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A Node-Link Perspective on the Impact of Local Conditions in Sensor Networks

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Abstract

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Sensor networks are made up of small battery-powered sensing devices with wireless communication capabilities, enabling the network to monitor the environment in which it is deployed. Through their flexible and cable-free design these networks open up for new deployment scenarios that were previously not plausible such as during a natural disaster. Motivated by scenarios where centralized oversight is not possible the focus of this thesis is to equip nodes with further adaptability to changes in the links it has with other nodes. This is achieved through contributions in three areas focusing on observations from a node-link perspective.

First, the impact the local environment has on the nodes is explored by deploying a sensor network outdoors next to a meteorological station to correlate the variations in link quality to the changes in the environment. The work identifies temperature as the main factor, where through further investigations in a controlled setting, a linear relationship between the decrease in signal quality and the increase in temperature is described.

Secondly, the thesis address how nodes in a sensor network can be motivated to exchange data by modeling it as a game. The game theoretic design is motivated by the absence of any centralized control and focus on the nodes as individual users in the network. The presented design motivates the selfish nodes to participate in the exchange of sensor data, showing that it is the best strategy.

Lastly, by exploring and understanding how connections in a mobile sensor network occur, nodes are given more flexibility to determine how to send and sample sensor data. This adaptability to contact occurrences is shown to provide better ways of sending data by selecting higher quality links as well as making sampling more energy preserving by reducing the rate in the vicinity of other nodes.

Keywords: Sensor networks, opportunistic communication, meterlological impact, packet corruption, multi-contacts

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to my loving wife and son...

List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals.

I Hjalmar Wennerström, Frederik Hermans, Olof Rensfelt, Christian Rohner, and Lars-Åke Nordén. *A Long-Term Study of Correlations between Meteorological Conditions and 802.15.4 Link Performance*. In Proceedings of the 10th Annual IEEE Communications Society Conference on Sensing, Communication, and Networking (SECON), 2013.

II Carlo Alberto Boano, Hjalmar Wennerström, Marco Antonio Zúñiga, James Brown, Chamath Keppitiyagama, Felix Jonathan Oppermann, Utz Roedig, Lars-Åke Nordén, Thiemo Voigt, and Kay Römer. *Hot Packets: A Systematic Evaluation of the Effect of Temperature on Low Power Wireless Transceivers*. In Proceedings of the 5th Extreme Conference on Communication (EXTREMECOM), 2013. Named *best paper* at ExtremeCom '13.

III Frederik Hermans, Hjalmar Wennerström, Liam McNamara, Christian Rohner, and Per Gunningberg. *All is not Lost: Understanding and Exploiting Packet Corruption in Outdoor Sensor Networks*. In Proceedings of the 11th European Conference on Wireless Sensor Networks (EWSN), 2014. Named *best paper* at EWSN '14.

IV Hjalmar Wennerström and David Smith. *A Game Theoretic Approach to Sensor Data Communications in an Opportunistic Network*. In Proceedings of the IEEE International Conference on Communications (ICC), 2015.

V Hjalmar Wennerström, Christian Rohner, and David Smith. *Considering Multi-Contact Encounters in Opportunistic Networks*. In Proceedings of the 10th ACM MobiCom Workshop on Challenged Networks (CHANTS), 2015.

VI Hjalmar Wennerström and Christian Rohner. *Towards Even Coverage Monitoring with Opportunistic Sensor Networks*. Accepted for publication at the 11th ACM MobiCom Workshop on Challenged Networks (CHANTS), 2016.

List of papers not included

In addition to the papers in this thesis I have authored or co-authored the following papers and poster abstracts.

- Hjalmar Wennerström, Liam McNamara, Christian Rohner, and Lars-Åke Nordén. *Transmission Errors in a Sensor Network at The Edge of The World*.
  In Proceedings of the 5th Extreme Conference on Communication (ExtremeCom), 2013.

- Marc Girons Lopez, Hjalmar Wennerström, Lars-Åke Nordén, and Jan Seibert. *Location and Density of Rain Gauges for the Estimation of Spatial Varying Precipitation*.
  Geografiska Annaler: Series A, Physical Geography, 97, 2015.

- Atis Elsts, Hjalmar Wennerström, and Christan Rohner. *IEEE 802.15.4 Channel Diversity in an Outdoor Environment.*
  In Proceedings of the 6th ACM Workshop on Real World Wireless Sensor Networks (RealWSN), 2015.

- Hjalmar Wennerström, Liam McNamara, Christian Rohner, and Lars-Åke Nordén. *A Study of Packet Errors on Outdoor 802.15.4 Links*.
  (Poster) In proceedings of the 9th Swedish National Computer Networking Workshop (SNCNW), 2013.

- Hjalmar Wennerström, Frederik Hermans, Olof Rensfelt, Christian Rohner, and Lars-Åke Nordén. *A Long-Term Study of Correlations between Meteorological Conditions and 802.15.4 Link Performance*.
  In proceedings of the 8th Swedish National Computer Networking Workshop (SNCNW), 2012.

- Hjalmar Wennerström. *Natural Disaster Sensor Networks.*
  Poster presented at PhD forum of the 11th ACM/IEEE Conference on Information Processing in Sensor Networks (IPSN), 2012.

- Hjalmar Wennerström. *Motivating User Driven Data Collection in Opportunistic Sensor Networks.*
  Poster presented at the National Symposium on Technology and Methodology for Security and Crisis Management (TAMSEC), 2015.

Contents

Part I:
Thesis Summary

1. Introduction

EXPLORING the physical world has for hundreds of years been a cornerstone of scientific discovery, leading to our current understanding of how the world works. With this knowledge comes the idea that we can monitor and comprehend our surroundings through observation, with the aim of improving our lives in some way. This could for example include collecting data on volcanic activity to predict an eruption, or to measure the quality of drinking water in a stream. The challenge lies in measuring and collecting the necessary data needed to predict the eruption or warn when the stream gets polluted. This is where sensor networks can be a useful tool, since it provides new monitoring opportunities that were previously not possible due to complexity and cost of installation.

A particular focus of this thesis is the deployment and operation of these networks in scenarios without existing infrastructure. In terms of networked services this means that there is no cellular or Internet connectivity or any other external resource that can be used. In scenarios where this is the case, for example monitoring in remote and isolated areas, or during extreme events such as a natural disaster, the network has to operate on its own. Such scenarios accentuate the need for independence and autonomous operation of the network, where reducing the reliance on centralized control of the system increases robustness. Ultimately this implies that the nodes, the devices that make up the network, should be more aware and adaptable to the current circumstances.

To this end, this thesis explores aspects of what impacts the network by understanding the performance and decision making of the nodes. Specifically, how the sampling and transmission of sensor data can be improved with additional local knowledge obtained by the nodes. The key challenge for nodes in a sensor network is the fact that they are typically battery powered. This means that there is a limited energy supply, making energy conservation an essential design aspect, which in the context of this thesis is achieved by making nodes more adaptable to the changes in link conditions.

In general, a sensor network can be used to capture information about the surroundings by sampling and wirelessly communicating the sensor data to the other nodes. This enables for example environmental monitoring using devices that are cable-free and low-cost, reducing installation complexity and allowing for new deployment scenarios. Once the network has been deployed it becomes increasingly difficult to monitor and reconfigure the network since direct remote access is not possible due to the lack of infrastructure in the considered scenarios. Instead, the network and its nodes should be equipped with local knowledge of how to respond to changes in the current conditions, making for a more distributed design approach that do not assume a coherent system view.

During the lifetime of a node it should be able adapt to variable conditions such as changes to the physical environment as well as changes to the connections it has with other nodes. The work presented here is motivated by a better understanding of the processes that influence this variability, which provides the node with better information when responding to such changes. This includes how the local environment may influence the successful transmission of data packets and how already broken packets might be recoverable. It also tackles how contacts and their occurrence patterns can be utilized to exchange, route and sample sensor data in more efficient ways, adapting to the ongoing changes perceivable to the node.

1.1 Wireless Sensor Networks (WSN)

In a wireless sensor network, or WSN, nodes are considered stationary and distributed over an area to monitor. The nodes are placed within communication range so that the network is fully connected, meaning there exists a path between all pairs of nodes. The network typically monitors a smaller area since nodes a stationary and use short range communication such as the IEEE 802.15.4 standard [24] at 2.4 GHz.

The work in this thesis is motivated by a scenario where such a network is deployed for remote monitoring in an isolated location with a harsh climate. The network might not be connected to the Internet so remote supervision is impractical. In essence the network and its nodes are left to function on their own, requiring some degree of autonomy. The data may be stored locally and collected when an opportunity arises.

Once deployed, nodes sample from their sensors either on-board the device itself or installed externally. The sensor data is collected by nodes relaying the data to a centralized node, called the *sink*, which in turn provide it to the user. These networks are typically owned and controlled by a single organization with a specific task and location in mind. As part of this thesis two such networks are deployed to collect extensive measurement data, described in Chapter 2.

1.2 Opportunistic Sensor Network (OSN)

Once node mobility is added the sensor network starts to look different, where nodes might connect to each other in an *ad-hoc* fashion. This opens up for a variety of network architectures that reflect different types of mobility patterns. From a sensing perspective this also changes the process of sampling sensors, where due to the mobility of nodes, samples can cover a much larger geographical area.

One such type of network are *opportunistic sensor networks* where the nodes are carried by humans, in the form of a phone or some other handheld device that can both communicate and take sensor samples. As such, the node movement reflects human mobility patterns, where large distances and areas can be covered within hours.

For this type of network we consider a scenario where a sensor network needs to be deployed rapidly, with little configuration and set-up time, prompted by a state of emergency such as during a natural disaster. The goal is to quickly gain situational awareness by collecting sensor samples of an area in a time where cellular and Internet connectivity may not be present.

An important feature of such a network is that the nodes use short-range communication, meaning that nodes can only communicate when they are in close vicinity of each other. Using the contacts that occur from this mobility is key in order to relay data in the network, where choosing what and to whom messages should be sent is an essential task for the nodes. The mobility of the nodes also impact where and when sensor data can be gathered, typically by taking samples as the node moves around, which is the scenario used in this thesis. The idea behind opportunistic networking is to make the network robust and resilient, not relying on centralized infrastructure, such as a server or cell-tower. Since humans power these networks, both physically and digitally, they become more participatory and social endeavors. This often means that the network is not necessarily owned by a single entity, seen in more traditional sensor networks.

