossy multichannel. Designing the protocol for multichannel raises several research challenges. The decision making process is (centralized and decentralized – explain here). The main benefits of this approach are ().

The work in this PhD will address the issues raised by (). More specifically it will investigate how the channel selection is determined from the nodes interactions. In addition, it will investigate the cross layer interaction.

## Current Work

In the context of the research efforts carried out from the beginning of the PhD research work, the followings have been investigated.

A new multi-channel protocol called Multichannel Cross-Layer Routing Protocol (MCRP) has been developed. The proposed approach is so that the nodes are able to communicate on many channels in order to avoid interference and channel congestion in a centralized and decentralized manner.

This paper presents a Multichannel Cross-Layer Routing Protocol (MCRP) which consists of two main parts; a centralised intelligence at LPBR, and decentralised nodes. LPBR implements a two-hop colouring algorithm to avoid interference between physically proximate nodes trying to communicate on the same channel. The information on channel interference and network topology from the lower layer is made available to the application layer. This allows the centralised controller (LPBR) to have an overall view of the system to make decisions at the network and MAC layers about which channels nodes should listen on. The systemis fail safe in the sense that the WSN functions if the central system which assigns channels fails temporarily or permanently. We implement MCRP in Contiki \cite{contiki}, an open source operating system for WSNs and evaluate the protocol in Contiki network simulator, Cooja \cite{cooja}.

We demonstrate that MCRP avoids channels with interference which greatly reduces the effects of interference on the network.

The performance of the approach has been evaluated using (). The evaluation has been performed with respect to the ().s

## Report Outline

The remainder of the report is organised as follows. Chapter 2 introduces the state-of-the art in the area of multichannel protocols. It also presents the main current research efforts towards () Section \ref{sec:relatedwork} presents related work to multichannel protocols. Chapter 3 presents the main features and mechanisms used in MCRP. It describes (). It also presents (). Section \ref{sec:multichannel} 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 \ref{sec:evaluation}. Chapter 7 summarises the current work and presents the future research works that will be investigated in the context of this PhD.

# Literature Review

(20-25 pages)



## Wireless Sensor Networks

### Overview (Application Scenarios for WSNs)

## Maximize Lifetime vs Minimize Energy

## Multichannel Protocol (Data Link Layer)

### Introduction (Solutions)

Multichannel communication has potential benefits for wireless networks that possibly include improved resilience against external interference, reduced latency, enhanced reception rate and increased throughput.

There have been some proposals/solutions for multichannel. These approaches focus on (the mac layer) and depending on ().

Radio duty cycling mechanisms can be classified into two categories; synchronous and asynchronous systems. A synchronous system is a system that requires a tight time synchronization between nodes. It uses time-scheduled communication where the network clock needs to be periodically synchronized in order for the nodes not to drift in time. Asynchronous system on the other hand, do not require synchronization but instead is a sender or receiver initiated communication. In asynchronous systems the nodes are able to self-configure without time synchronization and this can have advantages. There are many studies done in multichannel for both categories.

### Synchronous Systems

#### TSCH

#### MC-LMAC

#### Y-MAC

### Asynchronous Systems

#### EM-MAC

#### MuChMAC

#### Chrysso

#### MiCMAC – ContikiMAC?

### Comparison and Discussion

## Routing Protocols (Network Layer Protocols)

The network layer is responsible in routing the data across the network from the source to the destination. Routing protocols in WSNs differs from traditional routing protocols depending on the Operating System.

Contiki provides IP communication in both IPv4 and IPv6. However, as sensors have a small amount of memory, uIP, which is a small RFC-compliant TCP/IP stack that makes it possible to communicate over the Internet. uIP () to reduce the resources it requires.

uIP implementation is designed to have only the absolute minimal set of features needed for a full TCP/IP stack.

In order to maximize the use of multichannel in improving packet delivery, routing topology plays a big role in providing an optimized routing tree to the network that is scalable and energy efficient.

Routing protocol approaches can be classified into () types which are flat based and data centric, hierarchical, location based and network flow and quality of service (QoA) aware.

### Classification of Routing Protocol

#### Flat based and Data Centric

Data centric protocols are query-based and depend on the naming of desired data which helps in eliminating many redundant transmissions. In data centric routing, the sink sends queries to certain regions and waits for data from the sensors located in the selected regions. Since data is being requested through queries, attribute-based naming is necessary to specify the properties of data.

