Improving the Energy Efficiency and Transmission Reliability of Battery-Powered Sensor Nodes at the Edges of a Mains-Powered Wireless Network

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Dedication

For Mum, Bradley and Jonathan, thank you for all your encouragement and support

Abstract

A masters thesis focussing on achieving improvements in transmission reliability and energy efficiency for a battery-powered wireless sensor node on the edge of an industrial heterogeneous wireless network that consists predominantly of mains-powered nodes. A router-switching technique is proposed to allow the sensor node to make gains in transmission reliability and energy efficiency by taking advantage of the scenario where multiple wireless routers are in range and switching between them, instead of only being able to transmit to one router.

The research involves simulation of a number of network scenarios where the router-switching technique is enabled and disabled, to measure the advantage gained for the sensor in terms of its functional lifetime. The simulation is based on an abstract model that focusses on the edge of the mains-powered area of the network, where the battery-powered sensor is located.

The simulation results show that for many cases, router-switching provides a higher level of transmission reliability and lower levels of energy consumption than the scenario where router-switching is disabled, as well as improvements in data loss rates.

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Chapter 1

Introduction

This thesis proposes and investigates a router-switching technique in the scenario of an industrial heterogeneous wireless sensor network. The research involves analysing the effects on energy efficiency and transmission reliability for a battery-powered sensor node when the proposed router-switching technique is enabled and disabled. The proposed router-switching technique is intended to increase the functional lifetime of the sensor node by allowing it to switch between multiple wireless router nodes placed nearby, in order to use the wireless link that can provide the highest transmission reliability at any point in time, and consequently the most energy efficiency. The network is heterogeneous meaning that it contains nodes with different capabilities and so all router nodes have an unlimited supply of energy whereas the sensor does not.

The analysis of the potential advantage gained by the router-switching technique is performed using simulations of an abstract model that focusses on the edge of the "powered area" of the network, where the sensor node is able to connect to the mains-powered router nodes.

This chapter provides a comprehensive introduction to the area of wireless sensor networks, to set the context for the research performed. In section 1.3 a detailed description of the research problem is put forth.

1.1 What are wireless sensor networks?

A wireless sensor network (WSN) is a network made up of a number of small autonomous devices distributed throughout a physical environment to perform the task of monitoring one or more variables that exist in that environment. When monitoring one or more environmental variables, the wireless sensor network can also record or report what is observed and the numerous devices in the network can cooperatively transmit the observed data back to a main autonomous device for further analysis and processing. Newer WSNs have bi-directional functionality, meaning that activity of each sensor can be controlled at any time, whereas most sensors follow a predetermined schedule of actions.

There are many types of environmental variables or phenomena that can be monitored, including temperature, atmospheric pressure, sound and vibration. There is a large number of ways a WSN can be used and this is dependent on the scenario or environment. For example, a WSN may be used to measure temperature in different areas of a room, or motion in an outdoors area. Because their fundamental behaviour is sensing physical variables and reporting or recording information and events, it is up to the implementor of the network to decide which phenomena need to be sensed and how the sensor network will use the data or events it senses.

In the case of most WSNs, all nodes in the network are powered by their own internal battery, and cannot rely on an external power source. Because of this, it is important for wireless sensor networks to run efficiently in order to maximise the functional lifetime of the network.

1.1.1 How do they work?

WSN protocol stacks

WSNs consist of hardware devices that have a software-based network "stack" operating on them. This stack is similar to the network OSI model [15], which consists of seven layers:

Application

Presentation

Session

Transport

Network

Datalink

Physical

In normal computing scenarios the application layer is responsible for handling events where the software application being used receives and transmits data through the components of the software that are responsible for its network communication aspects. A WSN stack also contains an application layer but in a WSN stack the application layer differs as this layer defines the behaviour of the WSN node in terms of performing the real-world task. An example of this would be a WSN application layer defining how regularly a WSN node should sense and record the temperature of the surrounding environment.

The presentation, session and transport layers present in the OSI model are present in normal computer networking scenarios in order handle tasks such as encryption and conversion of data representation between different formats (Presentation layer), as well as interhost communication, managing sessions between applications (Session layer) and end-to-end connections and reliability of communication between hosts (Transport layer).

The Network layer present in the OSI model is an important layer in WSN stacks, as it is in normal computer networking scenarios. This is because the Network layer handles host-to-host communication, and determines routing paths through a network of devices.

Not all WSN stacks specifically define the presentation, session and transport layers mentioned above, but the network, physical and datalink layers always exist in a WSN stack. Different network "protocols", which can be defined as formats for communication, exist at the different layers and not all WSN protocol stacks are the same.

The fundamental layers of any network stack are the physical and datalink layers. The datalink layer is also known as the Medium Access Control (MAC) layer. The most widely used WSN protocol for the physical and MAC layers of a WSN stack is the IEEE 802.15.4 standard protocol for low-power low-bandwidth wireless sensor networks [6]. The IEEE-802.15.4 protocol is the main protocol that is considered in this thesis.

In the IEEE 802.15.4 protocol standard, the physical layer (PHY) provides the data transmission service and an interface to the "physical layer management entity". The physical layer management entity or "PLME" offers access to all management layer functions at the physical layer and keeps a record of information on any related personal areas networks (PANs). More importantly the PHY layer manages the physical RF transceiver and decides which frequency channel to select for transmission as well as performing energy and signal management functions.

The MAC (Medium Access Control) layer sits one level above the PHY layer and coordinates transmission of MAC "frames" across the physical channel. Additionally, the MAC layer provides a management interface known as the MAC Layer Management Entity (MLME). The MLME manages access to the physical channel and the network beaconing functions. The MAC layer also provides connection points for services that exist at the higher layers which are not defined in the IEEE 802.15.4 protocol standard.

Wireless sensor nodes

The IEEE 802.15.4 standard specifies two classes of nodes: "full function devices" (FFDs) and "reduced function devices" (RFDs). Full function devices are able to relay messages to other FFDs as well as RFDs, whereas RFDs can only relay messages to FFDs.

Each network will have at least one "PAN coordinator" node which controls and manages the network. This role in the network can only be performed by an FFD. The "PAN coordinator" role is not to be confused with the "coordinator" title, which is another term used to describe an FFD.

Full function devices can perform a sensing task as well as their other functions in the network but are not always required to. This is dependent on the how the WSN is designed and implemented. RFDs are dedicated to only performing a sensing task and relaying this information to a nearby FFD. RFDs are also referred to as "end devices".

WSN Topologies

In the IEEE 802.15.4 standard there are two main categories of network topology. These are the "star" based topologies, and the "peer-to-peer" based topologies. Although these types of network topology have a number of differences, every network requires at least one FFD to act as the PAN Coordinator for the network.

The "star" topology is arguably the most structured topology as one node in the network (an FFD) will declare itself as the PAN Coordinator and act as the central node of the star network. All other nodes in the network, regardless of node type, will be directly connected to this central node. Nodes in a star topology network cannot communicate with eachother directly, instead their information has to pass through the PAN Coordinator.

"Peer-to-peer" topology sensor networks, also known as "point-to-point" networks, allow for much more loosely constrained connections between nodes. This means an FFD who is not the PAN Coordinator can be connected to the

PAN Coordinator as well as being connected to at least one other FFD. RFDs are still only able to be directly connected to an FFD, and are unable to directly communicate with eachother.

The “peer-to-peer” sensor network topology serves as the basis for the development of “ad-hoc” wireless sensor networks which are capable or performing self-management and self-organisation, but because the IEEE 802.15.4 standard only defines the specification for the PHY and MAC layers of the network stack, no network (NWK) layer is defined and so no routing algorithms are directly or “natively” supported by 802.15.4. If the NWK layer is defined in the stack, then support for multi-hop routing can be made available.

Cluster-Tree Topology

The IEEE 802.15.4 standard also details the “cluster-tree” topology [6], which can be implemented by adding further restrictions into a peer-to-peer based network topology. The cluster-tree topology takes advantage of the fact that a RFD can only be connected (also known as being associated) with one FFD at a time. This creates a topology where the RFDs are “leaf-nodes” of a tree structure comprised of FFDs.

1.2 Heterogeneous WSNs

Many WSNs are classed as “homogeneous”, meaning that they are made up of identical nodes, whereas heterogeneous WSNs involve nodes with different levels of capability.

In heterogeneous WSNs (HWSNs), this is termed as “resource heterogeneity” [11]. The three common types of resource heterogeneity that can be present in a sensor node are computational heterogeneity, link heterogeneity and energy heterogeneity.

Computational heterogeneity means that some sensor nodes will have more powerful microprocessors and more memory than normal nodes. With more powerful computational resources, the heterogeneous nodes can provide more advanced data processing and longer-term storage of data.

Link heterogeneity means that a heterogeneous node will contain a network transceiver that has higher bandwidth capacity and a longer transmission range.

Energy heterogeneity means that a node can be powered by an external power source, which allows an unlimited supply of energy to the node. An example of this is line-power in a building. Energy heterogeneity can also mean that a power would instead have a larger interal battery than normal, or its battery is replaceable.

The most important of these three types of heterogeneity is energy heterogeneity as both computational and link heterogeneity will bring negative impacts to the whole sensor network in terms of network lifetime if there is no energy heterogeneity to compensate for the increase in power consumption that is occurring.

Kumar et al. [11] state that there are three main benefits that are obtained by placing a number of heterogeneous nodes in a wireless sensor network:

1. Prolonging network lifetime

   In a heterogeneous WSN, the average energy consumption for forwarding a packet from the normal nodes to the sink will be much less than the energy consumed throughout the network in a homogeneous sensor network.

2. Improving reliability of data transmissions

   Sensor network links tend to have low reliability, and each hop significantly lowers the end-to-end delivery rate. In a heterogeneous network, there will be fewer hops between normal sensor nodes and the sink. This means that heterogeneous WSNs can achieve much higher end-to-end delivery rates than a homogeneous sensor network.

3. Decreasing latency of data transportation

   Computational heterogeneity can decrease the processing time before data is transmitted, and if there is link heterogeneity as well, the waiting time of the data in the transmitting queue can be decreased as well. Less hops between a normal sensor node and the sink node also provides less forwarding latency.

Yarvis et al. [17] state in their research that energy heterogeneity was able to provide a five-fold increase in the functional lifetime of a large battery-powered network of sensors.

1.2.1 Heterogeneous WSNs in Industrial Environments

A lot of industrial heterogeneous networks involve wireless and wired nodes, working in tandem.

The industrial heterogeneous network being considered in this research only involves wirelessly communicating nodes, but some are powered by mains cables.

Heterogeneous WSNs are commonly preferred for industrial environments due to their ability to maintain a long functional lifetime under challenging conditions. This is due to the resource heterogeneity the nodes can possess.

Challenges faced in Industrial HWSNs

There are a number of challenges that are encountered in industrial heterogeneous WSNS. The majority of these challenges are caused by varying types of wireless signal interference and by the operation of heavy machinery in the environment. Additionally, signal strength can be heavily degraded due to signal reflections off walls, floor and nearby machinery.

Depari et al. [1] state that in regards to sensor networks for most industrial applications, sensor compactness and mobility are not critical requirements and that sensors are usually placed in a fixed place and power supply availability is practically everywhere. This is not true for the problem scenario in this thesis, as it assumed that the sensors are unable to be mains-powered due to the types of machinery they are fixed to. Depari et al. [1] also state that on the contrary, robustness is a key factor, as strong electromagnetic power sources (welders, smelting furnaces, motors and so on) can sensibly affect transmission quality. Additionally, it is stated that it is important to transfer information within a small, fixed and known time, therefore performance is a crucial point of most industrial sensor networks.