1.3 Sensor Nodes

Although the network architecture may look different in different sensor networks there are still several similarities, especially when looking at it from the nodes' perspective. As stated earlier, the underlying theme throughout this thesis is the nodes understanding of their current situation. Considering this and the network types discussed here nodes can make observations of the available links, the radio environment, or the data packets being sent. A node could also adapt its operation by considering the sensor readings it takes, its remaining battery capacity, or inclination towards obtaining new sensor data. These are aspects that are shared by different types of networks, but where the specific features of one network type may also be exploited.

The benefit of such approaches is that nodes can make local decisions without having to communicate or request information from some external entity, resulting in a smaller overhead and more autonomous operations. It also implies that performance of the network will not be globally optimized, since it would put additional requirements on the network in terms of keeping an up to date global view. Instead the focus of this thesis is on a more minimalist approach, by exploring and exploiting local knowledge. This also resonates very well with the deployment scenarios considered, where autonomous operations are important to enable a quick deployment of nodes or having nodes adaptable to harsh conditions with little oversight.

1.4 Main Contributions

This thesis presents contributions in areas of sensor networking related to a better understanding, and adapting to, the local conditions of nodes. The increased adaptation is to improve the transmission and sampling of sensor data in order to save energy without loosing efficiency.

Cause and Effect of Packet Corruption in Outdoor Wireless Sensor Networks

Experimentation in the outdoor deployments in Paper I show that temperature as opposed to humidity, precipitation or solar radiation is the major factor impacting the WSN nodes ability to communicate. This knowledge is used to derive an analytical first order model in Paper II, defining the relationship between temperature and Signal-to-Noise Ratio (SNR) for common sensor nodes. The model predicts how the node's SNR is impacted by the *local* temperature conditions, providing a way to foresee and countermeasure such an effect. Paper III identifies and explain biases in the way packet errors occur over intermediate links. Specifically how payload bit errors occur due to 802.15.4 symbol coding. By leveraging this information a method is proposed to probabilistically reconstruct data in corrupt packets in an 802.15.4 outdoor WSN.

Motivating Data Exchange in Opportunistic Sensor Networks

Using game theory in Paper IV, a scenario where sensor data is exchanged between nodes is modeled and analyzed. Although nodes are selfish, not wishing to waste energy by exchanging uninteresting data, the game ensures a fair exchange between nodes, showing that nodes benefit by participating in the exchange of sensor data. The game is shown to be a sub-game perfect Nash equilibrium that is also Pareto efficient, ensuring a globally beneficial outcome, which further motivate node participation.

Characterization and Utilization of Multi-Node Contacts in Opportunistic Sensor Network

The fact that multi-node contacts are a prevalent feature in social opportunistic networks is shown in Paper V. It also shows that this provides a node with additional choices and considerations when choosing whom to relay data to. This is exemplified by considering the quality of the wireless link as an additional metric when making a routing decision. In addition, the contact occurrences in an opportunistic sensor network can be further utilized by the node to adapt its sampling process, shown in Paper VI. This enables the node to make decisions, using only local knowledge, on how often to sample which can reduce the skewness and oversampling in affected areas.

2. A Network of Sensor Nodes

SENSOR networks are built, programmed and deployed to perform a sensing task, typically monitoring the surroundings in which they are set up. Once the network is deployed it is up to the nodes to maintain operability and performance, adapting to the changes that impact them. This chapter introduces different deployment scenarios, and some of the challenges that the network and its nodes may face, some of which are discussed in greater detail in the remaining parts of this thesis.

2.1 Outdoor Sensor Network Deployments

Looking back at the inception of sensor networks where the intention was to monitor the world around us, implying that these computer networks would be placed in new environments, where no previous network would have been deployed. This is reflected in one of the very well known early WSN deployments back in 2002, where nodes were placed in birds' nests on Great Duck Island, outside the coast of Maine to monitor the micro climate of the nests [33]. Since then, application areas have grown, where WSNs today have been deployed for extensive habitat and environmental monitoring [16, 22, 25, 33, 12, 34, 56] but also extended into more industrialized ideas including farming and logistics [32, 39, 48, 7, 35, 57]. Recent developments in new networking architectures, where mobile nodes participate in *social* or *people-centric* sensing [11], show that sensor networks can also be deployed to monitor the air quality or mapping the preferred bikepaths of an entire city [17]. Deployments with mobile nodes also extend to placing them on cars [18] or animals [16, 25], where street conditions or animal behavior can be studied. All these new environments challenge a sensor network in some way, be it by more physical constraints such as placing sensor nodes in turtle nests [58] or wireless constraints collecting data over unstable links for glacier monitoring in mountainous areas [46].

So even though sensor networks have been deployed in a variety of scenarios, there are still a multitude of challenges that can threaten the operation of the network. Reasons for experiencing difficulties in these deployments typically stem from the fact that they are inaccessible. This makes it harder to detect and correct mistakes (e.g. in code, hardware or configuration) once deployed since debugging and reprogramming can be difficult [28]. Another complicating factor is the difficulty to foresee the implications of the environment and the effect it will have on the operation of the network. This is for example illustrated by insights into unforeseen complications in the more traditional WSN literature [6, 27, 29, 52]. These factors can include challenges from both the physical environment, such as issues with plants and wildlife (bio fowling), as well at the radio environment where interference and fluctuating link quality is a concern [14]. Power supply and batteries are also known to cause issues, where changes in temperature [38] can cause unwanted voltage fluctuations [6]. When looking at opportunistic sensor networks the challenges from a physical environment remains, but the network is also more forgiving in terms of loosing connections to other nodes. Instead of keeping the node operational and connected at all times the challenges in these networks lie more in exploiting the available connections in the best possible way. Due to the decentralized design issues such as controlling and ensuring the sampling of sensors, data exchange and energy consumption of individual nodes are also a key challenge since no global optimization is plausible. Maintaining privacy and security is also a major concern in OSNs, but such issues lie outside the scope of this thesis. Instead the main challenges addressed are those that affect the transmission and sampling of sensor data, which includes understanding the link conditions and contact opportunities that nodes have. One of the ways in which these topics have been investigated has been to design, build and deploy experimental networks.

2.2 Experimental Deployments in this Thesis

Part of the work in this thesis lies in measuring and understanding how meteorological factors can influence the data transmissions between the nodes. In order to investigate this two experimental WSNs have been deployed, that have nodes mounted on poles aligned along a straight line. The nodes in both networks use the IEEE 802.15.4 standard [24] for wireless transmissions. The deployment sites were chosen to minimize interference caused by other networks.

Marsta Deployment

The first deployment, on the outskirts of a small village called Marsta, located north of Uppsala, consist of 16 TelosB [13] sensor nodes. The location was chosen due to the fact that there is a weather station at the site, operated by the Department of Earth Sciences at Uppsala University [2] as well as being isolated from any nearby settlement. The nodes are attached to the Sensei-UU testbed [40], which provides control and logging capabilities for the network. The nodes are encapsulated in weatherproof boxes and powered by USB-cables which also connects them to the testbed infrastructure.

(a) Aerial view of the Marsta deployment during spring. The large mast is the weather station and the poles with sensor nodes align outward towards the left-hand side of the picture.

(b) A closeup of the nodes and testbed infrastructure used in Abisko.

Figure 2.1. Pictures from the two deployments conducted, illustrating the layout and node installation together with the testbed equipment.

The deployment has for the most part been up and running since the spring of 2012. Long-term measurements, combined with extensive logging for research purposes meant that batteries were not a viable option. The area, seen in Figure 2.1(a), is a large grass field, where the mast of the weather station is also deployed, and the distance between the two poles furthest apart is 80 meters. The site experiences a varying climate with changing seasons, where temperatures typically lie between -20° and +30° degrees Celsius.

The nodes in the network send data in a round-robin manner and log a variety of parameters including the data packets themselves. The weather station also provides data on a multitude of meteorological parameters, with a resolution of 10 minutes. This setup allows us to closely correlate observation in the network with changes in the meteorological conditions, something that is explored in Papers I and II. The deployment was also used in Paper III, providing data in packet corruption in these networks.

Abisko Deployment

The second deployment is located in Abisko, a remote village in northern Sweden, where the network is situated in the vicinity of a sub-arctic research station [47]. The network consists of 12 TelosB sensor nodes, encapsulated and mounted in a similar fashion as the first deployment, illustrated in Figure 2.1(b). The network was deployed in March of 2013 where although initially successful, the network eventual experienced downtime due to issues with the connection to the testbed. The major difference compared to Marsta, is the arctic climate which provides a contrasting environment with a colder climate and very low precipitation. Temperatures in Abisko can range from

-40° to at most around +20° in the summer with a mean annual temperature of below 0°. This deployment allowed comparison of the collected data from the two sites, which was used in Paper III to show that the approach worked. The network has been taken down and discontinued since summer of 2015.

3. Transmissions in an Outdoor Environment

TRANSMITTING data in an outdoor environment can differ from a more traditional indoor network. In this chapter some of these differences and how they can impact the sensor node communication are discussed. Looking at performance from a link perspective focuses our discussions on observations that are perceivable by the node. The benefit of such observations, and the ability of the node to act accordingly is that they are independent and do not require knowledge about the state of the entire network. Understanding the aspects presented in this chapter enables nodes and network designers to be aware and compensate for some of the challenges a node may face.

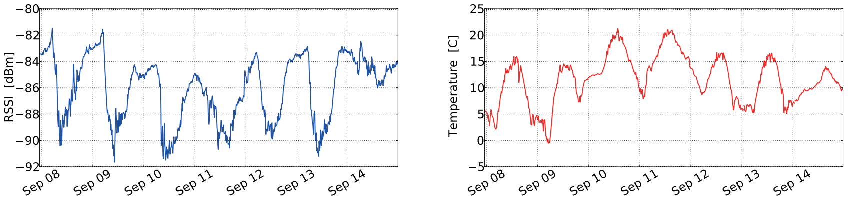
3.1 Meteorological Impact

Outdoor sensor networks are exposed to an ever-changing meteorological environment. This means that the condition at which nodes have to operate and transmit data constantly changes, where both fast and slow moving changes occur. From a network perspective however the changes are considered slow, since the rate at which data is transmitted is often much faster than any meteorological changes, as such these effects are often seen as constant. But when considering the lifetime of a network the impact to wireless transmissions can be looked at with a timescale of hours, days, months, and years. This allows us to ask if the meteorological changes impact the nodes ability to transmit and receive data, and if so, what causes these effects? Theoretical work states that radio signals under 10 GHz should not be impaired or susceptible to signal attenuation due to meteorological effects such as rain [37, 15].