Flooding and gossiping are two classical mechanisms to relay data in sensor networks without the need for any routing algorithms and topology maintenance. In flooding, each sensor receiving a data packet broadcast it to all of its neighbors and this process continues until the packet arrives at the destination or the maximum number of hops for the packet is reached. However causing duplicated messages sent to the same node, resource blindness by consuming large amount of energy without consideration for the energy constraints. Gossiping is a slightly enhanced version of flooding where the receiving node sends the packet to a randomly selected neighbor which picks another random neighbor to forward the packet to and so on. However, it cause delays in propagation of data through the nodes.

Data centric - all communication is neighbor to neighbor, no need for addressing mechanism.

Sensor protocols for information via negotiation (SPIN) is to name the data using high-level descriptors or meta-data. Before transmission, meta-data are exchanged among sensors via a data advertisement mechanism. Sensor advertise the availability of data allowing interested nodes to query that data. Each node needs to know only its single hop neighbors. A advertise to B. B responds, send request to A. A sends data. B advertises to its neighbors. Neighbors send request back to B, B send data. If B is not interested, data cannot be delivered to B's neighbors.

Directed Diffusion is by using a naming scheme for the data. An interest is defined using a list of attribute-value pairs. The interest is broadcast by a sink through its neighbors. Each node receiving the interest can do caching for later use. A gradient is a reply link to a neighbor from which the interest was received. By utilizing interest and gradients, paths are established between sink and resources. Directed Diffusion basically reinitiates reinforcement by searching among other paths which are sending data in lower rates. Employing multiple paths in advance so that in case of a failute of a path, one of the alternatives is chosen without any cost for searching for another one but at the extra overhead to keep the alternative paths alive. In Directed Diffusion the sink queries the sensor nodes if a specific data is available by flooding some tasks. Caching is a big advantage in terms of energy efficiency and delay. Sink sends interest. Reply back from where the interest was received to the sink. Data is sent from the path of lower rates.

Energy-aware routing use a set of sub-optimal paths to increase the lifetime of the network (chosen by means of a probability function depending on energy consumption of each path). Select a single path randomly from multiple alternatives to save energy. Complicate route setup than Directed Diffusion.

Constrained anisotropic diffusion routing (CADR) - two techniques namely information-driven sensor querying (IDSQ) and constrained anisotropic diffusion. Query sensors and route data in a network to maximize the information gain while minimizing the latency and bandwidth - achieved by activation only sensors that are close to a particular event and dynamically adjusting data routes. IDSQ mechanism to determine which node can provide the most useful information by using estimate theory. Each node evaluates information/cost objective and routes data based on local information/cost and end-user requirements. IDSQ provides a way of selecting optimal order of sensors for maximum incremental information gain - more energy efficient (select which sensors to get the data).

COUGAR - sensor nodes select a leader node to perform aggregation and transmit data to gateway (sink). In-network data computation from several nodes require synchronization.

ACtive QUery forwarding In SensoR nEtworks (ACQUIRE) - the query is forwarded by the sink and each node receiving the query tries to respond partially by using its pre-cached information and forward it to another sensor. ACQUIRE is to deal with one-shot, complex queries for data where a response can be provided by many nodes.

#### Hierarchical

Hierarchical protocols aim at clustering the nodes so that cluster heads can do some aggregation and reduction of data in order to save energy.

Single-tier network can cause the gateway to overload with the increase in sensors density - might cause latency in communication, inadequate tracking of events. Also not scalable for larger set of sensors. Hierarchical routing - to efficiently maintain the energy consumption of sensor nodes by involving them in multi hop communication within a particular cluster and performing data aggregation and fusion to decrease the number of transmitted messages to the sink. Network clustering to cope with additional load and to be able to cover a large area of interest without degrading the service. Cluster heads sometimes chosen as specialized nodes that are less energy-constrained. Cluster head performs aggregation of data and send to sink on behalf of the nodes within its cluster.

Low-energy adaptive clustering hierarchy (LEACH) - form clusters of the sensor nodes based on the received signal strength and use local cluster heads as routers to the sink. All data processing (data fusion and aggregation) are local to the cluster. Cluster heads change randomly over time to balance the energy dissipation of nodes. Nodes die randomly and dynamic clustering increases lifetime of the system - but extra overhead. Use single-hop routing where each node can transmit directly to the cluster head and the sink.

Power-efficient GAthering in Sensor Information Systems (PEGASIS) is an improvement of the LEACH protocol. Rather than forming multiple clusters, PEGASIS forms chains from sensor nodes so that each node transmits and receives from a neighbor and only one node is selected from that chain to transmit to the base station (sink). Use multi-hop routing by forming chains and selection only one node to transmit to the base station instead of using multiple nodes. However, introduces excessive delay for distant node on the chain.