1.3 Description of the Research Problem

The research problem considers the scenario of a wireless sensor network placed in an industrial environment. The network is heterogeneous as it is comprised of battery-powered sensor nodes, as well as a number of mains-powered routing nodes. The mains-powered nodes make up the "powered" area of the network as they have no constraint on the amount of energy they can use, and these nodes work together to relay data transmissions from the battery-powered sensors back to a central collection point or "sink" node. The first hop involved in relaying a data transmission from a sensor node to the "sink" node is always between the sensor itself and one of the mains-powered router nodes in range of the sensor. A diagram of this scenario can be seen below.

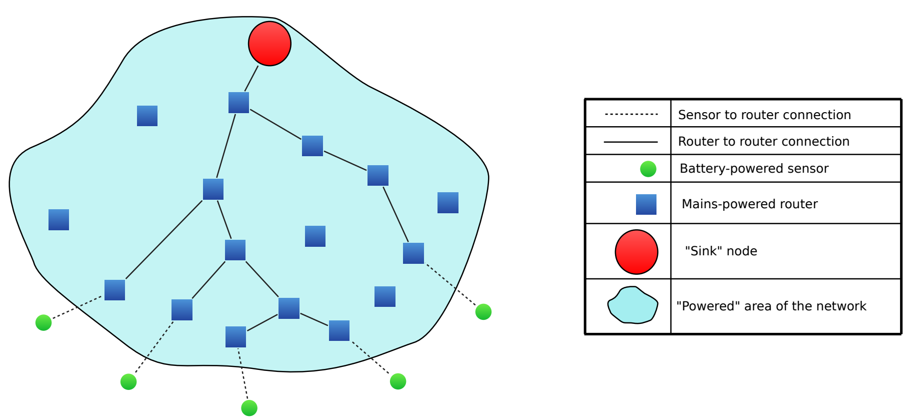

Figure 1.1: Industrial Heterogeneous Network Problem Scenario

Because the network is placed in an industrial environment, there are many external factors that can degrade the quality of the wireless link between the sensor node and mains-powered node it is currently connected to. These factors include objects such as vehicles moving around in the environment, as well as any electromagnetic inference from other machinery operating nearby and any inference caused by the sensor nodes transmitted signal reflecting off harsh surfaces and solid stationery objects. If the wireless link between the sensor and its current coordinator node experiences a high degradation in link quality, this will mean that any data packets that the sensor attempts to transmit to the mains-powered router will suffer from interference and not be correctly received by the router. This will require the sensor node to attempt to re-transmit these packets. Re-transmission of packets is not energy efficient as the amount of battery power usage is increased while the amount of data successfully sent stays the same. Additionally, the inefficient use of the sensors battery decreases the overall lifetime of the sensor and the functional lifetime of the network.

Because of the inefficiency of retransmissions when a wireless link is degraded, taking advantage of the fact that multiple coordinator nodes are in range of the sensor node becomes a potential solution to this problem. By employing a decision making process that allows the sensor to assess which router is most appropriate to be connected to at a given point in time, with respect to the quality of the wireless link, potential increases in energy efficiency and transmission reliability could be achieved. In this proposed solution, the decision made by the sensor is based on metrics about the available wireless links, which it receives from each router node in range. Using these metrics, the sensor node can make a decision to stay with the router it is currently connected to, or switch to an alternative router, in order to maintain the highest level of energy efficiency and transmission reliability possible. The resulting trade off of switching from one router to another is that the disassociation and reassociation process incurs signalling costs which create significant drain on the battery. Additionally, because it is difficult to predict how a wireless link may degrade or improve in the future, switching router nodes may not always be the most energy efficient action in the long term. The aim of this thesis is to study how much benefit is gained by allowing router switching to occur, in comparison to the scenario where the sensor node is unable to switch from the router node it begins with.

In Chapter 2 - "Relevant Research Issues in Wireless Sensor Networks", research issues in the field of wireless sensor networks are discussed, with a focus on existing research issues that have similarities to the research problem of this thesis.

Chapter 3 - "Problem Domain and Abstract Simulation Model" describes in detail the abstract simulation model that was implemented to summarise the problem domain and study the effects of switching parent nodes.

The results obtained from these simulations are presented and discussed in Chapter 4 - "Simulation and Numerical Results".

Chapter 5 - "Conclusion and Future Work", outlines the conclusions about the effects of parent switching that were drawn from the results analysis in Chapter 4, and discusses what further additions to the simulation model could be made to improve upon this research.

Chapter 2

Relevant Research Issues in Wireless Sensor Networks

This chapter discusses a number of relevant and common problems faced in homogeneous and heterogeneous wireless sensor networks and explains how other research performed has attempted to deal with these common problems. The approaches and scenarios put forth in this related research to deal with these common problems have a number of similarities and differences to the problem scenario and solutions put forth by this thesis, and these are explained in this chapter.

2.1 Energy Efficiency

Energy efficiency techniques and energy efficient routing techniques make up a large portion of the existing research into wireless sensor networks. This is due to battery life being a key constraint in sensor node performance. Energy efficiency techniques exist for both homogeneous and heterogeneous sensor networks. The key goal of energy efficiency is to extend the "functional lifetime" of the network to its possible maximum, by minimising battery use while still performing all tasks required by the specific application of the sensor network.

In the literature on energy efficiency for WSNs, a number of energy-aware routing protocols have been been proposed. These include the widely known protocols such as the "Low-Energy Adaptive Clustering Hierarchy" (LEACH) protocol [5], the "Energy-Aware Ad-hoc On Demand Distance Vector" (AODV) routing protocol [14] and the "Minimum-Transmission-Energy" (MTE) protocol [5][4]. In addition to these three protocols, the majority of energy efficient protocols discussed in the existing literature have been designed for homogeneous WSNs. MTE is a routing protocol that selects the route with minimum transmission energy to the destination. In MTE routing, the nodes closest to the base station are heavily used to route packets to the base station. Thus these nodes will die out quickly due to their high energy dissipation [8].

A common approach to achieve energy efficiency in homogeneous WSNs is to keep all the nodes in the network alive for as long as possible by avoiding complete depletion of energy on any particular node, which would result in one less node existing in the network. AODV implements this concept by avoiding specific nodes which are very low on energy when deciding on a source-to-destination route. More generally, this approach can be classified as an "Address-centric" routing method, also known as "Node-centric" routing, as "each source independently sends data along some established path to the sink", also known as "end-to-end" routing [9]. Additionally, AODV enhances the energy efficiency it can acheive by dynamically turning off the radio interfaces of nodes during the periods when the nodes are idle [8]. In contrast to "Address-centric" routing, a "Data-centric" routing method involves the scenario where "the sources send data to the sink, but routing nodes enroute look at the con- tent of the data and perform some form of aggregation or consolidation function on the data originating at multiple sources" [9].

LEACH can be classified as a "Data-centric" routing method because the LEACH protocol achieves energy efficiency by using a technique known as "clustering". Clustering involves the aggregation of data, also known as "data fusion" from a number of nodes in a localised area to one node in the same area that has been designated as the "cluster-head". The cluster-head is responsible for transmitting the aggregated data from the localised group of sensor nodes back to the PAN Coordinator or "sink" node of the network. The literature on LEACH states that "large energy gains can be achieved by performing the data fusion or classification algorithm locally, thereby requiring much less data to be transmitted to the base station" [5], and that "LEACH is able to distribute energy dissipation evenly throughout the sensors, doubling the useful system lifetime for the networks we simulated" [5]. LEACH achieves this even energy dissipation by performing randomisation of cluster-head selection during the lifetime of the network, so that one particular node is never performing as a cluster-head for the entire time.

Like LEACH, and other homogeneous energy efficient clustering schemes, there are also energy efficient clustering schemes for heterogeneous WSNs. One of these is the "Energy Efficient Heterogeneous Clustered Scheme for Wireless Sensor Networks" [11]. This paper discusses a method to increase the energy efficiency of a wireless sensor network by enhancing the clustering protocol. The paper states that the key area of clustering algorithms, in terms of presenting opportunities for increased energy savings, is the "cluster-head selection" process. Because of this, the paper focusses on studying the impact of the "heterogeneity of nodes" in terms of their available energy in hierarchically clustered WSNs.

The paper assumes that a percentage of the sensor node population is provided with additional energy resources, and states that homogeneous clustering protocols assume that all the sensor nodes are equal in terms of available energy and therefore cannot utilise node heterogeneity. The authors adapt this heterogeneous approach and build on it by introducing an energy efficient heterogeneous clustered scheme, which is based on a "weighted election probability" for each node to become a cluster head. This probability is weighted based on the residual energy present in each node.

The simulations performed for this publication demonstrate that the EEHC technique was able to extend the lifetime of the network by 10%, when compared with the homogeneous LEACH technique using the same number of powerful nodes in the network [11].

There are a number of similarities and differences between the energy efficiency techniques discussed above and the problem scenario and proposed solution put forth in this thesis. Although LEACH does aim for energy efficiency, LEACH has been designed for homogeneous WSNs and therefore aims for energy efficiency for all of the nodes in network. In the problem scenario of this thesis, we are not concerned with the energy efficiency of all nodes, as there are a large number of mains-powered nodes present. Instead, the main concern is the battery-powered nodes only.

Additionally, the problem scenario put forth in this thesis does not require aggregation of data in localised clusters but the concept of increasing energy efficiency by switching which node is acting as a cluster-head is similar to the proposed solution where the battery-powered sensor node switches from one router to another to maintain energy efficiency. The key distinction is that switching which node is acting as the cluster-head is done so that the node acting as the cluster-head does not completely deplete its battery, where as the battery-powered sensor in the problem scenario switches which router it transmits to in order to benefit its own energy efficiency instead.

In the "Energy Efficient Heterogeneous Clustered Scheme for Wireless Sensor Networks" paper [11], clustering and data aggregation are still being used, but the paper does assume "energy heterogeneity" exists in the network, as some nodes are provided with additional energy resources, and are therefore more likely to be used as cluster-head nodes. This is similar to the research problem scenario except that the heterogeneous nodes are not mains-powered in [11], and therefore still have a limited amount of energy available to them.

2.2 Reliable and Adaptive Routing

Reliable and adaptive routing are related to the idea of energy efficiency in the sense that if packets are routed in a reliable manner they will not be lost, and therefore the transmitting sensor does not have to spend additional energy to transmit those same packets again, or to transmit new packets of data. Reliable routing is important for scenarios where each data reading performed by a sensor is critically valuable to the application of that specific sensor network, as another data reading being performed may not produce the same result as the inital reading. Although it can help with energy efficiency, some reliable routing methods are not always the most energy efficient routing method, as additional energy may need to be used in some cases to guarantee that data is delivered in a reliable (and consistent) manner, and so tradeoffs between reliability and energy efficiency have to be made in a large number of WSN routing protocols.

The common approach in address-centric reliable routing is to send data across the wireless links that are least likely to be interrupted or experience weak signal strength. In order for this to occur, metrics that give indications about the quality, signal-strength, or signal-stability [2] of all possible node-to-node connections that are being considered during the routing, need to be measured and compared, so that the most appropriate link can be picked. In address-centric reliable routing, this measurement and comparison is generally performed by each node that is required to forward the data onwards to the next hop in the route.