In contrast, by looking at some of the data collected from our deployments there is seemingly more to the story. Plotting the received signal strength over a given link for an entire week in the Marsta deployment in Figure 3.1(a) a clear performance trend is observed. A higher average Received Signal Strength Indicator (RSSI) means a stronger link, where Figure 3.1(a) show that the link is at its weakest during the middle of the day. This shows that there is clearly some systematic effect at work, since the nodes are stationary and deployed in an isolated location.

3.1.1 Understanding The Root Causes

When looking at the meteorological impact on sensor nodes both when intentionally explored and accidentally observed, some insights into the effects



(a) Average received signal strength (RSSI) for a link, weakest during midday.

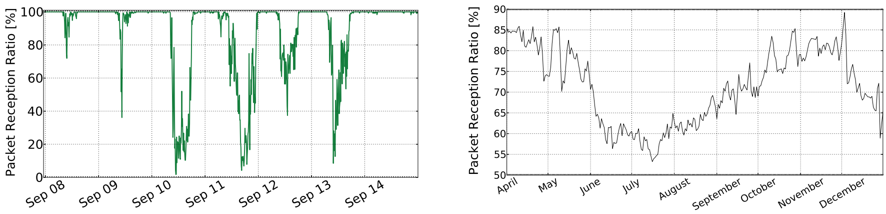
(b) Ambient temperature during the week, where the highest temperatures are during midday.

Figure 3.1. Example of how RSSI and temperature measurements vary, with a visible pattern in both graphs. Measurements from September 2012.

from related work can be found [5, 8, 21, 48, 3, 45]. The findings attribute changes in the nodes performance to changes in the meteorological environment, albeit with sometimes contradicting conclusions. The main focus has been to look at temperature, where a higher temperature has been suggested to decrease the strength of the received wireless signal, with adverse effects [5, 8]. The effect of water in the air, measured as humidity, rain, or fog is also something that has been of interest. Here there exists more discrepancies between the results in literature, with findings suggesting positive [48], negative [3, 45] or no observable impact [8]. A likely reason for these differentiating results may be due to differences in methodology, especially in how the meteorological data was collected. The papers contain measurements from the on board sensor of the nodes [4, 8, 21], using the local public weather data in the area [8, 45] or by deploying a small weather station alongside the WSN [3, 48]. These observations heavily influenced our own deployments of sensor networks and the methodology in Papers I and II, ensuring that the meteorological data accurately reflected the local conditions of the WSN.

Looking back at Figure 3.1 and observing the measured temperature in Figure 3.1(b) during the time of the measurements show a similar yet inversed pattern as that in Figure 3.1(a). This lead us to further investigate the relationship between temperature and link quality and how it impacts the performance of the network.

The fact that a signal gets weaker does not necessarily mean a disruption in the transmission of data over all links. As a reference Figure 3.2(a) shows the Packet Reception Ratio (PRR), the amount of successfully received packets, for a single link. As opposed to RSSI this metric shows if the packet actually got through or not, where the trend is not as clear as with RSSI but there is still a definite impact. Aggregating all links in our network and looking at the average daily PRR over several months, illustrated in Figure3.2(b), there is a clear variation in network wide performance between different months. This shows that a WSN deployed outdoors can experience slow moving large fluctuations in performance. The insight from this is that making the network operational



(a) PRR computed over 10 minutes for one link over seven days.

(b) Average daily PRR for all links in the Marsta network over nine months.

Figure 3.2. Two examples of how successful packet transmissions can be measured over time. Comparing (a) to plot in Figure 3.1 indicate some correlation but with more sudden fluctuations.

during the deployment day is not a sufficient guarantee that it will continue to work in the coming months. Models to predict how the performance will change are needed in order to improve the likelihood of keeping the network functional.

3.1.2 Conclusions

The observed impact and conclusions from Papers I and II states first that temperature, more specifically the on-board temperature, is the dominating meteorological impact factor and secondly that as temperature rises one can expect a node to have a linear decrease in the received signal strength, according to the equation outlined in Paper II. The underlying cause of the impact originates from the low-cost electrical components used in the nodes, which are susceptible to temperature variation. The equation can be used to anticipate the signal attenuation a node should be able to handle, given the expected temperature range in the deployment environment.

The observations are that the weakening of the signal primarily causes issues of packet loss to the links that exhibit intermediate quality and intermittent connectivity. This are the links that can be perfect at times, with no packet loss, but where there exists times of severe packet loss as well. Another way to phrase it would be to say that these are the links that are close to the maximum transmission range between these two nodes. These links are found to be the most interesting, since for perfect links that never exhibit any issues there is no improvement to make, and links that are very weak all the time also presents few opportunities for improvement.

3.2 Packet Corruption

Transmitting data packets between nodes ensures that the sensor data can be disseminated and collected, maintaining the functionality of the WSN. How-

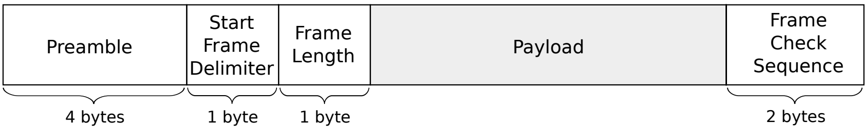


Figure 3.3. The structure of a 802.15.4 packet where the frame length contains the size of the payload.

ever transmissions do fail and cause packet loss, due to the error prone wireless medium, signal attenuation, or as shown earlier due to fluctuating temperatures.

Lost packets are either retransmitted or sometimes even discarded depending on the application. Retransmitting a packet lead to both the sender and the receiver having to spend more energy to successfully convey the same amount of information, making the transaction more expensive in terms of energy usage. Therefore to prolong the lifetime of the energy scarce network it is important to keep the number of retransmissions to a minimum.

In order to do this there exists several techniques, where a common idea is to protect the data using Forward Error Correction (FEC). The concept is to encode redundant data into a packet in order to detect and correct corrupt segments of the packet. There is a mountain of different techniques, or codes, where the exact choice depends on factors such as how many errors should be detectable, how many should be correctable, if the errors are bursty or not etc. Choosing a code capable of handling a higher number of errors typically adds to the cost and complexity of transmitting the data. This means that the choice of FEC technique should reflect the conditions of the link between the two nodes in the network. A very good link would only need a 'light' code capable of correcting maybe one error whereas a poor link would need a more robust code capable of correcting more. Although FEC is a well-known and used technique an alternative approach to handle packet corruption in an outdoor WSN was devised. To outline the idea behind it, a bit more in-depth knowledge on wireless transmission in 802.15.4 networks is needed.

3.2.1 Receiving a 802.15.4 Packet

A node can receive a 802.15.4 packet by listening to the channel and detecting the start of a transmission, by identifying a fixed format of four bytes known as the preamble, show at the left most side in Figure 3.3. If the preamble and start frame delimiter is not detected, the node will stop listening to the channel and go back into idle or sleep mode, resulting in the packet being *missed* and consequently lost. On the other hand if everything goes well the whole packet will be received the node which will then computes a Cyclic Redundancy Check (CRC). This verification step is computed using the Frame Check Sequence (in Figure 3.3) and is there to confirm that the data received is the same as what was sent. If this check fails the packet has been corrupted and gets discarded by the node, also resulting in a lost packet. This corruption occurs when a node matches a received sequence of 32-bits to an incorrect chip sequence (also 32-bits long) defined by the standard. The chip sequence although 32-bits long only represent four bits, or one *symbol* of data in the packet. This design allows a receiver to decode some zeros and ones incorrectly, still matching the chip sequence to the correct symbol, making the process more robust. Once the number of errors is too big, the wrong sequence will be matched resulting in corrupt data in the packet, which as mentioned earlier will then be discarded by the node.

The approach presented in Paper III take a new stance on how to treat corrupt packets. The argument is that a node spends energy on receiving an entire packet, performs a computation and then, if corrupt, drops it immediately. The fact that this can occur due to a single symbol in the entire packet being incorrect, where everything else is intact, presents a large waste due to a small error. Instead the question becomes if it can be possible to accept a corrupt packet and try to estimate what was sent by understanding more of how corruption occurs. Paper III explores this idea and shows that it is possible to assign a high probability to the correct 16-bit long *word* which is part of a corrupt packet. The knowledge that can be leveraged to compute the probability of a word being sent given a known received word uses information of how the chip sequences were designed and implemented.

This process of reducing the uncertainty of what was sent works best when interference is low, which is what is observed in our outdoor WSN deployments. This means that packet corruption occurs due to failing links, for example when the temperature rises, and not some external radio interference. Because of this the number of symbol errors in a corrupt packet is most of the time very low (1-3 symbols), making it meaningful to try and recover from it.

Looking forward, the paper outlines the feasibility of reconstructing corrupt packets, designing a system and appropriate application use still remains to be explored. This type of approach, allowing for corrupt data, would likely be applicable in certain cases where obtaining sensor data is crucial, and possibly where the analysis could be done offline for example, since it requires a bit of computation.

3.3 Intermittent Connectivity

The observations of the link quality of nodes showed how meteorological factors fluctuating over time influence them. This sometimes makes the link unusable, where none or very few packets are transmitted successfully. One of the ways to address this was to consider corrupt packets, which are normally seen as lost. This is only a partial fix and cannot save a link from total packet loss when packets are never even detected. These times of intermittent connectivity means that the nodes cannot receive any data over the link, isolating the nodes unless they have additional links that are still functional. In a static WSN this is of course unwanted behavior which damages the networks ability to collect the desired data. However in a mobile network the effect differs a bit, where it can be treated as part of the natural order of things, since nodes come and go. Especially for opportunistic sensor networks where intermittent connectivity is built into the design, since it is assumed to occur a lot. In OSNs the issue of link availability is reversed, what should a node do when there is a link, instead of asking how to handle a failing link. In the next chapter a more detailed introduction to OSNs and how they can be used to collect sensor data is presented.