Hierarchical-PEGASIS - extension of PEGASIS. Reduce delay by simultaneous transmissions of data. Chain-based protocol with CDMA capable nodes - to avoid collisions. Tree like hierarchy, each selected node in a particular level transmit data to the node in the upper level. Nodes that are receiving at each level rise to next level. Avoid clustering overhead but still require dynamic topology adjustment since sensor's energy is not tracked.

Threshold sensitive Energy Efficient sensor Network protocol (TEEN) - designed to be responsive to sudden changes in the sensed attributes. Responsiveness is important for time-critical applications. Closer nodes form clusters. Cluster head broadcasts two thresholds to nodes. Hard threshold allows the nodes to transmit only when the sensed attribute is in the range of interest. It is the minimum value to trigger sensor node. Soft threshold will further reduce the number of transmissions if there is little or no change in the value of sensed attribute. However, user may not get any data at all if the thresholds are not reached. Adaptive Threshold sensitive Energy Efficient sensor Network protocol (APTEEN) - extension of TEEN, capture periodic data collections and reacting to time-critical events. Drawbacks - overhead, complexity of forming clusters in multiple levels, implementing threshold-based functions and dealing with attribute-based naming of queries.

Energy-aware routing for cluster-based sensor networks; sensors are grouped into clusters prior to network operation. Algorithm employs cluster heads, namely gateways. Gateways maintain the states of the sensors and set up multi-hop routes for collecting sensor's data. The command node (sink) communicates only with the gateways. Sensor nodes in cluster can be sensing only, relaying only, sensing-relaying and inactive. Gateway will continuously monitor the available energy level at every sensor that is active - gateway is powered. Rerouting is triggered by an application related event.

CTP

RPL

#### Location Based

Location based protocols utilize the position information to relay the data to the desired regions rather than the whole network.

Location information needed to calculate distance between two particular nodes so that energy consumption can be estimated. Query can be diffused only to the particular region (if known) which eliminate the number of transmission significantly.

Minimum energy communication network (MECN) sets up and maintains a minimum energy network by utilizing low power GPS. The main idea of MECN is to find a sub-network which will have less number of nodes and require less power for transmission between any two particular nodes. Performed using a localized search for each node considering its relay region. Use distributed Belmann-Ford shortest path algorithm with power consumption as the cost metric. MECN is self-reconfiguring and thus can dynamically adapt to node's failure or the deployment of new sensors. The small minimum energy communication network (SMECN) is an extension to MECN. The sub-network constructed by SMECN for minimum energy relaying is smaller; the number of hops for transmissions will decrease. However, fining a sub-network with smaller number of edges introduces more overhead in the algorithm.

Geographic adaptive fidelity (GAF) - energy-ware location-based routing algorithm. Conserves energy by turning off unnecessary nodes in the network without affecting the level of routing fidelity. It forms a virtual grid for the covered area. Each node uses its GPS-indicated location to associate itself with a point in the virtual grid. Nodes associated with the same point on the grid are considered equivalent in terms of the cost of packet routing. Keep some nodes located in a particular grid area in sleeping state in order to save energy. GAF can increase the network lifetime as the number of nodes increases. Nodes 2, 3, and 4 are equivalent and two of them can sleep. Nodes changes states from sleeping to active in turn so that the load is balanced. GAF can be considered as a hierarchical protocol; clusters are based on geographical location. However, does not do any aggregation or fusion.

Geographic and energy-aware routing (GEAR) uses energy aware and geographically informed neighbor selection heuristics to route a packet towards the target region. Only considering a certain region rather than sending the interests to the whole network. Each node keeps an estimated cost and a learning cost of reaching the destination through its neighbors. Estimated cost is a combination of residual energy and distance to destination.

#### Network flow and QoS-aware

Routing approaches that are based on general network-flow modelling and protocols that strive for meeting some QoS requirements along with the routing function.

Network flow - route setup.

QoS aware - end to end delay requirements while setting up the paths in the sensor network.

Energy aware QoS routing in sensor networks will ensure guaranteed bandwidth (or delay) through the duration of connection as well as providing the use of most energy efficient path.

Maximum lifetime energy routing - maximize the network lifetime by carefully defining link cost as a function of node remaining energy and the required transmission energy using that link. Use Bellman-Ford shortest path algorithm.