Another approach to ensure reliable of transmission of data can be observed in the "Directed Diffusion" protocol for scalable and robust communication [7]. Directed Diffusion can be classified as a data-centric routing method and operates by having the sink broadcast "interests" to all sensor nodes in the network. Each sensor node "keeps the "interest" in its local cache and uses the gradient fields within the "interest descriptors" to recognize the most suitable routes to the sink" [16]. Once these routes have been established, they are then used by the source nodes to forward the data to the sink [16]. Although Directed Diffusion provides reliable routing, it still suffers from a high overhead in energy consumption [16].

A proposed improvement upon Directed Diffusion titled EARS (Energy Efficient and Reliable Routing Scheme) is put forth in [16]. This protocol takes a more "Node-centric" approach , and the routing at the Network (NWK) layer is based on a "Radio-aware Metric", which contains radio information from the Medium Access Control (MAC) layer. In this routing scheme, data is forwarded to a designated neighbor who is selected based on the "Radio-aware Metric", instead of flooding exploratory data from the sink into the whole network like with Directed Diffusion [16]. It is stated that EARS is almost 4.3 times more efficient in terms of energy consumption and 2.6 times more reliable in terms of data delivery. The interaction between the NWK and MAC layers that occurs in the EARS protocol in order to gain relability of routing can be described as a "cross-layer" scheme or optimisation.

"Cross-layer" schemes have also been used for reliable routing in industrial environments. In "A Reliable Routing Protocol for Industrial Wireless Sensor Networks" [12], a reliable and energy efficient protocol for homogeneous WSNs in industrial environments, titled "REEP", is proposed.

The routing protocol is based on a "cross-layer" scheme where a new protocol layer is inserted in between the MAC and Network layers of the protocol stack. This additional layer can offer information about link qualities to the Network layer. This allows the transmitting node to choose a suitable neighbour-node to take over the role of forwarding a packet, in the case that the link to the current forwarding node degenerates.

The routing protocol is derived from a general architectural extension to routing protocols called "Cluster-based Forwarding" (CBF), which takes influence from cooperative communication. The authors state that the routing protocol is adapted from the original CBF protocol, because it focusses on end-to-end energy efficiency, which is important for reliability in industrial WSNs. Their protocol is an advanced form of CBF and is combined with an energy balancing routing protocol based on using the minimum number of hops to transmit a packet. The new protocol layer that works as part of the protocol is labelled as the CBF_A layer. The CBF_A layer can communicate with the NWK and MAC layers, and when the loss of a packet is detected, the CBF_A layer can consider information from both the NWK and MAC layers and use this to select a neighbouring node of the original next-hop node to replace the original next-hop node in the forwarding process.

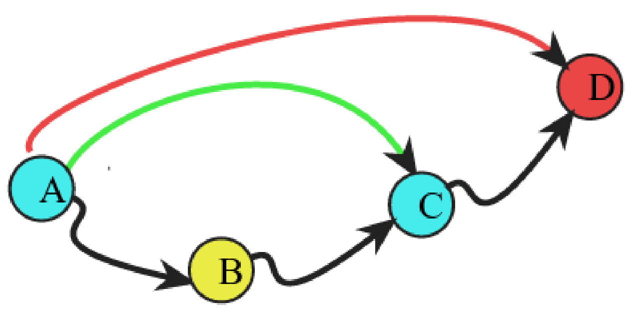

Figure 2.1: Hop-wise forwarding using the CBF_A Layer

An example is given to explain this in more detail. This example can be seen in the figure above. The example defines node A as the transmitting node and node B as the receiver. Nodes C and D are located within one hop of node B. The routing layer chooses B as the next-hop node. The routing layer can see that node C is located somewhere between A and B, and does not provide a link quality as good as B. Conversely, while node D is a better node than B because it is closer to the destination, it is not selected because the link quality between A and D is too weak to guarantee a high chance of successful transmission. The paper states that although the routing layer neglected nodes C and D, there are two observations that can be made concerning their roles in improving packet delivery. Firstly, the authors state that if the quality of the link between C and B is better than the link between A and B, then under the assumption that C has received the packet from A while B has not, it is better to shift the transmission task from the AB link to the CB link. Secondly, the authors observe that if node D receives the packet from A that because D is better than B then regardless of whether B has received the packet or not, D can skip node B and continue the forwarding task.

The paper concludes that by including the CBF_A sub-layer between the NWK and MAC layers, the shortage of stable links in the industrial environment is compensated for. It is stated that as a result, the REEP protocol can reduce the retransmissions of data packets and therefore save energy on nodes in the network [12].

There are a number of similarities and differences between the reliable routing methods discussed and the problem scenario and solution proposed in this thesis. Directed Diffusion makes use of the "sink" node to broadcast information into the network to assist with the routing. Although this technique is suitable for reliable routing involving homogeneous sensor networks, it would not provide as much benefit, in terms of reliable transmission, to the sensor node existing in the heterogeneous network scenario as the solution proposed in this thesis. This is because although Directed Diffusion does established suitable routes from a source to the sink node, these established routes are multi-hop and therefore do not specifically emphasise picking the absolute best first-hop available, which is the only hop that needs to be considered by the sensor in the heterogeneous scenario, as the mains-powered routers are able to handle data transmission inside the "powered" area of the network with no energy limitations.

Although EARS improves on Direction Diffusion and performs selection of the most suitable neighbouring node based on its "Radio-aware" metric calculation, it is still intended to be used in a homogeneous WSN and therefore requires exploratory data to be transmitted from the sensor node to the sink. This exploratory data would not be required in the heterogeneous scenario that is considered in this thesis, and therefore it represents an overhead in energy consumption that can be avoided in a heterogeneous WSN that employs a concentration of mains-powered routers.

Finally, REEP shares the same approach as the proposed solution of this thesis by taking link quality information from the MAC layer into account when performing routing, but similarly to EARS and Directed Diffusion, REEP is intended for homogeneous wireless sensor networks and works by forwarding to an immediate neighbour of the next-hop node if a transmission to the next-hop node fails. This approach is different to the proposed solution for maintaining reliability in the problem scenario of this thesis as seperate router nodes in the "powered" area of the network in this research are not guaranteed to be within one routing hop of eachother.

2.3 Router or Coordinator Selection to Maintain Connectivity

Router or Coordinator selection exists as a subset of the research problems of energy efficient routing and reliable routing but holds strong relevance to the problem scenario put forth in this thesis, as the problem scenario focusses the connection between a reduced function device (sensor node) and a full function device (router or coordinator). Router or Coordinanator selection is different to cluster-head selection as a cluster-head aggregates data from a number of nodes connected to itself, before transmitting this data back to the PAN coordinator or sink node, whereas a router or coordinator node performs no aggregation of data from multiple nodes, and always regards multiple transmissions from multiple nodes as seperate. Intelligent router or coordinator selection is important as it allows a sensor node to stay connected to the rest of the network for the longest amount of time possible, based on the information that is available to it about the connection between itself and its current router, or the available but un-utilised connections to routers in range of itself. In this sense, router or coordinator selection is related to both energy efficiency and reliable routing. This is because losing connection or association to a router can require disassociation and reassociation of a particular sensor node with the rest of the network, via the same router or an alternate router, which incurs an energy cost that could have been prevented had a smarter router selection been made. Additionally, by making a bad decision on which router to select, the chance of experiencing interrupted transmission increases, especially in industrial network environments.

Coordinator selection has been considered in research into mobile wireless sensor networks. “A Seamless Coordinator Switching Scheme for Wireless Personal Area Networks” [10], discusses a new technique for “seamlessly” switching which node is acting as the coordinator in a piconet, which is one type of wireless personal area network. The coordinator is referred to as the PNC (Piconet Coordinator) in this paper. The paper outlines that in a piconet, the general approach for selecting the PNC is to select the “most capable device”, based on some criteria. In the case of [10], a homogeneous piconet where all devices are battery powered is considered and the “most capable” device is designated to be the device with the most remaining battery power.

The Seamless Coordinator Switching Scheme deals with the problem of the PNC leaving the network due to unforeseeable event, which causes disruptions to the service that the piconet provides. [10] states that part of the function of the MAC layer is to perform the PNC handover process whenever a PNC leaves the piconet. When this occurs, the MAC layer must choose which device to hand the PNC position to, and then the piconet has to be re-initialised with the new device acting as the PNC. This creates a delay as well as an ineffciency in power consumption as the piconet must be re-initialised. To deal with this problem, the SCS Scheme selects an “alternative” coordinator in the piconet which can be immediately determined to work as the PNC, which avoids the overhead of re-initialising the entire piconet.

Another approach that has been proposed to deal with coordinator selection and node connectivity in mobile WSNs has been put forth in [18]. The technique involves predicting the LQI (Link Quality Indicator) of a beacon-frame that has failed to have been received from a coordinator. The technique uses the predicted LQI value to determine the distance between the mobile node and the respective coordinator node. If the predicted LQI value is below a certain threshold, this signifies that the mobile node is barely in range of the current coordinator node, and so the mobile node will begin the re-association process with a new coordinator node. If the predicted LQI value is above the threshold, the mobile node will wait for the next beacon frame from its current coordinator.

The authors state that this technique has proven to shorten the time where the mobile node is inaccessible by other coordinator nodes by cutting out the waiting time required by the "aMaxLostBeacon" feature of the IEEE 802.15.4 protocol. This enables a decrease in inaccessibility time of 74% [18].

Although this technique has been applied to a homogeneous mobile sensor network, there are similarities between this technique and the proposed solution put forth for the industrial heterogeneous WSN problem scenario. In this paper, the mobile node makes a prediction on what the LQI value of a lost beacon frame could have been, had the beacon frame been received, and uses this LQI value as part of a distance calculation which influences whether a coordinator switch occurs or not. This is similar to the proposed solution in this thesis as the LQI value of the wireless link is considered but in [18] it is a predicted LQI value based on previous LQI values that is helping to determine whether to switch coordinators or continue to wait for the current coordinator. In the industrial HWSN problem scenario, only concrete indicators of link quality are considered and no link quality values are predicted. Predicted link quality values could be inaccurate or misleading with respect to longer time scales and may cause an energy inefficient decision to be made when switching parents.

Additionally, although the technique proposed is strongly focussed on lengthening the connectivity time of the mobile node to the coordinator nodes, it is not for the direct purpose of increasing energy efficiency. Instead the overall aim of the technique is more focussed on allowing the mobile node to move at high speeds, with smoother switching between coordinators than normally provided by the standard 802.15.4 protocol. The technique discussed is also using beacon-enabled mode which is used to keep synchronisation between nodes, and is less energy efficient due to the periodic beaconing that occurs. This is a difference as the problem scenario in this thesis assumes non-beacon mode and therefore does not require periodic beacons for synchronisation, and maintains a stronger focus on energy efficiency.

[10] states that the most capable device to act as the PNC is based on the remaining power of each candidate node, whereas for the problem scenario considered the most capable device to act as a parent for the sensor in the problem scenario of this thesis is the coordinator can provide the highest quality wireless link. The Seamless Coordinator Switching technique considers situations where the coordinator leaves the piconet due to an unforeseen event, but in the proposed problem scenario, the coordinator only becomes unavailable for communication due to a weak or blocked link, and not because it has disassociated from the network. It is more likely that (under real world circumstances in an 802.15.4 network), that the sensor has to leave the network and attempt to re-associate with a different coordinator/router. Additionally, in the SCS scheme, the devices are mobile, and can leave the network due to movement.