4. Intermittently Connected Sensor Networks

A type of network where intermittent connectivity is assumed, and part of the design, are so called *delay-tolerant networks* [19]. These networks do not rely on end-to-end connectivity, a fundamental aspect of most other networks, to operate since it is typically not available due to the mobility of nodes. This means that there might be no immediate and direct link between two nodes that wish to communicate. Instead, the data has to be stored and carried by the nodes such that when a contact opportunity arises due to the mobility, they are able to forward the data to the next node with the hope of reaching its destination. This principle is known as the *store-carry and forward* paradigm. A delay-tolerant network implies that nodes are more isolated and the network more decentralized, where global knowledge and control is not feasible due to this. This however also makes them more robust against any single point of failure, suitable in scenarios where cellular or Internet connectivity is not available or desired. The initial use case for delay-tolerant networks was for space communication, but since then envisioned application areas have extended to include communication in remote areas [30], scenarios where government oversight is to be circumvented [31], or for use during disasters [53] when infrastructure is wiped out.

Opportunistic sensor networks (OSN), which are considered in this thesis is a specific type of delay-tolerant network which uses *opportunistic communication* that in turn relies on the mobility of humans, which carry the nodes to both *sample* and *disseminate* sensor data. Data is exchanged during contact opportunities, dictated by the underlying mobility patterns, which are assumed to be unknown or uncontrollable. The network is set up to monitor the environment in which the participants move, both allowing users to gain awareness of their surroundings as well as collecting the data at central point(s) for further processing. A distinct feature of OSNs is that the communication and sensing is intertwined, both limited by the opportunities given by the movement of nodes.

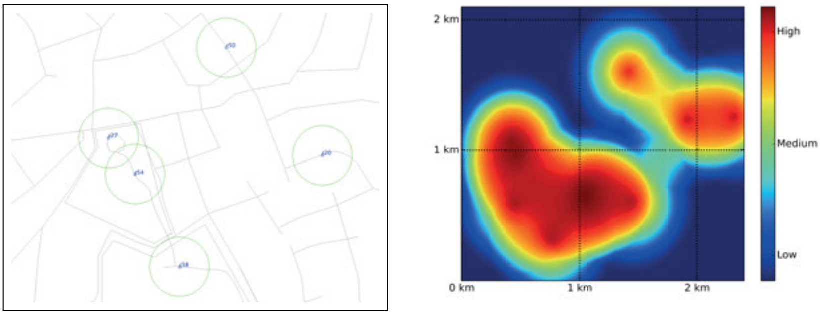
An OSN relies on the participating nodes in the network to collect and communicate the sensor data. As such, it can also be classified as a special type of *people-centric sensing* [11] system, where the users are part of the general public, lending their resources in some way to contribute to a sensing task. The approach in people-centric systems is typically that there exists an always on cellular or Internet connection, so that the collected data can be uploaded onto a central server for further processing and presentation [17]. In this regard OSNs differ, not having an always on connectivity, and instead of a centralized server relying on node-to-node communication to acquire and spread data.

In general, the broader area of opportunistic networks is much less explored than the traditional WSN architecture. This is both due to it being a more specialized network as well as the deployments being more cumbersome given the number of participants that need to be involved. As such, the majority of the work in this area is in an earlier stage, where simulation and analytical modeling is the dominating approach. There are however some real-world measurements, or *traces* [23, 49, 41], that have been collected to capture contacts in order to understand how data can be disseminated in such a network. A collection of such traces can be obtained from CRAWDAD [1], a community run website which provided us the traces used in Paper IV, V and VI.

4.1 Opportunistic Sensor Nodes

A node in an opportunistic network is often considered to be a mobile phone, since this is a common object for people to carry around, typically with WiFi and Bluetooth capabilities. Here however the assumed communication technology is the IEEE 802.15.4 standard [24], reflected in the transmission range and data rates achievable. This standard is considered since it is low-power and established as a sensor network technology. This has the potential of reducing the strain on the battery of the device as well as making it interoperable with already existing sensor network technologies. The chosen network technology also implies that the sensing modalities are low-complexity, typically what you would get from a low-power sensor.

These features of the nodes define how the OSN is simulated, and what scenarios are envisioned. Given that this type of network is still in its infancy there are no real deployments as of yet, instead fundamental features are explored through analytical modeling and computer simulations. When simulating OSNs, the ONE simulator [26], a discrete event simulator especially designed for delay-tolerant networks is used throughout this thesis. The simulator can represent nodes moving over an area, how contacts occur and the data exchange between nodes, a visual snapshot of the simulator is shown in Figure 4.1(a). The simulator does however not contain a way to add sensor data that can be measured by the nodes. To incorporate this, the simulator has been extended with such capabilities, where an underlying *sensor cloud*, depicted as a heatmap in Figure 4.1(b), can be sampled by the nodes based on their current location.



(a) Illustration of nodes on a map in the ONE simulator. The green circles indicate communication range.

(b) A simulated underlying phenomenon that can be measured by the sensor nodes in an OSN.

Figure 4.1. Simulations in OSNs can contain both simulated movement as well as the sensor data to be collected.

4.2 Node Participation

A good reason for using low-power communication is that one of the challenges in an OSN is to motivate users to participate. The participants are lending resources to the network in order to complete some task, which inevitably means increased power consumption, reducing the battery lifetime of their device. Since the nodes are not viewed as being owned by a specific organization one typically assumes that users are motivated by some external factor (e.g. monetary, ideological, altruistic etc.) or that the network provides them with the incentive to participate. Motivating the nodes is a known issue and something that has been studied when designing incentive mechanisms for opportunistic network routing protocols [36, 54, 42]. One way to incentivize nodes is to model the network as a game, and analyzing it using game theory [44], a mathematical tool to analyze behavior during competition.

There are a few reasons why game theory is a good way to to model the incentive mechanisms of opportunistic network participation. As the name implies it deals with strategies of how to play against other players, in our case how nodes should interact with one another when relaying data. The standpoint is that each player(node) is selfish and wants to maximize its own outcome, called *utility*, and does so by considering and responding to the actions of the other player(s). The decision-making is done locally at the node, only considering its own benefit, but by careful design the game can still achieve a favorable global outcome. The alternative of globally optimizing the exchange requires a central entity with complete knowledge of the entire network in order to make decisions, something that is difficult to obtain in an OSN. As a downside however, outcomes of a game may not be optimal and the design of the utility function is crucial, since it should reflect what nodes really care about when making decisions.

In our case of OSNs the underlying problem that game theory tries to solve is how to motivate a node to send sensor data to someone else, since it consumes energy when doing so. Although nodes are selfish, not wanting to waste energy relaying data for someone else, they are at the same time interested in getting data from other nodes. This is explored in Paper IV where a game is designed to model the exchange of sensor data between the nodes in the network. When a contact occurs between two nodes they exchange sensor messages in a *tit-for-tat* manner, meaning that they only get as good as they give in terms of the quality of the sensor data. The game produces a *Nash equilibrium*, meaning no player can be made better off by changing their strategy, given the other players strategy. The Nash property is a fundamental aspect of game theory, showing that there exists a clear strategy to a game that the nodes can use when making decisions. To conclude that the outcome of this strategy is actually a desired outcome, one can show that it is *Pareto optimal*. This property of the game prove that it is efficient by showing that no player can be made better off (in terms of efficiency) without making some other player worse off.

4.3 Contact Opportunities

A node in an OSN moves around, establishing connections to other nodes when they are within communication range of each other. These connections are then utilized to transmit data between the nodes, where which data to relay and to whom is decided by the routing protocol that runs on the node.

4.3.1 Opportunistic Routing

The goal of a routing protocol in an opportunistic network is to increase the *probability* that a piece of data arrives to its intended destination, since data can never be guaranteed to arrive due to the lack of end-to-end connectivity. As such the most straightforward way would be to always transfer all the data during a contact and hope that by spreading the data in an epidemic fashion one node would eventually relay the data to the intended recipient. Although this approach, implemented in the Epidemic routing protocol [51], is optimal in terms of maximizing the chances of delivery it is easy to see that the resource consumption is very high, making it the most resource hungry approach as well.

From this, researchers have proposed a multitude of alternatives with the aim of maintaining the best possible message delivery while using fewer resources than the epidemic approach. Here solutions include limiting the number of replicas of a message in different ways [50, 43], or making more informed decision on which messages to relay by keeping track of the contact probabilities of nodes [20, 10].

In the end the decision comes down to *should I relay this data to this node*? As such, many routing protocols do not explicitly consider or handle the scenario when there is more than one other node to communicate with. There is often no detailed mechanism describing how to prioritize or choose node, treating them on a first-come first-serve basis or just picking at random. This also includes the notion that nodes only communicate in pairs, not considering the idea of locally broadcasting messages. One of the reasons for this is that the contact duration is often viewed as being sufficient to transfer all desired data, making prioritizing between nodes irrelevant.

With this as a the backdrop, our approach in Paper V is to show that multiple simultaneous contacts between nodes are not that rare in an opportunistic network. This then motivates a discussion on how can routing protocols be improved by considering this information. In the end, the proposition is to extend current commonly used routing protocols with the information that links between contacts can vary in quality. This is inspired by observations from the traditional WSNs deployment conducted in Marsta and Abisko, where link quality is definitely a factor when routing messages in the network. The general idea is to incorporate a cost of a routing decision where the cost in this case is the probability of successfully transmitting a message. A general routing metric for message m_k being sent to node n_i can be specified as

$$RM(n_i, m_k) = RM_{orig}(n_i, m_k) - Cost(n_i, m_k), \tag{4.1}$$

where $RM_{orig}(n_i, m_k)$ is the original routing metric defined by a routing protocol. This addition means that a node will consider the quality of a link when routing, balancing the gain of routing a message to a node with the expected cost of doing so. If two or more nodes are available the one where the connection is the strongest will generally be favored, saving energy by reducing retransmissions.