Sequential assignment routing (SAR) - table driven multi-path approach striving to achieve energy efficiency and fault tolerance. SAR protocol creates tree rooted at one-hop neighbors of the sink by taking QoS metric, energy resource on each path and priority level of each packet into consideration. Multiple paths from sink to sensors are formed. One of these paths is selected according to the energy resources and QoS on the path. Any local failure causes an automatic path restoration procedure locally - failure recovery is done by enforcing routing table consistency between upstream and downstream nodes on each path. Drawback - overhead of maintaining the tables and states at each sensor node.

Energy-aware QoS routing protocol - find a least cost (using Dijkstra's algorithm) and energy efficient path that meets certain end-to-end delay during the connection. A class-based queuing model is employ to support best effort and real time traffic at the same time.

SPEED - requires each node to maintain information about its neighbors and uses geographic forwarding to find the paths. SPEED strive to ensure a certain speed for each packet in the network so that each application can estimate the end-to-end delay for the packets by dividing the distance to the sink by the speed of the packet before making the admission decision. SPEED can provide congestion avoidance when the network is congested.

# Multichannel Routing Protocol (Prot & Algo)

(20-25 pages)

In this chapter, we focus specifically on the reliability of radio communication links in sensor networks.

The channels used by this technology often suffer interference from Wi-Fi and Bluetooth.

Suffer in data reliability on account of frequent occurrences of external interference.

WSNs need to be able to operate reliably in the presence of such interference.

Sensor node transceivers offer communication on different non-overlapping frequency channels. This multichannel feature could be leveraged to ensure a seamless operation in the face of severe external interference. Reducing packet loss (hence retransmissions) and increasing the efficiency of spectrum usage.

As a multichannel solution for mitigating external interference, MCRP is introduced as a routing protocol that communicates across layers.

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 minimize latency and minimal number of failures.

Multichannel Cross-Layer Routing Protocol concentrates on finding channels for the nodes that are free from or have low interference. It allows the allocation of these channels in a way likely to minimize the chances of nodes which are physically near to communicate on the same channel. Hence, it reduces cross interference between different pairs of nodes.

We present MCRP, a decentralized cross-layer protocol with a centralized controller. Our cross layer multi-channel protocol focuses on the network and application allows. 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 and selects which channel each node should listen on; and a protocol which allows the network to communicate the channel change decision, probe the new channel and either communicate the success of the change or fall back to the previous channel.

In the rest of this chapter, (the outline of the chapter is as follows…)



## MCRP Design

Before presenting the design on MCRP and the main components, we introduce the general design goals (several crucial observations). The design of the multichannel protocol is motivated/based on several crucial observations:

The design of MCRP is based on these observations:

1. Channel assignment – Sensors have limited memory and battery capabilities. In order to maximize the sensors lifetime, a centralized LPBR that has larger memory and fully powered in used for decision making. LPBR has complete knowledge of the topology which enables it to make good channel assignment decisions based on a two-hop colouring algorithm – centralized; thus nodes computation is transferred to LPBR.
2. 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 maximize throughput.
3. Frequency diversity – Multichannel increases the robustness of the network towards interference. However, applying multichannel to the existing RPL may hinder detection of the new nodes and cause problems for maintaining the RPL topology. We overcome thus problem by two mechanisms. (((((??)Existing nodes maintain a table of channels on which their neighbours listen and use unicast to contact those nodes. New nodes listen on a Contiki default channel (26) and when connecting search through all channels. As in RPL, periodically all nodes broadcast RPL control messages on the default channel in an attempt to contact new nodes.

Our work (make use) of existing standards and focus on improvement that can be used with the standards. MCRP is compatible with RPL with minor changes in order to be able to be used as a multichannel protocol as MCP concentrates on cross layers between the network and application layers. Minor changes on the MAC layer (ContikiMAC – that is energy efficient DETAILS???) in order to be compatible with multichannels – to be able to change to the correct channel when transmitting/retransmitting by accessing the channel information that are stored on the network layer.

## Channel Selection Strategy

## Channel Switching

## Channel Quality Checking

## Reconnection Strategy

# Implementation

### Protocol Stack (changes at MAC, RT, NBR TB, BR etc.)

### MCRP Implementation

### Memory Footprint

-how many packets more than usual?

-memory consumption?

# Energy vs Loss Tradeoff

-requires more energy (to do MCRP) but reduce retransmissions in the long term

-how much energy than usual?

-improvement in loss when using MCRP?

# Results and Discussions

(10-15 pages)

-include prelim results from testbed



## Experimental setup

## Evaluation

# Future Works

-include gantt chart

## Conclusions

## Future Works

(2-4 pages)

# Bibliography