To conclude, a large amount of research has been performed in the areas of energy efficiency and reliable routing for homogeneous wireless sensor networks, while research into these same problems for heterogeneous WSNs has been performed to a lesser degree. Techniques for fast and reliable coordinator selection have been considered in the area of homogeneous mobile sensor networks, where consideration of link quality is important, but similar techniques have not been applied to heterogeneous WSNs in industrial environments.

Chapter 3

Problem Domain and Abstract Model

This chapter defines an abstract model of the problem domain being investigated. This abstract model was implemented as a simulation in the OMNeT++ simulation software.

The abstract model captures the essence of the problem without reference to the details of specific network protocols, delineates the scope of our research effort, and captures the assumptions we have made about the underlying research problem.

3.1 The problem domain:

The problem domain consists of a wireless network of sensors, where 3 types of wireless node exist. A network (PAN) coordinator node, a router/coordinator node, and an end device or sensing node. The network (PAN) coordinator will not be modeled in the simulation but it is mentioned here as it is part of the problem domain. The first two node types have unlimited energy resources so are not constrained in the amount of operations they can perform. The third node type (sensor node) has a finite amount of energy available and therefore has to perform efficiently to preserve energy when transmitting or receiving. The sensor node will always have at least 2 coordinators (parent nodes) in its transmission range when parent-switching is enabled.

Only the "edge" of the network is considered, where the sensor node transmits to the mains-powered nodes. This is assumed because once the sensors data is inside the "powered" area of the network, there is unlimited energy available to help transmit the data back to the PAN coordinator or "sink" node. Modelling the transmission of data amongst the mains-powered routers is outside the scope of this research as it does not affect the energy efficiency or transmission reliability for the sensor.

The task assigned to the sensor node is to take a reading of some environmental data, when requested by the network coordinator, and transmit this data to its parent node. A sensor node can only be connected to one parent node at a time, but multiple parent nodes (routers) are in range of the sensor node. This means the sensor node has to make a decision about which parent is the best choice for connecting to at any given time, with respect to the sensor nodes energy consumption from re-transmitting any data packets that fail to transmit on their first attempt.

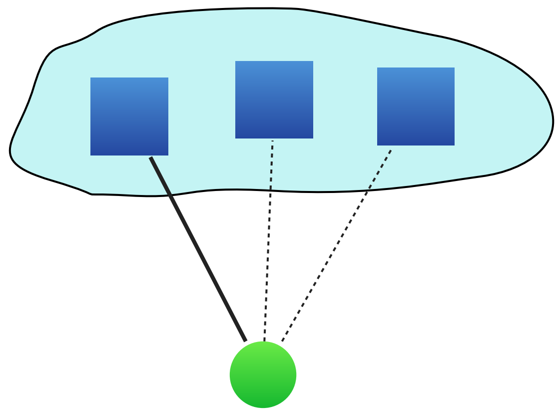

Figure 3.1: Problem Scenario for the Abstract Model - The sensor node, depicted in green, is connected to one parent node via the solid line, with two potential connections available via the dotted lines

Each occurrence of the sensor having to take a data reading, make a decision about the most suitable parent-node and transmit its data to that parent, has been summarised in the concept of a simulation “round”. These “rounds” consist of two phases, one where the sensor node makes a decision about whether to switch from its current parent to a new parent, and one where the sensor then attempts to transmit its data reading to the parent it decided to select.

Simulation “Rounds” and Parent Switching:

The simulation of the network has been design to operate in “rounds” of decision making. Each round has a set length and all rounds last for this set length of time. Each round is split into two “phases”. The “Decision” phase, and the “Transmission” phase.

At the beginning of each simulation round, the round is in the decision phase.

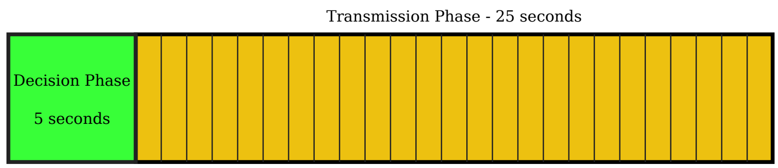

Figure 3.2: Round model, split into the Decision and Transmission phases

It is during this time that the sensor performs the decision making process which allows it to make a comparison of the link qualities of the available parent (router) nodes. If the sensor node finds its current parent node is offering the best link quality, it will stay connected to this node, otherwise it will switch to a new parent. Once this has occurred the decision phase ends and the transmission phase begins

During the transmission phase the sensor simply attempts to transmit 10 packets of data to the parent it chose in the decision phase. The number of attempts to send a packet available to the sensor is limited by the length of the transmission phase. The transmission phase is 25 “seconds” of simulation time. The sensor node will always attempt to transmit its data to its current parent during the transmission phase. The figure below depicts the setup of a round.

Assumptions and Justification:

This section explains a number of assumptions that have been made in the Abstract Simulation Model, and justifies these assumptions.

Assumption 1 is that the **wireless channels between the router (parent)**

nodes and the sensor node are statistically independent. The degradation of one channel does not affect the quality of the other channels. Although in real industrial network environments a certain amount of interference between the wireless links may exist, this assumption allows for clearer analysis of the benefits gained by switching between routers.

Assumption 2 is that **battery consumption on the sensor caused by the sensor checking the channel quality of the available links is not modelled**. Battery consumption is only modelled for packet transmissions and for the cost of switching from one parent node to another. In summary, the sensor is assumed to have "perfect" information about the available links. The justification for this is that if multiple sensor nodes were being considered, as in a real world application of this type of network, then all the sensors in the network would have to use some energy to check the state of the links that are available to them. So therefore this checking would be a base-line energy consumption requirement of all sensors in the network, and could not be avoided. In future work, the abstract simulation model could be enhanced to calculate the additional energy cost, to the sensor, of inspecting the channel state or link quality.

Assumption 3 is that **the number of packets to be sent in each round is the same**. Currently this is 10 packets. This number is a variable and could be set to a higher number as long as the length of the transmission phase was adjusted accordingly.

Assumption 4 is that **the "rounds" of decision making and data transmission that repeatedly occur last for a total of 30 simulated seconds**.

5 seconds for the decision making phase, and 25 seconds for the data transmission phase. The round time, decision making phase time and data transmission phase time are all variables that can be modified for different simulations.

Assumption 5 is that **there is a limit on the number of retransmissions permitted when the sensor node is attempting to send its 10 packets**. WSN protocols such as IEEE-802.15.4 commonly implement a field for limiting the number of permitted retransmission attempts and this value can be varied depending on the specific application of the WSN [6][13]. In the simulation model, this maximum number of attempts has been set to 25. This is equal to the number of simulated seconds in the data transmission phase of each round. By adjusting this variable to a higher value, an increase in the number of attempted retransmissions would be observed during times when the sensor is transmitting data across a weak link.

Assumption 6 is that **the formation of the network has already occurred**. This is because network formation is irrelevant to the focus of the research, and therefore no energy costs are recorded for this. This process has to occur in all sensor networks so calculating the energy usage of this is out of scope of the research.

Assumption 7 is that **the cost of switching between parent nodes is proportional to the energy cost of sending one packet of data**. This cost is a variable initially set to 5. The simulation results will also show values less than and greater than 5 being used, but a 5:1 ratio is a reasonable baseline figure. To justify this, in real world scenarios the cost of re-associating with a new router or parent node can also be varied, as the number of frequency bands that are sensed on the channel to make an estimation of the channel quality can be varied [6], depending on the application of the sensor network.

Assumption 8 is that **channel quality can be modelled using a two-state Markov Model**. The two state model is assumed as it summarises different wireless link qualities into a "usable" or "non-usable" state. This is similar to the Gilbert-Elliot model [3], but has been abstracted based on Assumption 9. A random uniform distribution is used, of the numbers between 1 and 100 inclusive, in order to calculate the chance that a parent node will change its channel state or not. To justify this, choosing from an unbiased distribution of random numbers allows for simplistic modelling of the unpredictability of a channels state in an industrial environment where external events can affect the quality of transmission between nodes.

Assumption 9 is that a packet is either transmitted successfully the first time or requires re-transmission. There is no calculation of bit-errors or re-transmission of only the bits that were not successfully received in the first attempt at transmission. This simplifies the simulation and allows for clearer observation of the benefits gained over long periods of time by router switching being enabled. If bit-errors were modelled, this would require a retransmission of part of a data packet or the potentially the whole packet. The latter being the case already considered.

Assumption 10 is that there are always two or more parent nodes avaiable to transmit to. This is a basic assumption as it would not be possible to study the effects of switching without at least two parent nodes available.

Assumption 11 is that the transmission power of the sensor's transceiver is assumed to be set to "full". This is assumed because it helps to simplify the results from the simulation for anyone wishing to adjust the estimations of power consumption on the sensor using their own transmission power adjustment schemes, which would be different for each real world network.

Decision process:

The sensor nodes decision about staying connected to the current parent node or switching to a new parent node is based on the channel state of the links between the sensor and its available parent nodes.

If a sensor node is experiencing bad link quality with its current parent node, it will decide to switch to a new parent node if a parent node with better link quality is available, but there is an energy cost involved in making this switch to the new parent. In a real-world network, this energy cost comes from disassociating from the current parent and searching for a new parent node to associate with, as well as the cost of information acquisition from the new parent.

Although the sensor may search for a new parent to switch to, there is no guarantee that switching to this new parent node will always provide better link quality over longer time scales than the current parent node.

In some topologies, such as a tree topology, the node must leave and re-join the network as part of the disassociation and re-association process. This can increase the energy cost of switching to a new parent node.

Another option for switching parent nodes is that the current parent node is responsible for directing the sensor node to switch to a new parent. This option will not be considered initially but it does represent a possible switching/decision technique. In order for this option to be pursued, the coordinators would have to communicate information with each other about the quality of the links between themselves and the sensor node.

Algorithm 3.1 Decision Phase Switching Process

Sensor inspects the available qualities of all the parent nodes
If there is a parent node offering a stronger link than the current parent then sensor switches to the new parent and the switching cost is incurred
Otherwise the sensor does not make a switch

Disruption of transmission:

Disruptive external events are the only way that a packet can be corrupted or that link "quality" between two nodes can be negatively affected. In an actual network these events might be vehicles, or obstructing objects, as well as distance-dependent pathloss.

In the simulation, there are two different types of state that a wireless link can be in. These states are the "usable" state and the "non-usable" state. The chance of a wireless link transitioning from one state to the other is based on a percentage probability value that has been assigned in the state transition model. We can label this value as "$\propto$" (alpha).

Depending on which state a wireless link is currently in, the percentage chance of a packet being successfully transmitted on the first attempt is either very

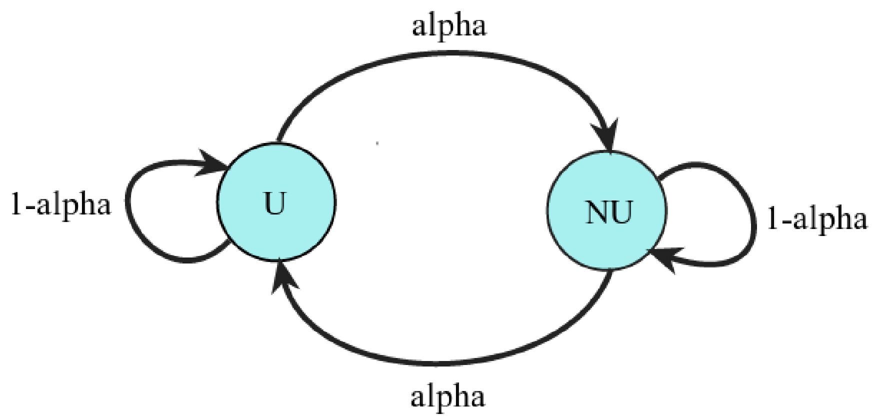

Figure 3.3: State Transition Model for Channel Modelling - The “usable” state is denoted as “U” and the “non-usable” state is denoted as “NU”

high or very low. The usable state represents a 95% chance that an attempt to transmit a packet will result in success. Conversely, the non-usable channel state represents a 5% chance that an attempt to transmit a packet will result in success.