4.3.2 Opportunistic Sensing

In parallel to sending and receiving sensor data from other nodes, a node in an OSN also takes samples from its current environment. This sampling process is just as the communication assumed to be opportunistic, meaning that the node does not control when and where samples are taken, neither is it assumed that nodes can be directed towards certain areas for example. This is so that the person carrying the node does not have to be actively involved, telling the node when to sample, instead this is an autonomous process running on the node. A standard approach to do this is to set a periodic sampling interval, having the node take samples at a fixed rate. This does however have its drawbacks which are highlighted and discussed in Paper VI. Figure 4.2 illustrate one of the issues that occur, where due to the mobility of nodes, samples are not evenly spread between different locations in the area monitored.

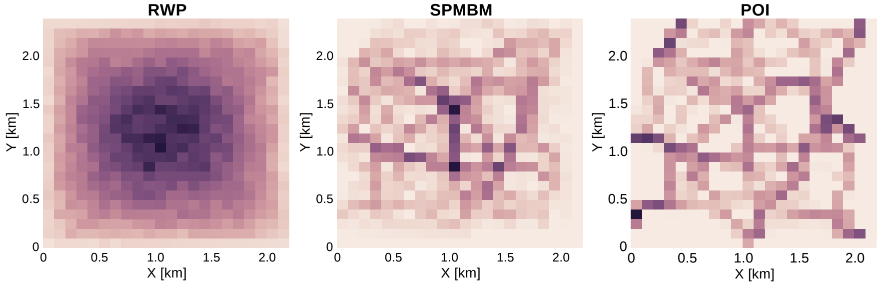


Figure 4.2. Illustration of the distribution of samples when using periodic sampling for three different mobility patterns. Darker areas contain more samples where the center*(SPMBM)* and rightmost*(POI)* figures have nodes moving according to a map. The leftmost*(RWP)* figure show the sample distribution when nodes move randomly, without being confined to moving according to a map.

The biggest issue with this is actually that some areas become overrepresented and producing a large amount of samples from the same area is often not beneficial for the monitoring purposes of the network. Since the sampling is opportunistic nodes cannot be told to go to certain areas, where there are few samples for example. Instead the approach outlined in Paper VI is to develop adaptive sampling methods to decide when it is a good time to sample. A key challenge in doing this is that since there is no global coordination in an OSN, due to the isolation of the nodes from the network, nodes need to have local methods to set the sampling rate.

To conclude, this chapter presents some of the addressed issues in OSNs and how nodes can become more informed and make autonomous decisions by better understanding their local environment. Due to the node isolation in OSNs such heuristics are both the simplest and most reliable since synchronizing information in these networks is very challenging.

5. Summary of Papers

Paper I

A Long-Term Study of Correlations between Meteorological Conditions and 802.15.4 Link Performance.
Hjalmar Wennerström, Frederik Hermans, Olof Rensfelt, Christian Rohner, and Lars-Åke Nordén.
In Proceedings of the 10th Annual IEEE Communications Society Conference on Sensing, Communication, and Networking (SECON), June 2013.

Summary

The fact that 802.15.4 wireless links are affected by changes in the meteorological environment is something that has been observed in various deployments. The complexity and interplay between meteorological conditions has however lead to some contradicting results, due to short-term and ad-hoc measurements which can difficult to generalize. This paper address such issues by deploying a WSN over a long period of time, systematically measuring how meteorological conditions correlate with link measurements in the network.

The paper presents an analysis of six months of data from an outdoor WSN collocated with a high quality meteorological weather station. The variation in packet reception rate (PRR), both over long and short term, is shown as well as how RSSI can vary over a few days. The results show a clear variation in PRR over different months of the year. We evaluate five of the most likely meteorological factors to impact sensor nodes and compute the correlation with both RSSI and PRR. The two most dominating factors studied, temperature and humidity, are decoupled to further implicate which has the bigger impact.

Contribution

The paper systematically and over long time studies the correlation to some of the most common meteorological factors that are thought to influence WSN performance. We find that temperature correlates the most with RSSI and PRR and by decoupling temperature from absolute humidity we still see a stronger correlation to temperature in regards to RSSI. The paper also illustrates the long-term impact this can have on the variation in overall link performance in a WSN.

My Contribution

I am the main author of this paper. I developed the initial idea and was responsible for the deployment and maintenance. I performed all the data analysis and wrote most parts of the paper in collaboration and discussion with the co-authors. I presented the paper at SECON 2013.

Paper II

Hot Packets: A Systematic Evaluation of the Effect of Temperature on Low Power Wireless Transceivers.
Carlo Alberto Boano, Hjalmar Wennerström, Marco Antonio Zúñiga, James Brown, Chamath Keppitiyagama, Felix Jonathan Oppermann, Utz Roedig, Lars-Åke Nordén, Thiemo Voigt, and Kay Römer.
In Proceedings of the 5th Extreme Conference on Communication (ExtremeCom), August 2013.

Summary

In here we extend the work from the previous paper by doing a more detailed study of how temperature impacts common sensor nodes. Motivated by our previous and continued observations for the outdoor WSN we set up an indoor WSN in a controlled environment to compare the results. In the indoor setup we can control and vary the temperature in order to more closely test the impact. The results agrees with the observed behavior in the outdoors deployment and highlights additional aspects related to the temperature dependence of specific transceiver models.

Based on both the outdoor and indoor measurements we derive a general analytical model that captures the relationship between Signal-to-Noise (SNR) ratio and the temperature of the sensor node. The model can be adjusted to a specific hardware platform by doing some reference measurements.

Contribution

The paper investigates, confirms and quantifies in detail the impact of temperature on RSSI using real-world and controlled traces. It defines an analytical model that can be used to predict the decrease in SNR due to temperature. This is a useful tool when deploying WSNs, ensuring links are not disrupted due to temperature changes in the designated environment.

My Contribution

I contributed with collecting and analyzing all the data for the outdoor deployment. I participated in the general discussions together with Carlo, where we analyzed the data, comparing the controlled experiments to the observation outdoors. I helped write the parts of the paper detailing the analysis of the outdoor deployment.

Paper III

All is not Lost: Understanding and Exploiting Packet Corruption in Outdoor Sensor Networks.
Frederik Hermans, Hjalmar Wennerström, Liam McNamara, Christian Rohner and Per Gunningberg.
In Proceedings of the 11th European Conference on Wireless Sensor Networks (EWSN), February 2014.

Summary

This paper investigates packet loss and corruption in 802.15.4 based outdoor WSNs. Based on insights gained from one of our earlier papers [55] we illustrate the difference between *missed* and *corrupt* packets, showing that corrupt packets are a common reason for packet loss in interference free outdoor WSN. We highlight that even though a packet is corrupt, the amount of corruption it typically very small in such a network. The motivation is to see if we can avoid trowing away corrupt packets and try to use the information instead.

We further analyze how the corruption occurs by studying the inferred transmitted symbols and the structure of the underlying chip sequences used. By identifying a pattern in how transmitted symbols get mistaken at the receiver we are able to reduce the uncertainty in what was sent. We then show that this allows us to probabilistically reconstruct parts of a data packet. The result is a ranked list of possible sent values. We show that the ranking is sound as it ranks the correct symbol with a high probability in 95% of cases.

Contribution

The paper shows that it is possible to probabilistically reconstruct broken packets that have been received. The key insight is a previously unknown pattern influencing how symbols get corrupted, which occurs due to the design of the chip sequences in the 802.15.4 standard.

My Contribution

I contributed with the experiential setup, data collection and initial analysis. I wrote minor parts of the paper together with Frederik and Liam, and took part in discussions of the work.

Paper IV

A Game Theoretic Approach to Sensor Data Communications in an Opportunistic Network.
Hjalmar Wennerström and David Smith
In Proceedings of the International Conference on Communications (ICC), June 2015.

Summary

The motivation behind node participation in an OSN can either be viewed as an altruistic choice or driven by some incentive mechanism. This paper outlines a game theoretic construct in order to motivate nodes to participate in the exchange of sensor data. As defined by the game, when two nodes meet they exchange messages in a *contrite tit-for-tat* manner, meaning that a node only gets as good as it gives, and where the nodes do not hold a grudge if treated poorly. The game is centered on a utility function that express a nodes desire to obtain sensor data of high interest and large size. The game is shown to produce a sub-game perfect Nash equilibrium, showing that nodes will not deviate from the strategy in that equilibrium. The game is further shown to be Pareto efficient, where the total efficiency cannot be improved by changing strategy. The game obtains the highest overall efficiency during simulating compared to three alternative approaches that are altruistic, random or minimizing energy expenditure.

Contribution

The paper proposes and analyzes a game designed to motivate node participation in an OSN where data is shared among the nodes. The game contains a unique sub-game perfect Nash equilibrium, which is also shown to be Pareto efficient, proving that the Nash strategy results in an efficient outcome.

My Contribution

I am the main author of this paper; I came up with the idea and designed the game with input from David. I performed all the simulations and analysis of the results. I wrote the majority of the paper and presented it at ICC 2015.

Paper V

Considering Multi-Contact Encounters in Opportunistic Networks.
Hjalmar Wennerström, Christian Rohner, and David Smith
In Proceedings of the 10th ACM MobiCom Workshop on Challenged Networks (CHANTS), September 2015.

Summary

Opportunistic networks are often viewed as a network of very isolated nodes, since this is a fundamental characteristic. In the paper we however highlight the fact that although nodes can be isolated from one another, once nodes are within communication range of one node, there are likely more nodes close by as well. This is explained by the social patterns we humans have, moving in and out of groups or gatherings. From a network and routing perspective this means that so called multi-contacts, having multiple simultaneous connections to a set of nodes, are not as rare as one might think. Furthermore we found that this information is not something explicitly considered by routing protocols used in opportunistic networks.

The previous observations lead us to discuss and extend routing protocols to consider this information. Specifically the fact that simultaneous contacts (or links) would exhibit a different and variable quality over time. To this end the paper proposes a general purpose addition to some of the more common routing protocols already proposed in the literature to include this new information in the routing metric. The result is that nodes choose which link to relay data over by also considering the quality of that link. The evaluation shows that we can reduce the amount of lost messages in an OSN that exhibit packet loss, reduce the number of relays started while maintaining the delivery ratio.