Packet types:

The only packet type present in the abstract model is the data packet. This is the packet of data that an end device will attempt to transmit after performing a “reading” action. The data packet only holds the destination address of the parent node it is intended for. This is because the abstract simulation model could be applied to networks of many different implementations and therefore a specific packet size is not required for the simulation experiments to successfully record failed packet transmissions.

Chapter 4

Simulations and Results Analysis

This chapter details and discusses the numerical and statistical results produced from the simulations performed. As explained in the previous chapter, the simulations were designed to allow for comparison between configurations where parent switching was enabled and disabled.

The simulation is based on the abstract model detailed in the previous chapter, and was implemented in the OMNeT++ Discrete Event Simulator software. This software was chosen as it allowed for flexible modification of the simulation parameters such as the number of parent nodes, and the switching cost through the .ini file mechanism.

Time scales of channel quality variance:

The simulation allows the time scales of channels and round times to be modified separately. This means that the average state holding time $\propto$ in the channel model is easily modified, without having any effect on the time scales of rounds. Additionally, round times are freely configurable with no dependence or effect on channel time scales.

4.1 Comparison of switching scenarios (Experiments performed)

The approach to performing these simulations involved variation of a number of factors. The main point of difference between simulation configurations was whether parent-switching was enabled or disabled. For the case where parent-switching was disabled, the cost of making a switch was not applicable and therefore no range of values were selected for this parameter. In the case where switching was enabled, the two main parameters that were varied were the number of parent nodes available for the sensor node to switch between, and the energy cost of making the switch between parents. Additionally, for all the simulation configurations, a range of $\propto$ values were selected, beginning with 0.05 and increasing by 0.05 until the maximum $\propto$ value of 0.95. A total of 17 simulation configurations were selected. These are detailed in the Table 4.1 below.

Each simulation configuration consists of 5000 rounds of decision-making and data transmission. This 5000 round instance was replicated 100 times for each simulation configuration, with a different random seed for each replication. This is detailed in Table 4.2.

It is important to note that the points visible in Figures 4.1, 4.2, 4.4 and 4.6

were calculated using the average of the resulting values from the 100 replications that were performed for that specific configuration.

	Non-Switching	2 parents	3 parents	5 parents	10 parents
$\propto$	0.05-0.95	0.05-0.95	0.05-0.95	0.05-0.95	0.05-0.95
Switching Cost of 3	NA	Y	Y	Y	Y
Switching Cost of 5	NA	Y	Y	Y	Y
Switching Cost of 10	NA	Y	Y	Y	Y

Table 4.1: Simulation Table 1 - Simulation Scenarios

	Non-Switching	2 parents	3 parents	5 parents	10 parents
Rounds per replication	5000	5000	5000	5000	5000
Replications per sample	100	100	100	100	100

Table 4.2: Simulation Table 2 - Rounds and Replications

Results with respect to Energy Consumption

Figure 4.1 (page 52) details the simulation results of all the listed simulation scenarios, with respect to the energy consumption on the sensor. Energy consumption is listed on the Y-axis as a ratio value, with 1.0 representing the perfect or optimal performance case. 1.0 on the Y-axis is equivalent to 50,000 units of energy consumed on the sensor, which is calculated from the number of rounds (5000) multipled by the number of packets (10) to be sent in each round. The worst case performance on the Y-axis, assuming a switching cost of 5 or higher, would involve a ratio of 3.0 or higher. This would represent the case where 150,000 or more units of energy are consumed by sensor. This is calculated by taking the assumed switching cost of 5 and adding the energy cost of using all 25 transmission slots in each round. This would result in a total energy consumption of 30 units per round, multipled by 5000 rounds.

As mentioned previously, each point on the result curves presented represents an averaged value calculated from the 100 replications of that simulation scenario.

This results figure shows an interesting comparison of energy consumption between the scenario with parent-node switching disabled and the scenarios with parent-switching enabled.

Firstly, in the **non-switching case**, it can be observed that for all values of $\propto$ from 0.05 to 0.95 the energy consumption curve lies between approximately 77.1% and 77.8% higher than the perfect performance case, with ratios of 1.771 and 1.778 respectively. This is due to the fact that the sensor node has no choice of parent, and so it is subjected to all occurrences of bad link quality on the particular channel it is transmitting across. In the lower ranges of $\propto$, the wireless channel will, on average, hold in the usable state and non-usable state for long periods of time, which means the sensor has long periods of time where the transmission of packets is generally very successful on the first attempt, as well as long periods of time where the number of retransmissions occurring is very high. Low $\propto$ values can represent the scenario where a wireless link in an industrial environment experiences generally high channel quality, due to few obstructions in the environment, but sometimes becomes blocked for long periods of time due to an obstruction such as a stationary heavy vehicle, which can cause high interference with the channel. As $\propto$ increases towards 0.95, the average state holding time of the wireless channel model decreases. This gives the effect of a very intermittent channel as the model transitions between the usable and non-usable state much more frequently. High $\propto$ values can be used to represent wireless links in an industrial environment that are very frequently subjected to degraded quality due to the signal bouncing and reflecting off other machinery or objects nearby, or suffering from electromagnetic interference from other machinery. Overall, the non-switching case shows no significant change in energy consumption when a range of $\propto$ values are applied.

In the scenarios **where switching is enabled**, the energy consumption curves show a much more diverse set of results.

The scenarios where a **switching cost of 3** is implemented, with 2, 3, 5 and 10 available parents, yield much lower energy consumption across all values of $\propto$ than the non-switching case. For the 2 parent case, we find that energy consumption is lowest with an $\propto$ value of 0.05, with an energy consumption inefficiency of approximately 41.8%, when compared with the optimal case. We see the highest energy consumption for the 2 parent case at $\propto$=0.95, with an energy consumption inefficiency of approximately 55.8%. This shows that with only with one more available parent node than the non-switching case, an energy consumption improvement of between 20.0% and 35.3% can be achieved when switching is enabled.

For the 3 parent case, we find similarly that the energy consumption is lowest with an $\propto$ value of 0.05, with an energy consumption inefficiency of approximately 24.2%. This is a tripling in energy consumption efficiency compared to the non-switching case, and almost twice as efficient as the 2 parent case. At the $\propto$ value of 0.95 we can see the highest energy consumption for the 3 parent case, with a value of approximately 44.9%. This maximum value is still significantly less than for an $\propto$ value of 0.95 in the non-switching case. The 5 parent-node case improves on these values further, with a minimum energy consumption of approximately 11.1% above the perfect case, less than half of the respective energy consumption at $\propto$=0.05 for the 3 parent-node case, and a maximum energy consumption inefficiency of 36.5%, for $\propto$=0.95. When the number of parents is doubled to 10, even further reductions are visible. At $\propto$=0.05, we can observe an energy inefficiency of approximately only 6.8%, and only 33.8% when $\propto$=0.95.

Althought it is clear from these values that with a switching cost of 3, an increase in the number of parents creates a more energy efficient result over all values of $\propto$, it can be observed that as $\propto$ increases, the energy efficiency improvement gained will diminish. This can be clearly observed when comparing the 3 parent and 5 parent cases. At $\propto$=0.05, the relative improvement in efficiency is 13.1% over the 3 parent case, whereas for $\propto$=0.95, the relative gain diminishes to approximately 8.4%. This decrease in relative energy efficiency as $\propto$ increases is caused by the increasing number of switches that occur when the number of parents available is increased. This will be discussed further in the next section of results.

When the **switching cost is increased to 5**, for the 2, 3, 5 and 10 parent scenarios, faster increases in energy inefficiency can be observed as $\propto$ is increased. For $\propto$=0.05, the 2 parent case yields an energy consumption ineffiency of approximately 42.4% with respect to the perfect performance scenario. This is close to the respective value when the switching cost was set to 3, but it can be seen that at $\propto$=0.95, the 2 parent case has an energy inefficiency of approximately 65.3%, which is 9.5% higher than before.

The 3 parent scenario yields an energy inefficiency of only 24.9% at $\propto$=0.05, but for an $\propto$ value of 0.95, we see that the inefficiency is 14.2% higher than in the scenario of a switching cost of 3, with its value now at 59.1%.

In the 5 parent case for $\propto$=0.05, this value is approximately 12.1%, only 1.0% higher than before. Yet at $\propto$=0.95, this value is approximately 54.3%, which represents an increase of 18.8% over the 5 parent scenario using a switching cost of 3.

When 10 parent nodes were used, the energy consumption was approximately only 7.9% at $\propto$=0.05, but still reached a value of 52.8% when $\propto$ was set to 0.95, which is 19.0% higher than for a switching cost of 3.

From these values, it can be observed that as the switching cost is increased, the relative energy efficiency gain diminishes at even higher rates. For $\propto$=0.05, the relative energy efficiency gain of the 5 parent case over the 3 parent case is approximately 12.8%, but this can be seen to degrade greatly compared to the scenario where the switching cost is 3, as at $\propto$=0.95, the relative improvement between the 5 parent and 3 parent cases is only 4.8%, instead the 8.4% relative improvement observed earlier. What this shows is that an increase in switching cost even further decreases the advantage provided by an increase in the number of available parents, as $\propto$ is increased. Additionally, although the higher switching cost of 5 creates a less energy efficient scenario for the sensor, this scenario still provides a minimum benefit of 11.8% over the non-switching case, as can be seen when comparing the 2 parent case to the non-switching case, where the 2 parent case has a maximum energy inefficiency of 65.3% in comparison to the minimum non-switching energy inefficiency of 77.1%.

When the **switching cost is doubled to a value of 10**, the energy consumption curves display some important behaviour. It can be seen that the energy consumption curves for the 2, 3, 5 and 10 parent scenarios all cross the non-switching energy consumption curve at an $\propto$ value of approximately 72.5%. From this $\propto$ value onwards, the switching-enabled scenarios all become less energy efficient than the non-switching case. Additionally, the 10 parent case becomes the least energy efficient instead of the most, and the 2 parent case becomes the most energy efficient out of the 4 scenarios. The 3 and 5 parent cases also switch, and the 5 parent case becomes less energy efficient than the 3 parent case. With respect to real world scenarios, this means that if a wireless channel experiences fairly regular fluctuations in signal strength, a crossover or threshold point exists where the presence of a high signalling cost to perform a switch between router nodes outweighs the energy consumption benefit gained by performing the switch. Furthermore, these curves demonstrate that there exists a crossover point where an increase in the number of router nodes can become detrimental instead of beneficial to the energy efficiency of the sensor node, when using the current decision algorithm for performing router switching. This crossover point would vary depending on the energy cost for switching, of different WSN protocols.