Contribution

The paper highlights the fact that multiple simultaneous contacts opportunities are commonplace in many opportunistic networks, something that is not explicitly considered by routing protocols. We extend common routing protocols to consider this information by including a metric for link quality, which varies for different connections. It shows that choosing the right link can reduce the amount of lost messages, saving energy.

My Contribution

I am the main author of this paper; I developed the idea of multi-contacts and proposed how it could be used with input from my co-authors. I implemented the idea and performed and analyses all the simulation results. I wrote the majority of the paper and presented it at CHANTS 2015.

Paper VI

Towards Even Coverage Monitoring with Opportunistic Sensor Networks.
Hjalmar Wennerström and Christian Rohner.
Accepted for publication at the 11th ACM MobiCom Workshop on Challenged Networks (CHANTS), October 2016.

Summary

The ability of an OSN to monitor an areas depends largely on the mobility of the nodes, since that dictates where and when samples can be taken. In this work we explore how periodic sampling cause large differences in the number of samples at a given location. This uneven distribution is caused by the nodes not being uniformly distributed over the area, rather they congregate towards certain locations. The effect is shown to be especially severe when node movement is restricted according to a map. The solution to this is to have the nodes sample in an adaptive manner, with the aim of reducing the unbalance in where samples are taken.

To this end the paper propose five simple and complementary methods to adjust the sampling interval, only requiring information that can be local attained by a node. The methods do not rely on a verbalized knowledge of the network or training data in order to sample adaptively. The main insight, inspired by observations from our earlier work in Paper V, is that where there are many nodes, there are also many samples and contact opportunities. The five methods are evaluated based on coverage and the difference in load on the network compared to a periodic scheme. Findings show that we are able to reduce oversampling in the most affected areas, while maintaining the number of samples in the least samples areas. The proposed additions also show that we can maintain a certain level of coverage while reducing the total number of samples, easing the load of the network.

Contribution

This paper shows how periodic sampling in an OSN causes large biases in the distribution of sensor samples. We propose a way to alleviate this issue through an adaptive sampling process that adjusts the rate using only information that can be locally assessed by the node.

My Contribution

I am the main author of this paper; I developed the ideas of adaptive sampling and coded the implementations. I performed the analysis, discussing the results with Christian.

6. Conclusions

THE research areas explored and presented in this thesis address different ways in which nodes can be made more aware of the current context in which they are to function. This has meant seeking out ways to understand and adjust to changes in contacts, sensor data and environmental factors, with the goal of enlightening the nodes.

Our work studying the meteorological effects in outdoor WSNs has lead to a much more precise understanding of how temperature impacts sensor nodes. The long-term measurements have also shown how the outdoor sensor network performance can vary both on a diurnal and seasonal scale, for which insights in how-to deploy networks, can be gained. The work in understanding how the network responds to the temperature effect has also resulted in further work, providing researchers with a testbed infrastructure to run tests under different temperature settings [9]. This knowledge is something that the nodes can use on its own, since many nodes contain a temperature sensor by default. Something that was observed in the Marsta and Abisko deployments is that the node specific temperature can vary considerably between different nodes during the same time. This is primarily due the nodes being mounted in different location and directions, meaning that some nodes may be shaded whereas others are exposed to direct sunlight, increasing the temperature significantly. This can for instance be the difference between a successful and a corrupt packet.

The insights and idea on recovering data from corrupt packets is a bold step in asking, how can corrupt data be trusted? The notion that data cannot be 100% trusted is new from a network perspective, yet something that applications deal with all the time. A sensor reading by default is not 100% trustworthy either; there may be scenarios where faults in the data is acceptable to some degree. The underlying motivation that drew us to the idea in the first place, trying to make use of data that has already been received instead of just trowing it away, still seem appealing in low-power wireless networks. Allowing the nodes to store and forward corrupt data may be a decision that the nodes should take, for example by regarding how much non-corrupt data it has managed to obtain and forwarded recently.

When looking at the specific OSN network architecture the issue of how to motivate users to participate in the exchange of sensor data was addressed. This is an important aspect in a distributed system where nodes participate based on their own free will. The insight this game brings is that nodes (people) can be motivated without any external incentive scheme (monetary for example) if they wish to improve their situational awareness by obtaining sensor data from other nodes. This allows nodes to obtain data from areas that they have never visited, yet since they may want to go there in the future information on such areas may be of value. The game also shows that having misbehaving nodes who do not share their sensor data with the other nodes in a fair way will be worse of than the ones who play fair, dissuading unwanted behavior. The behavior of the nodes considers both the gain of receiving new sensor data as well as the cost of sending some of its own data.

The cost of sending a piece of (sensor) data is something that is also included in the work on opportunistic routing protocols. The insights gained from this work is that although there is always a certain cost for sending data of a given size, the probability that it will be lost can add to this perceived cost, which is something an opportunistic routing protocol may want to consider. Incorporating physical and link layer features into opportunistic routing protocols have the benefit of reducing retransmissions, preserving node energy. The highlighted aspect, used as the motivation behind this work, is the fact that in many opportunistic networks it is not uncommon for nodes to have multiple simultaneous connections, making link quality a factor in such cases. A conclusion here is that although opportunistic networks typically consist of disjoint and disconnected nodes, when contacts occur they are often not just pairwise. Since communication only occur during contacts, it follows that considering the possibility of multiple contacts is something that should be considered when routing.

Not only can the deeper understanding of contact opportunities be used for routing but also to extended these insights into adjusting the sensor sampling at the node. When studying the sampling process in OSNs, the results obtained gave a clear indication that more sophisticated adaptive sampling techniques were needed. Without the possibility to globally coordinate the network to produce an optimal outcome, the goal was instead to explore methods that would allow the nodes to individually adjust the sampling rate according to simple heuristics based on local knowledge. The results obtained conclude that having the nodes make local decisions is indeed a viable option, alleviating some of the issues caused by an uneven distribution of nodes.

On a whole, the argument is that the network can become *'smarter'* by having the nodes understand their context in a better way. This is of course only one part of the solution, where coordination and intelligence in the network as a whole have the potential of providing further improvements. Finally, giving the energy-scarce and sometimes disconnected sensor node more autonomous control can make it consume less power, since decisions can be made without communicating with other devices.

6.1 Future Work

Looking beyond the footprints of this thesis into new research areas there are a few potential paths that may be worth traversing. On a larger scale, research into OSNs could benefit by looking and being inspired by the extensive work already in place for WSNs. Although the network architectures differ, there are still similarities that merit further exploration of any bilateral gains. For example considering the link and physical layer to a larger extent in OSNs would open up for new ideas, much like our work on including link quality into opportunistic routing. For example, extending our work on recovering corrupt data in 802.15.4 packets to operate within a OSN would have the potential to address some of the issues regarding the trustworthiness of the data. Since there likely exists copies of the same data carried by other nodes, a corrupt piece of data could be verified against such a copy once nodes are in contact. This would require a mechanism to do the verification with minimal overhead, yet providing incentives to store corrupt data.

As mentioned earlier the work on packet corruption is also something we believe can spark new and interesting research ideas. Since the patterns we observed are due to the specific coding scheme used in 802.15.4 similar observations may be plausible in other wireless standards. The uncertainty of dealing with corrupt data is also something that could be better understood. It appears plausible that if an application knows the type of data to expect, a much better estimate of the likelihood of the data being corrupt or not should be achievable.

Sensor Data Collected by the Node

Our work on sensor data exchange in OSNs considers the problem of two nodes establishing a connection and sharing data. However, at a later stage it became clear that nodes commonly have multiple connections at once when exchanging data. This means that one could extend our two player game to an n-player game, something that should not be to hard to achieve yet the game analysis would require some additional steps. Another interesting aspect that would be worthwhile is to design a game to improve communication during these times when multiple nodes are co-located. A concrete idea would be a power control game that could use input from the application layer to determine at what transmission power a node should broadcast. This is a classical application of game theory in wireless networks yet OSN provide new considerations from the application layer where the sensor data content could be considered when playing the game.

Finally, a closer tie to the actual measured sensor data could also be used to explore other ideas in adaptive sampling. Our approach did not consider the content of the sensor data samples, while doing so may prove to enable further improvements in deciding when to samples. A clear way forward would be to also adjust by considering how interesting the previous samples were, do they for example show *'high'* values or a large variation in the measurements.

7. Summary in Swedish

TRÅDLÖSA sensornärverk är en typ av nätverk som kan användas för att samla in sensordata från den intilliggande omgivningen. Ett sensornärverk utgörs av sensornoder som är små digitala enheter vilka består av en eller flera sensorer, en beräkningskrets samt en radio för trådlös kommunikation. Målet med denna typ av nätverk är att kunna övervaka miljöer och platser där det tidigare varit svårt eller väldigt dyrt att samla in sensordata. Detta möjliggörs av att noderna är batteridrivna och behöver således inte vara anslutna till ett eluttag, vilket förenklar installation. Idén är att noderna skall var helt självförsörjande och kräva så lite övervakning som möjligt. Eftersom noderna är batteridrivna så är en väldigt central del av design och implementationen att de ska vara så energisnåla som möjligt.

Användningsområdet för dessa nätverk är många, och någonting som fortfarande utforskas aktivt. Fokus i denna avhandling är på användning av sensornätverk i situationer utan fast infrastruktur så som en Internet eller mobil anslutning. Arbetet kring detta innefattar två olika typer av sensornätverk, ett scenario med en mer traditionell fast installation samt ett där sensornoderna är mobila och rör sig i en miljö som skall övervakas, så kallat opportunistiskt sensornätverk. Nätverken speglar den större bilden av tilltänkta scenarion där sensornätverk kan användas både på avlägsna och svåråtkomliga platser, samt i situationer där ett nätverk måste komma igång snabbt och tillhandahålla information utan att kunna använda sig av Internet eller mobilnätet, exempelvis vid en naturkatastrof.

En stor andel av dessa nätverk placeras utomhus, i en ibland tuff och svåråtkomlig miljö. Detta får till följd att noderna och nätverken måste vara robusta och hantera förändringar i förutsättningarna på bästa sätt, då felsökning och reparationer kan vara svåra att utföra. Grundutmaningen för ett sensornätverk ligger i att trådlöst förmedla den uppmätta sensordatan till andra noder i nätverket så att den kan samlas in och analyseras. Denna avhandling beskriver hur noderna i ett sensornätverk kan göras mer insiktsfulla om sin nuvarande lokala omgivning, för att på så sätt kunna ta bättre beslut kring hur sensordata ska mätas och skickas.

Det första bidraget kommer från att studera hur meteorologiska variationer påverkar den trådlösa kommunikationen i ett sensornätverk. Detta har gjorts genom att designa och sätta upp sensornätverk utomhus i närheten av meteorologiska forskningsstationer för att på så sätt få tillgång till högkvalitativ data. Efter att ha genomfört experiment under lång tid och tittat på korrelationen av länkkvalité jämt emot temperatur, nederbörd, luftfuktighet och solstrålning fastslogs att temperatur har störst påverkan. Detta ledde vidare till fortsatta och mer detaljerad studie kring hur temperatur påverkar några av de vanligt förekommande sensornoderna. Den insamlade datan från experimenten utomhus jämfördes med mer kontrollerade experiment som genomfördes inomhus i en testbädd där temperaturen kan styras. Detta resulterade i en analytisk modell som beskriver hur signal till brusförhållandet påverkas negativt vid stigande temperatur. Insikterna kring detta kan till exempel användas för att förutse hur mycket en trådlös länk kan försämras vid en viss installation givet att man vet vilka temperaturer den kommer att utsättas för.

Denna påverkan gör också att datapaket som skickas mellan två noder kan bli korrupt och kastas således bort av den mottagande noden. I detta fall undersöks hur data som är korrupt kan återskapas korrekt med en viss sannolikhet. Detta möjliggörs av en djupare förståelse för hur korruption uppkommer, och mönster som skapas kring detta gör att osäkerheten i vad som kan ha skickats minskar. Med hjälp av denna information kan data som annars skulle kastats bort sparas och en sannolikhetsbaserad rekonstruktion blir möjlig. Idén bygger alltså på att försöka minimera energiåtgången genom att inte slänga bort information som redan har tagits emot av mottagaren.

Att motivera noderna att delta i ett opportunistiskt nätverk är en viktig aspekt om vi antar att noderna inte ägs av ett företag eller organisation. I ett sådant sensornätverk bör det alltså finnas något som motiverar noderna att delta i utbytet av data då det innebär en ökad energikonsumtion. Detta problem ligger till grund för den spelteoretiska modell som presenteras och används för att motivera noderna att dela sensordata med varandra. Speldesignen innebär att alla beslut tas individuellt av noderna, som anses vara själviska, men analysen visar ändå på ett fördelaktigt resultat, då nodernas bästa strategi är att delta i utbytet av sensordata.

Slutligen så undersöks hur kontakter mellan noder i opportunistiska nätverk sker, speciellt det faktum att flertalet kontakter sker samtidigt, vilket inte speglas i de existerande routingprotokollen. Denna insikt betyder att noder inte endast skall välja vad som ska skickas under en kontakt men även till vem. Som ett exempel på detta implementeras ett sätt att ta hänsyn till länkkvalitén när routingbeslut ska tas, något som sparar energi genom att minska antalet omsändningar mellan noder. Förståelsen kring kontakter används också för att förändra hur ofta noderna mäter med sina sensorer. När noderna mäter periodiskt i dessa opportunistiska sensornätverk skapar det olikheter i hur bra områden täcks av mätningar. Detta beror på att nodernas mobilitet gör att de ofta samlar sig kring en viss plats (i sociala grupper), vilket i sin tur betyder att dessa platser har ett mycket högt antal mätningar. Lösningen som föreslås är att inte mäta periodiskt och istället ta fram enkla metoder för att variera intervallet, främst med insikten att många kontakter innebär att noderna skall mäta mer sällan. På så sätt minskas ojämlikheter mellan områden och antalet mätningar kan också minskas utan att försämra nätverkets förmåga att samla in tillräckliga mätningar, vilket spar energi.

Till sist så diskuteras framtida utmaningar och olika inriktningar kring det fortsatta arbetet. Något som påpekas speciellt är möjligheter kring att sammanfläta beslut om hur och vad som skickas med den faktiskt uppmätta sensordatan. En svårighet kring detta är att lösningar kan bli applikationsspecifika då de tar hänsyn till specifika egenskaper hos en viss typ av sensordata. Även fortsatt arbete kring utnyttjandet av korrupt data ses som lovande och kan möjligen översättas till andra teknologistandarder så som WiFi till exempel.

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9. References

[1] CRAWDAD: A Community Resource for Archiving Wireless Data At Dartmouth. `http://www.crawdad.org/`.

[2] Marsta weather station. `http://celsius.met.uu.se/?pageid=12`.

[3] G. Anastasi, A. Falchi, A. Passarella, M. Conti, and E. Gregori. Performance measurements of motes sensor networks. In *Proceedings of the 7th ACM international symposium on Modeling, analysis and simulation of wireless and mobile systems*, MSWiM '04, New York, NY, USA, 2004. ACM.

[4] K. Bannister. Impacts of thermal reduction in transceiver performance on outdoor sensing networks. Master's thesis, Arizona State University, Phoenix, AZ, USA, 2009.

[5] K. Bannister, G. Giorgetti, and S. K. S. Gupta. Wireless sensor networking for hot applications: Effects of temperature on signal strength, data collection and localization. In *Proc. of the 5th Workshop on Embedded Networked Sensors (HotEmNets)*, 2008.

[6] Guillermo Barrenetxea, François Ingelrest, Gunnar Schaefer, and Martin Vetterli. The hitchhiker's guide to successful wireless sensor network deployments. In *Proceedings of the 6th ACM conference on Embedded network sensor systems*, SenSys '08, pages 43–56, New York, NY, USA, 2008. ACM.

[7] L. Benini, D. Brunelli, C. Petrioli, and S. Silvestri. Genesi: Green sensor networks for structural monitoring. In *Sensor Mesh and Ad Hoc Communications and Networks (SECON), 2010 7th Annual IEEE Communications Society Conference on*, pages 1–3, 2010.

[8] C.A. Boano, J. Brown, Z. He, U. Roedig, and T. Voigt. Low-power radio communication in industrial outdoor deployments: The impact of weather conditions and ATEX-compliance. In *Proc. of the* 1^{st} *International Conference on Sensor Networks Applications, Experimentation and Logistics (SENSAPPEAL)*, 2009.

[9] Carlo Alberto Boano, Marco Zúñiga, James Brown, Utz Roedig, Chamath Keppitiyagama, and Kay Römer. Templab: A testbed infrastructure to study the impact of temperature on wireless sensor networks. In *Proceedings of the 13th International Symposium on Information Processing in Sensor Networks*, IPSN '14, pages 95–106, Piscataway, NJ, USA, 2014. IEEE Press.

[10] J. Burgess, Brian Gallagher, D. Jensen, and B.N. Levine. Maxprop: Routing for vehicle-based disruption-tolerant networks. In *INFOCOM '06*.

[11] A. T. Campbell, S. B. Eisenman, N. D. Lane, E. Miluzzo, R. A. Peterson, H. Lu, X. Zheng, M. Musolesi, K. Fodor, and G. S. Ahn. The rise of people-centric sensing. *IEEE Internet Computing*, 12(4):12–21, July 2008.

[12] Rachel Cardell-Oliver, Mark Kranz, Keith Smettem, and Kevin Mayer. A reactive soil moisture sensor network: Design and field evaluation. *International Journal of Distributed Sensor Networks*, 1(2):149–162, 2005.

[13] Crossbow Inc. TelosB datasheet. `http://www.xbow.com/Products/Product_pdf_files/Wireless_pdf/TelosB_Datasheet.pdf`.

[14] A. de la Piedra, F. Benitez-Capistros, F. Dominguez, and A. Touhafi. Wireless sensor networks for environmental research: A survey on limitations and challenges. In *EUROCON, 2013 IEEE*, pages 267–274, July 2013.

[15] A. Dissanayake, J. Allnutt, and F. Haidara. A prediction model that combines rain attenuation and other propagation impairments along earth-satellite paths. *Antennas and Propagation, IEEE Transactions on*, 45(10):1546–1558, 1997.

[16] Vladimir Dyo, Stephen A. Ellwood, David W. Macdonald, Andrew Markham, Cecilia Mascolo, Bence Pásztor, Salvatore Scellato, Niki Trigoni, Ricklef Wohlers, and Kharsim Yousef. Evolution and sustainability of a wildlife monitoring sensor network. In *Proceedings of the 8th ACM Conference on Embedded Networked Sensor Systems*, SenSys '10, pages 127–140, New York, NY, USA, 2010. ACM.

[17] Shane B. Eisenman, Emiliano Miluzzo, Nicholas D. Lane, Ronald A. Peterson, Gahng-Seop Ahn, and Andrew T. Campbell. Bikenet: A mobile sensing system for cyclist experience mapping. *ACM Trans. Sen. Netw.*, 6(1):6:1–6:39, 2010.

[18] Jakob Eriksson, Lewis Girod, Bret Hull, Ryan Newton, Samuel Madden, and Hari Balakrishnan. The pothole patrol: Using a mobile sensor network for road surface monitoring. In *Proceedings of the 6th International Conference on Mobile Systems, Applications, and Services*, MobiSys '08, pages 29–39, New York, NY, USA, 2008. ACM.

[19] Kevin Fall. A delay-tolerant network architecture for challenged internets. In *Proceedings of the 2003 Conference on Applications, Technologies, Architectures, and Protocols for Computer Communications*, SIGCOMM '03, pages 27–34, New York, NY, USA, 2003. ACM.

[20] Samo Grasic, Elwyn Davies, Anders Lindgren, and Avri Doria. The evolution of a dtn routing protocol - prophetv2. In *CHANTS '11*.

[21] M.M. Holland, R.G. Aures, and W.B. Heinzelman. Experimental investigation of radio performance in wireless sensor networks. In *Wireless Mesh Networks, 2006. WiMesh 2006. 2nd IEEE Workshop on*, sept. 2006.

[22] Wen Hu, Nirupama Bulusu, Chun Tung Chou, Sanjay Jha, Andrew Taylor, and Van Nghia Tran. Design and evaluation of a hybrid sensor network for cane toad monitoring. *ACM Trans. Sen. Netw.*, 5(1):4:1–4:28, February 2009.