For the non-switching case, a maximum confidence interval of 0.0071 was calculated, with a confidence level of 95%. This yields an interval of error of 0.0142 when in ratio format. In percentage format, this results in an interval of error of 1.42%. In the 2 parent, 3 parent, 5 parent and 10 parent scenarios, maximum confidence intervals of 0.0051, 0.0038, 0.0016 and 0.0003 were calculated. These yield intervals of error of 0.0102, 0.0076, 0.0032 and 0.0006 in ratio format. In percentage format these equate to maximum intervals of error of 1.02%, 0.76%, 0.32% and 0.06% respectively, at a confidence level of 95%.

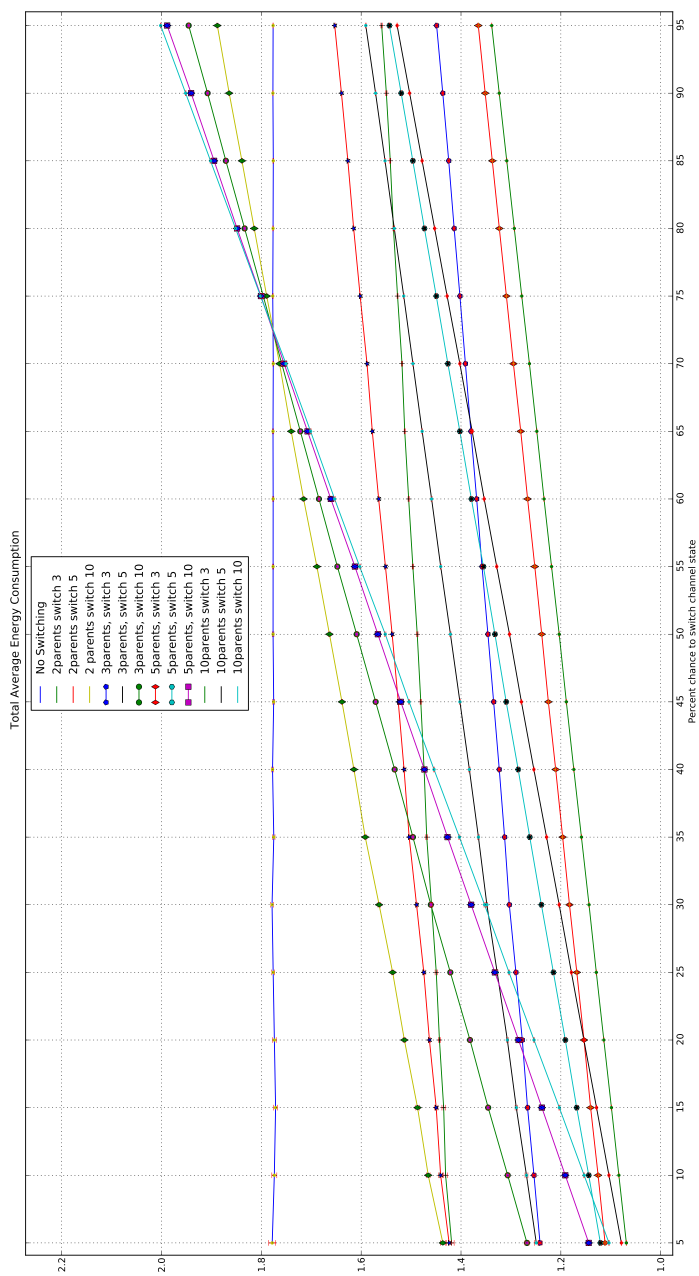

Figure 4.1: Total Average Energy Consumption, for all simulation scenarios

Results with respect to Retransmissions

Figure 4.2 (below) details the simulation results obtained with respect to the number of retransmissions that had to be performed by the sensor in the different simulation scenarios. It can be observed that the cost of making a switch between parent-nodes has no effect on the number of retransmissions occurring, but the number of parents available effects retransmissions considerably. The Y-axis represents the percentage of retransmissions that occurred, with respect to a maximum possible number of retransmissions of 75,000. This maximum is calculated from the number of available retransmission slots in each round (15), multiplied by the number of simulation rounds (5000).

For the non-switching scenario, the percentage of retransmissions occurring with respect to the maximum is approximately 81.1%, for an $\propto$ value of 0.05. This curve does not demonstrate a significant relationship between retransmissions and $\propto$, as for an $\propto$ of 0.95, the retransmission value still lies at approximately 80.9%.

When only 2 router nodes are available to switch between, a strong reduction in the number of retransmissions can be seen, with a minimum value of 41.9% at $\propto$=0.05, and a maximum of 42.6% at $\propto$=0.95.

When 3 router nodes are available to switch between, a very strong reduction in the number of retransmissions occurring can be observed compared to the non-switching case. With a percentage value of approximately 22.5% at $\propto$=0.05, this decreases the number of retransmissions by approximately 58.6% compared to the non-switching case. This is close to 4 times as efficient in terms of retransmissions. At $\propto$=0.95, the retransmission percentage lies at approximately 23.1%, which yields a similar improvement of 57.8%. When comparing the number of retransmissions against the 2 parent case, we can observe a reduction of 19.4% at $\propto$=0.05, and similarly, a reduction of 19.5% at $\propto$=0.95.

Increasing the number of router nodes to 5 creates an even further reduction of retransmissions, with a percentage of approximately 8.3% at $\propto$=0.05. The retransmission curve demonstrates this trend across all $\propto$ values considered, with a value of approximately 8.4% for $\propto$=0.95. In comparison to the non-switching case of 81.1% at $\propto$=0.05, the 5 parent case provides a relative improvement of 72.8% in terms of retransmission reduction. Against the 2 parent case, the 5 parent case achieves a reduction in transmissions of 33.6% at $\propto$=0.05, and 34.2% at $\propto$=0.95. This shows that the 5 parents case is just over 5 times as efficient as the 2 parents case. Additionally, in comparison to the 3 parent case, the 5 parent case proves to be close to 3 times as energy efficient in terms of retransmissions, when comparing the value of 8.3% to the 3 parent value of 22.5%.

When the number of parent nodes is increased to 10, we can observe additional improvements in the decrease of retransmissions for all values of $\propto$, but the relative improvement compared with the 5 parent case is less significant than the relative improvement observed when comparing the 5 parent case with the 3 parent case. For an $\propto$ value of 0.05, the 10 parent case achieves a value of only 3.65%, and only 3.69% at $\propto$=0.95. Compared to the 5 parent case this relative improvement is only approximately 5.7% compared with the difference between the 5 parent and 3 parent cases, which yielded a value of 12.2%. This is just over twice as efficient as the 5 parent case, but required a doubling in the total number of parent nodes available. With respect to real world scenarios, this shows that a higher number of router nodes available for the sensor to switch between does decrease the percentage of retransmissions occurring, but the size of this decrease diminishes as more router nodes are made available. Out of 75,000 potential retransmissions, the 10 parent case reduces this number to approximately 2750 retransmissions.

For the non-switching case, a maximum confidence interval of 0.762% was calculated, with a confidence level of 95%. This yields an interval of error of 1.424%. For the 2, 3, 5 and 10 parent cases, the maximum confidence intervals with a confidence level of 95% were 0.542%, 0.403%, 0.178% and 0.023% respectively.

Figure 4.3 displays these results in an alternate format to show the trend of reduction in retransmissions with respect to the number of parent nodes present in each simulation configuration. To calculate the value for each configuration, the average of all 19 $\propto$ values for each configuration was used. In the non-switching case this resulted in an average of 80.9%, and for the 2, 3, 5 and 10 parent cases, the resulting values were 42.2%, 22.9%, 8.4% and 3.7% respectively.

These results show that in a real world application, increasing the number of parent nodes that are within range of the sensor node will improve the functional lifetime of the sensor network. In sensor networks where the number of retransmissions the sensor is permitted to perform is set to a high value the increase in available parent nodes significantly decreases the potential energy inefficiency caused by the sensor attempting multiple retransmissions to one specific parent node.