[23] Pan Hui, Augustin Chaintreau, James Scott, Richard Gass, Jon Crowcroft, and Christophe Diot. Pocket switched networks and human mobility in conference environments. In *WDTN '05*.

[24] IEEE Computer Society. *802.15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low-Rate Wireless Personal Area Networks (WPANs)*.

[25] Philo Juang, Hidekazu Oki, Yong Wang, Margaret Martonosi, Li Shiuan Peh, and Daniel Rubenstein. Energy-efficient computing for wildlife tracking: design tradeoffs and early experiences with zebranet. *SIGOPS Oper. Syst. Rev.*, 36(5):96–107, October 2002.

[26] Ari Keränen, Jörg Ott, and Teemu Kärkkäinen. The one simulator for dtn protocol evaluation. In *Proceedings of the 2Nd International Conference on Simulation Tools and Techniques*, Simutools '09, pages 55:1–55:10, ICST,

Brussels, Belgium, Belgium, 2009. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering).

[27] Lakshman Krishnamurthy, Robert Adler, Phil Buonadonna, Jasmeet Chhabra, Mick Flanigan, Nandakishore Kushalnagar, Lama Nachman, and Mark Yarvis. Design and deployment of industrial sensor networks: experiences from a semiconductor plant and the north sea. In *Proceedings of the 3rd international conference on Embedded networked sensor systems*, SenSys '05, pages 64–75, New York, NY, USA, 2005. ACM.

[28] Veljko Krunic, Eric Trumpler, and Richard Han. Nodemd: Diagnosing node-level faults in remote wireless sensor systems. In *Proceedings of the 5th International Conference on Mobile Systems, Applications and Services*, MobiSys '07, pages 43–56, New York, NY, USA, 2007. ACM.

[29] K. Langendoen, A. Baggio, and O. Visser. Murphy loves potatoes: experiences from a pilot sensor network deployment in precision agriculture. In *Parallel and Distributed Processing Symposium, 2006. IPDPS 2006. 20th International*, pages 8 pp.–, 2006.

[30] Anders Lindgren, Avri Doria, Jan Lindblom, and Mattias Ek. Networking in the land of northern lights: Two years of experiences from dtn system deployments. In *Proceedings of the 2008 ACM Workshop on Wireless Networks and Systems for Developing Regions*, WiNS-DR '08, pages 1–8, New York, NY, USA, 2008. ACM.

[31] Anders Lindgren and Pan Hui. The quest for a killer app for opportunistic and delay tolerant networks: (invited paper). In *Proceedings of the 4th ACM Workshop on Challenged Networks*, CHANTS '09, pages 59–66, New York, NY, USA, 2009. ACM.

[32] Kay Soon Low, W.N.N. Win, and Meng Joo Er. Wireless sensor networks for industrial environments. In *Computational Intelligence for Modelling, Control and Automation, 2005 and International Conference on Intelligent Agents, Web Technologies and Internet Commerce, International Conference on*, volume 2, pages 271–276, Nov 2005.

[33] Alan Mainwaring, David Culler, Joseph Polastre, Robert Szewczyk, and John Anderson. Wireless sensor networks for habitat monitoring. In *Proceedings of the 1st ACM international workshop on Wireless sensor networks and applications*, WSNA '02, pages 88–97, New York, NY, USA, 2002. ACM.

[34] K. Martinez, R. Ong, and J. Hart. Glacsweb: a sensor network for hostile environments. In *Sensor and Ad Hoc Communications and Networks, 2004. IEEE SECON 2004. 2004 First Annual IEEE Communications Society Conference on*, pages 81–87, 2004.

[35] Luca Mottola, Gian Pietro Picco, Matteo Ceriotti, Ştefan Gună, and Amy L. Murphy. Not all wireless sensor networks are created equal: A comparative study on tunnels. *ACM Trans. Sen. Netw.*, 7(2):15:1–15:33, September 2010.

[36] Ting Ning, Zhipeng Yang, Xiaojuan Xie, and H. Wu. Incentive-aware data dissemination in delay-tolerant mobile networks. In *Sensor, Mesh and Ad Hoc Communications and Networks (SECON '11), 8th IEEE Conference on*, pages 539–547, June 2011.

[37] A.D. Panagopoulos, P.-D.M. Arapoglou, and P.G. Cottis. Satellite communications at ku, ka, and v bands: Propagation impairments and mitigation

techniques. *Communications Surveys Tutorials, IEEE*, 6(3), 2004.
[38] Chulsung Park, K. Lahiri, and A. Raghunathan. Battery discharge characteristics of wireless sensor nodes: an experimental analysis. In *Sensor and Ad Hoc Communications and Networks, 2005. IEEE SECON 2005. 2005 Second Annual IEEE Communications Society Conference on*, pages 430–440, 2005.
[39] F.J. Pierce and T.V. Elliott. Regional and on-farm wireless sensor networks for agricultural systems in eastern washington. *Computers and Electronics in Agriculture*, 61(1):32 – 43, 2008.
[40] Olof Rensfelt, Frederik Hermans, Lars-Ake Larzon, and Per Gunningberg. Sensei-uu: A relocatable sensor network testbed. In *Proceedings of the Fifth ACM International Workshop on Wireless Network Testbeds, Experimental Evaluation and Characterization*, WiNTECH '10, pages 63–70, New York, NY, USA, 2010. ACM.
[41] Injong Rhee, Minsu Shin, Seongik Hong, Kyunghan Lee, Seong Joon Kim, and Song Chong. On the levy-walk nature of human mobility. *IEEE/ACM Trans. Netw.*, 19(3), June 2011.
[42] U. Shevade, Han Hee Song, Lili Qiu, and Yin Zhang. Incentive-aware routing in dtns. In *Network Protocols, 2008. ICNP 2008. IEEE International Conference on*, pages 238–247, Oct 2008.
[43] Thrasyvoulos Spyropoulos, Konstantinos Psounis, and Cauligi S. Raghavendra. Spray and wait: An efficient routing scheme for intermittently connected mobile networks. In *WDTN '05*.
[44] V. Srivastava, J. Neel, A. B. Mackenzie, R. Menon, L. A. Dasilva, J. E. Hicks, J. H. Reed, and R. P. Gilles. Using game theory to analyze wireless ad hoc networks. *IEEE Communications Surveys Tutorials*, 7(4):46–56, Fourth 2005.
[45] J. Sun and R. Cardell-Oliver. An experimental evaluation of temporal characteristics of communication links in outdoor sensor networks. In *Proc. of the 2th International ACM Workshop on Real-World Wireless Sensor Networks (REALWSN)*, 2006.
[46] Igor Talzi, Andreas Hasler, Stephan Gruber, and Christian Tschudin. Permasense: Investigating permafrost with a wsn in the swiss alps. In *Proceedings of the 4th Workshop on Embedded Networked Sensors*, EmNets '07, pages 8–12, New York, NY, USA, 2007. ACM.
[47] The Swedish Polar Research Secretariat. Abisko Scientific Research Station. `http://www.polar.se/abisko`.
[48] J. Thelen, D. Goense, and K. Langendoen. Radio wave propagation in potato fields. In *Proc. of the 1st Workshop on Wireless Network Measurement (WiNMee)*, 2005.
[49] P. Tournoux, J. Leguay, F. Benbadis, V. Conan, M. Dias de Amorim, and J. Whitbeck. The accordion phenomenon: Analysis, characterization, and impact on dtn routing. In *INFOCOM 2009, IEEE*, 2009.
[50] P. Tournoux, J. Leguay, F. Benbadis, J. Whitbeck, V. Conan, and M. Dias de Amorim. Density-aware routing in highly dynamic dtns: The rollernet case. *Mobile Computing, IEEE Transactions on*, 2011.
[51] Amin Vahdat, David Becker, et al. Epidemic routing for partially connected ad hoc networks. Technical report, Technical Report CS-200006, Duke University, 2000.

[52] T. Voigt, F. Osterlind, N. Finne, N. Tsiftes, Zhitao He, J. Eriksson, A. Dunkels, U. Bamstedt, J. Schiller, and K. Hjort. Sensor networking in aquatic environments - experiences and new challenges. In *Local Computer Networks, 2007. LCN 2007. 32nd IEEE Conference on*, pages 793–798, 2007.

[53] H. Wang, M. Uddin, G. J. Qi, T. Huang, T. Abdelzaher, and G. Cao. Photonet: A similarity-aware image delivery service for situation awareness. In *Information Processing in Sensor Networks (IPSN), 2011 10th International Conference on*, pages 135–136, April 2011.

[54] Lifei Wei, Haojin Zhu, Zhenfu Cao, and Xuemin Shen. Mobiid: A user-centric and social-aware reputation based incentive scheme for delay/disruption tolerant networks. In *Proceedings of the 10th International Conference on Ad-hoc, Mobile, and Wireless Networks*, ADHOC-NOW'11, pages 177–190, Berlin, Heidelberg, 2011. Springer-Verlag.

[55] Hjalmar Wennerström, Liam McNamara, Christian Rohner, and Lars-Åke Nordén. Transmission errors in a sensor network at the edge of the world. In *5th Extreme Conference on Communication (ExtremeCom), 2013*, 2013.

[56] G. Werner-Allen, J. Johnson, M. Ruiz, J. Lees, and M. Welsh. Monitoring volcanic eruptions with a wireless sensor network. In *Wireless Sensor Networks, 2005. Proceeedings of the Second European Workshop on*, pages 108–120, 2005.

[57] Ning Xu, Sumit Rangwala, Krishna Kant Chintalapudi, Deepak Ganesan, Alan Broad, Ramesh Govindan, and Deborah Estrin. A wireless sensor network for structural monitoring. In *Proceedings of the 2nd international conference on Embedded networked sensor systems*, SenSys '04, pages 13–24, New York, NY, USA, 2004. ACM.

[58] Thomas Zimmerman, Britta Muiznieks, Eric Kaplan, Samuel Wantman, Lou Browning, and Eric Frey. Design and field testing of a system for remote monitoring of sea turtle nests. In *Proceedings of the 16th International Conference on Human-computer Interaction with Mobile Devices & Services*, MobileHCI '14, pages 637–642, New York, NY, USA, 2014. ACM.

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