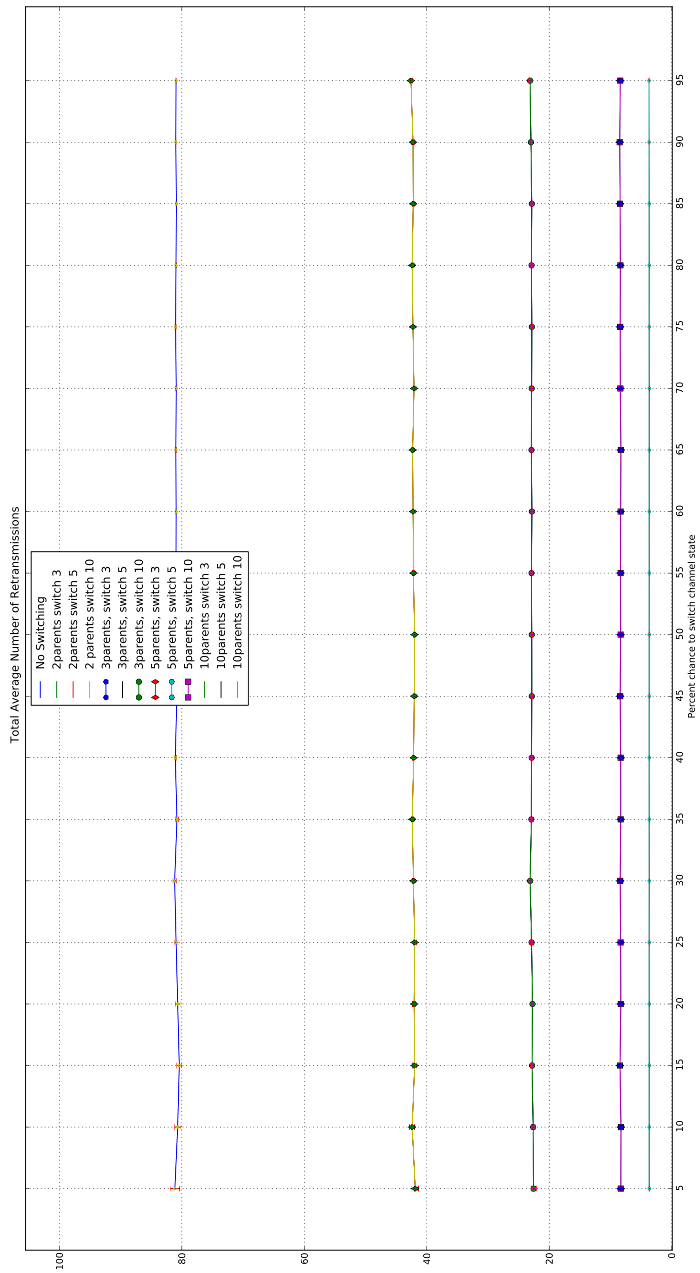

Figure 4.2: Total Average Number of Retransmissions, in percentage measurements

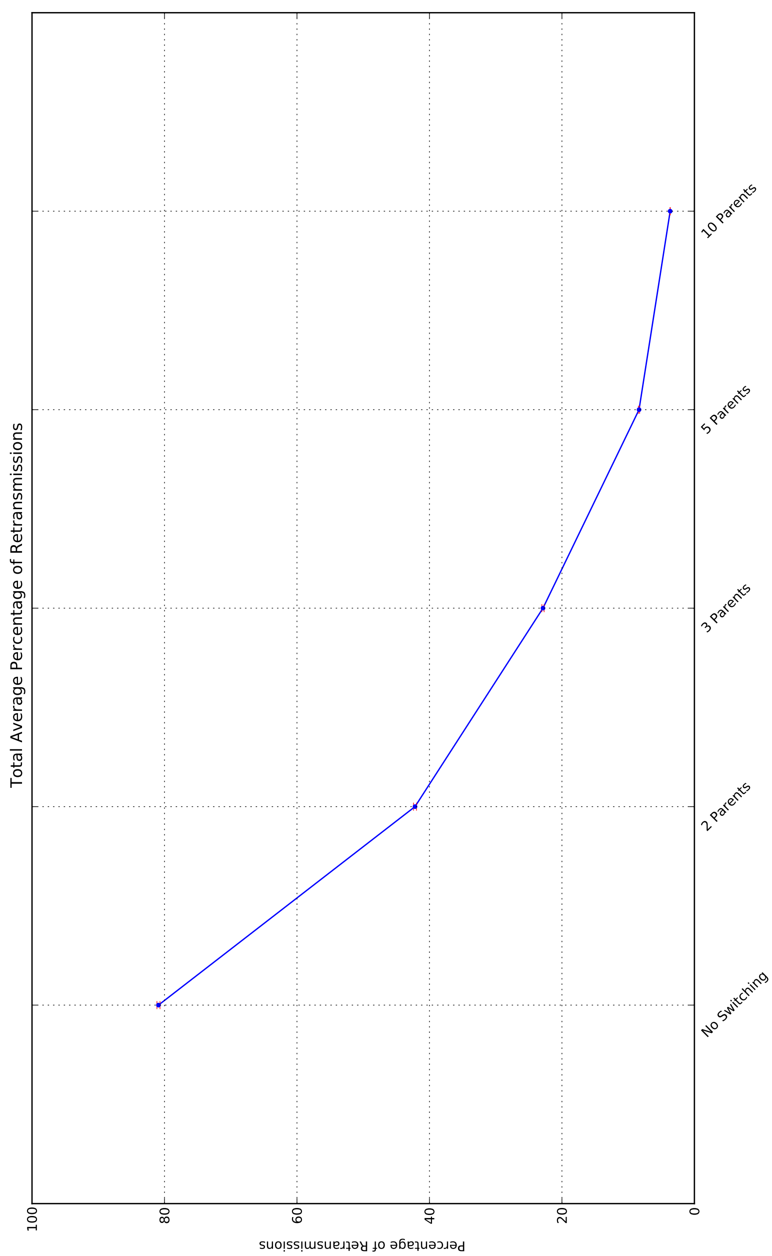

Figure 4.3: Trend of Retransmissions, with respect to the number of parent nodes

Results with respect to Dataloss

Additional to retransmissions, which affect the energy efficiency of the sensor node as well as transmission reliability, it was important for the simulations to explore a measure of transmission reliability in terms of how many packets would be received by the PAN coordinator of the network. This is important to measure because a packet can be retransmitted a number of times but still fail to transmit every time. This measure of data packets lost can also be described as the "overall throughput" of data. To measure this, the percentage of data lost was recorded and averaged based on the 100 simulation replications performed for each simulation scenario. These measurements are visible in Figure 4.4, included below.

In the non-switching scenario, it can be observed that the dataloss is consistently high, with an approximate value of 43.4% at $\propto$=0.05, and an approximate value of 43.1% at $\propto$=0.95. This equates to approximately 21,700 lost packets out of a total of 50,000 packets for $\propto$=0.05, and approximately 21,550 lost packets for $\propto$=0.95.

When switching is enabled, the 2 parent case yields a dataloss rate of approximately 21.2% at $\propto$=0.05, and approximately 21.6% at $\propto$=0.95. This is a 22.3% reduction at $\propto$=0.05 when compared to the non-switching case, which equates to just over double the reliability in terms of overall data throughput. Additionally, at $\propto$=0.95, we can observe a reduction of approximately 21.7%.

Similarly, the 3 parent case demonstrates a more significant reduction in dataloss, with an approximated value of only 10.3% for $\propto$=0.05, and 10.6% for $\propto$=0.95. In comparison to the non-switching case, the 3 parent case provides a reduction in dataloss of approximately 33.1% for $\propto$=0.05, with approximately 5150 packets lost, and a reduction in dataloss of approximately 32.5% for $\propto$=0.95, with approximately 5300 packets lost.

When 5 parent nodes are available for the sensor to switch between, the reduction in dataloss is even greater, with an approximate value of 2.2% of all packets being lost at $\propto$=0.05, and 2.3% dataloss at $\propto$=0.95. These results demonstrate the large advantage gained when parent switching is enabled in terms of data throughput, in comparison to the non-switching case, with a reduction of 41.2% at $\propto$=0.05, and 40.8% at $\propto$=0.95.

Finally, when the number of parent nodes is doubled from 5 to 10, a dataloss percentage of only 0.08% can be observed for $\propto$=0.05, and approximately 0.11% for $\propto$=0.95. This is a reduction of approximately 43.0% for both $\propto$=0.05 and $\propto$=0.95. This means that approximately only 40 packets out of 50,000 are lost for $\propto$=0.05, and approximately only 55 packets out of 50,000 for $\propto$=0.95.

For industrial heterogeneous WSNs where all data readings received from the sensor by the PAN coordinator are critically important, then implementation of a protocol specific adaptation of this switching technique could provide large improvements in data throughput. In a real world application, the number of available chances to retransmit a packet could also be increased, to assist reaching very high rates of successful data throughput.

For the non-switching case, a maximum confidence interval of 0.430% was calculated, with a confidence level of 95%. This yields an interval of error of 0.860%. For the 2, 3, 5 and 10 parent cases, the maximum confidence intervals with a confidence level of 95% were 0.307%, 0.232%, 0.105% and 0.012% respectively.

Figure 4.5 displays another view of these results, showing the trend of data loss with respect to the increase in the number of parent nodes available. For this, the average of the 19 data loss values, one for each value of $\propto$, for each simulation configuration was calculated. For the non-switching case, this calculation yielded a value of 43.2%. The 2, 3, 5 and 10 parent scenarios yielded values of 21.4%, 10.6%, 2.2% and 0.9% respectively. Figure 4.5 gives a clearer view of the reductions in data loss than can be achieved when the number of parent nodes in increased.

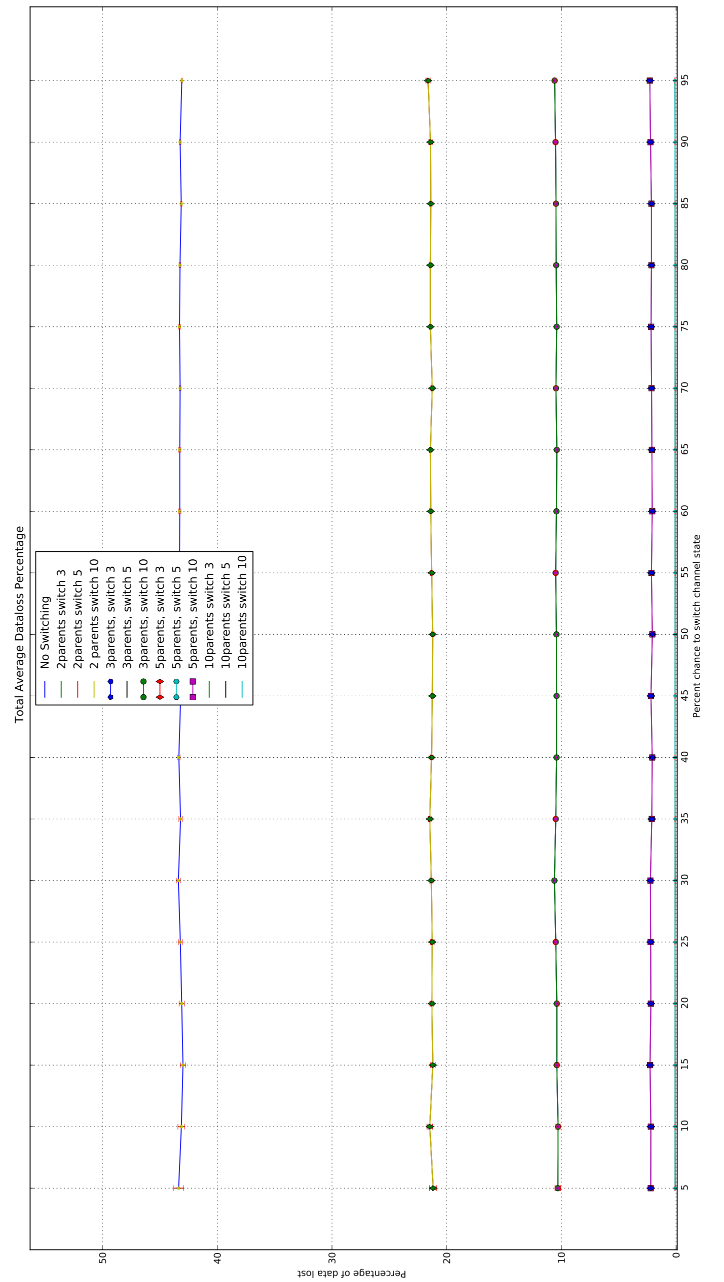

Figure 4.4: Total Average Percentage of Dataloss

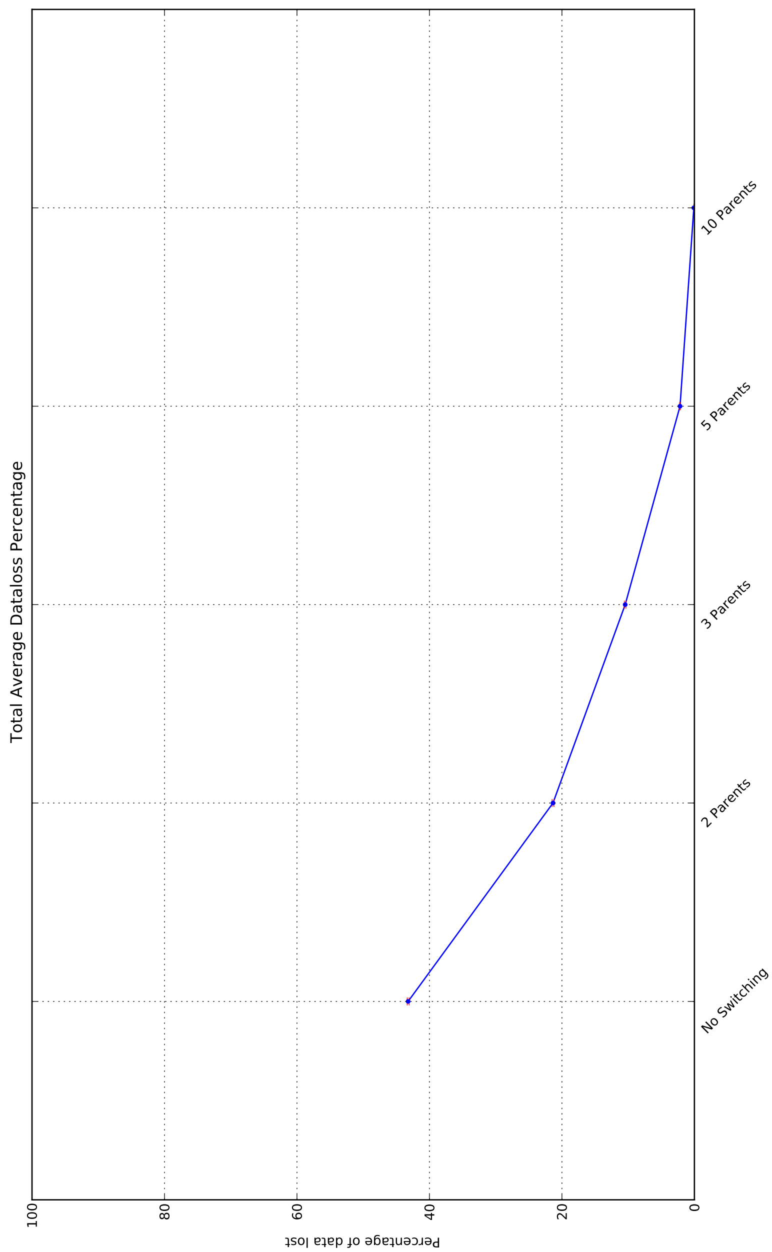

Figure 4.5: Trend of dataloss, with respect to the number of parent nodes

Results with respect to the number of switches performed

As part of the simulations, it was important to measure the number of switching operations that the sensor performed between the available parent nodes in the scenarios where switching was enabled. The non-switching case is not applicable in this scenario but has been graphed as a flat line at with a value of 0. The values obtained from the simulations are presented in real values, with 5000 representing the total number of possible switching operations, equivalent to one switching operation per round. These values are presented below in Figure 4.6.

For the 2 parent switching case, we can observe the number of switches performed by the sensor is approximately 125 at $\propto$=0.05, and approximately 2351 at $\propto$=0.95. This equates to a percentage of 0.025%, with respect to a possible maximum of 5000 switches, at $\propto$=0.05. At $\propto$=0.95, this percentage is approximately 47.0%.

In the 3 parent case, the number of switches at $\propto$=0.05 is slightly higher, at a value of approximately 186. At $\propto$=0.95, we can observe a total of 3548 switches performed, much higher than the 2 parent case. These values equate to percentages of approximately 3.72% at $\propto$=0.05 and approximately 71.0% at $\propto$=0.95. This demonstrates an increase of 24% in the number of switches occurring at $\propto$=0.95.

Utilising 5 parents, we can observe approximately 233 switches occurring at $\propto$=0.05, and approximately 4452 switches occurring at $\propto$=0.95. These equate to approximately 4.7% at $\propto$=0.05, and approximately 89.0% at $\propto$=0.95. At $\propto$=0.95, the 5 parent case demonstrates an increase of approximately 18.0% in the number of switches occurring.

When the number of parent is doubled to 10, we can observe the number of switches is at its highest for all values of $\propto$. At $\propto$=0.05, approximately 248 switches occurred, and we can observe that 4737 switches occurred at $\propto$=0.95.

For the non-switching case, no confidence interval of 0.0 exists as no switching operations were performed. For the 2, 3, 5 and 10 parent cases, the maximum confidence intervals with a confidence level of 95% were 18.31 switches, 14.06 switches, 9.183 switches and 6.303 switches respectively.

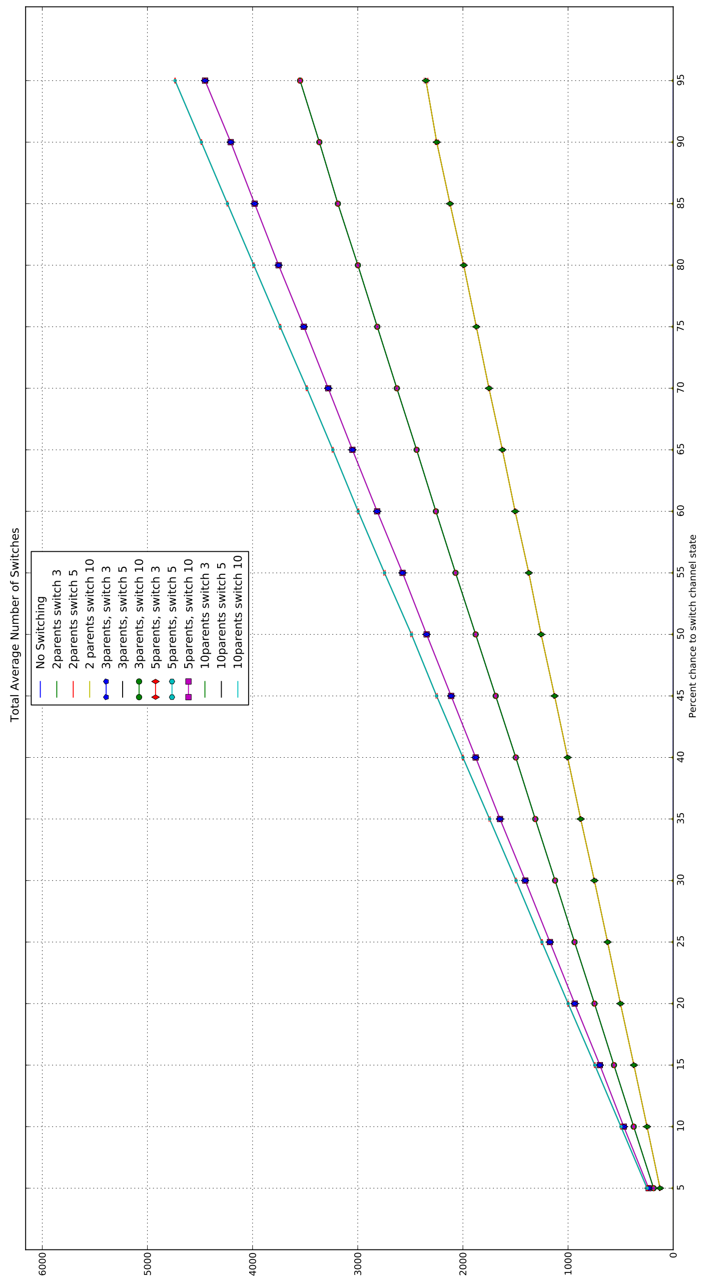

Figure 4.6: Total Average Number of Switching Operations Performed

Cross-comparison of results

Having analysed the different types of results collected, it is now possible to make a cross comparison about the relationships between these measurements of performance.

Firstly, it can be observed that there is a direct relationship between energy consumption and the number of switching operations being performed during a particular simulation scenario. The graph displaying energy consumption shows that the 10 parent scenario with a switching cost of 10 yields the highest energy consumption out of any of the explored scenarios. In relation to this, it can be observed that any of the 10 parent scenarios, regardless of switching cost and the $\propto$ value set, yield the highest number of switching operations performed. This is due to the fact that when the number of parents is high, the chance of at least one usable wireless channel existing between the sensor and a parent node is significantly increased.

To explain this further, it be can observed that although the $\propto$ value set in the two-state channel model is varied in each simulation scenario, the long term probability of a channel being in a non-usable state is 0.5. This is because the same $\propto$ value is used to determine the probability of a transition from a usable state to a non-usable state, as well as from a non-usable state to a usable state.

Taking this into consideration, we can calculate that the overall probability of all channels being in a non-usable link state to be P to the power of N, where P = 0.5 and N = the number of parent nodes present. As N is increased, this probability decreases considerably, and so in the situation where the sensor nodes current parent is providing a non-usable channel state, the likeliness of at least one other parent node providing a usable channel state increases. Therefore a switching operation is much more likely to be performed. For N=10, we can observe this probability as being approximately only 0.001, or 0.1%. Furthermore, it can be observed that the number of switches increases as $\propto$ is increased. This is because each channel becomes more intermittent as $\propto$ is increased, and therefore the probability of the sensor needing to make a switch in each round increases.

Secondly, it can be seen that there is no direct relationship between the number of retransmissions and the number of switches performed. Instead, the main factor that affects both of these measurements is the number of parent nodes available in the scenario. If we consider the probability calculation in the previous paragraph, we can observe that the number of retransmissions decreases as the probability of all parent nodes simultaneously being in a non-usable state decreases. The number of switching operations and the cost of switching has no affect on retransmissions as retransmissions only occur in the transmission phase of each simulation round.

Thirdly, we can see that there is a direct relationship between the number of retransmissions that occur and the percentage of data packets lost in each simulation scenario. From the results we can observe that as the number of parents present in the simulation scenario increases, the percentage of retransmissions occurring drops significantly, and this is evident with the percentage of dataloss as well. Conversely, if we consider the case where there are a high number of retransmissions occurring in one particular simulation round, the chance of all 10 packets being successfully transmitted decreases and therefore dataloss increases. If the maximum number of attempts to retransmit packet was increased, we would see less dataloss for each scenario, but it would still be proportional to the number of retransmissions occurring. Additionally, there is no direct relationship between retransmissions and the trends visible on the energy consumption graph, this is because retransmissions stay very consistent over all values of $\propto$, where as higher values of $\propto$ increase the amount of switching operations, affecting the overall energy consumption.

To conclude, from the simulation results collected and discussed, we can make a number of useful observations about the benefits of the parent-switching technique. It is evident that for moderate switching costs with a ratio of 5:1 and below with respect to the energy cost of transmitting a single packet, that the ability to switch between at least 2 available parent nodes is much more energy efficient for the wireless sensor node than only being able to transmit to one parent node. Additionally, we find that as the number of parent nodes is increased the sensor's energy efficiency improves proportionally, as the number of retransmissions are decreased. It is also evident from the results that switching between parent nodes achieves the most energy efficiency when the available wireless channels are less intermittent and more likely to stay in a usable or non-usable state for a longer period of time. The switching technique also displays the benefit of improving overall throughput of data, as the data loss rate decreases when the number of available parent nodes is increased.

These improvements show that for many cases the signalling costs incurred by using the parent-switching technique are exceeded by the advantage gained for the sensor in terms of energy efficiency and transmission reliability.

Chapter 5

Conclusion and Future Work

In conclusion, the research performed in this thesis has displayed the benefits and tradeoffs involved in the implementation of channel quality aware router selection, in terms of energy efficiency and transmission reliability for a battery-powered sensor existing in a heterogeneous wireless network in an industrial environment.

Through the use of an abstract model of the problem domain and a software-based simulation of this model, it can be observed that for most cases, the parent-switching technique provides significant improvements in energy efficiency and transmission reliability for the sensor node. The use of the abstract model allows the knowledge gained from this research to be applied to a number of real world wireless sensor network protocols, including the IEEE 802.15.4 protocol discussed. The parent switching technique provides significant improvements in energy efficiency for the sensor node up to a considerable frequency of intermittence in the wireless channel that data is being transmitted across. This holds true even in scenarios where the energy cost of switching between parent nodes is high. The parent switching technique also provides significant reductions in the number of packets that need to be retransmitted, which contributes to the overall increase in energy efficiency.

Additionally, the parent switching technique has proved to be effective in increasing the overall throughput of data packets, which is important for real world applications where reliable delivery of all data packets is critical to the successful operation of the network.

5.1 Future work

As part of future work, there a number of avenues to create further improvements to the abstract model, as well as the switching-technique itself. Firstly, it would be valuable to observe the current switching-technique being used with a more complex state model representing the wireless channel between the sensor and the parent nodes. If a 3-state model was introduced with optimal, moderate and unusable states, then a more complex switching algorithm could be developed. This switching algorithm could select a moderate channel over an unusable channel, in the scenario where an optimal channel is unavailable.

It is also possible to develop a "continuous" model of the parent switching scenario. This would use a predetermined set of network events, and would involve creating a decision algorithm that gets as close to the optimal set of decisions as possible. This model could provide the sensor with less than perfect information about the available link qualities in order to test if increases in energy efficiency are possible when only occasional analysis of the wireless links is performed.

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