Link Stability in a Wireless Sensor Network – An Experimental Study

Stefan Lohs, Reinhardt Karnapke, and Jörg Nolte

Distributed Systems/ Operating Systems group,
Brandenburg University of Technology,
Cottbus, Germany
{Slohs,Karnapke,Jon}@informatik.tu-cottbus.de

Abstract. Most routing protocols proposed for wireless sensor networks are based on the standard approach also used in many other types of networks, e.g. MANETS, even though the conditions are drastically different. To evaluate the usefulness of reactive routing protocols based on route discovery by flooding of route request messages it is necessary to understand the nature of the underlying wireless communication links.

In this work we present the results of connectivity measurements conducted with current sensor node hardware, taking special interest in the number of unidirectional links present and the frequency of link changes.

Keywords: wireless sensor networks, link stability, unidirectional links.

1 Introduction

The most common way to search for a route in a wireless network is to flood a route request message from the source to the destination, which then answers with a route reply message. In some protocols, this route reply is transmitted using the inverted path taken by the fastest route request (e.g. AODV [7]), in others, it is also flooded and may take a different route entirely (e.g. DSR [5] when using unidirectional links). Sometimes a second route reply from the originator of the route request is necessary. In some other protocols other names may be used, but the basic mechanism is the same.

All of these protocols are based on one assumption: If a route can be discovered by these flooding mechanisms at some time, the route can be used at least for a certain time. If routes break due to link changes, different handling methods are used. But these route maintenance mechanisms are often expensive, and should be performed as seldom as possible. Therefore, a certain link stability is the basic requirement for these protocols to perform according to their specification.

Another frequently made assumption is that unidirectional links are uncommon and that it is better to ignore them when making routing decisions [6].

In this paper we present connectivity measurements conducted with real sensor network hardware and show that unidirectional links are not only common, but their number exceeds that of bidirectional links by far. Also, we show that

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the number and frequency of link changes is even higher than expected, making changes to the way routing information is handled in traditional routing protocols necessary.

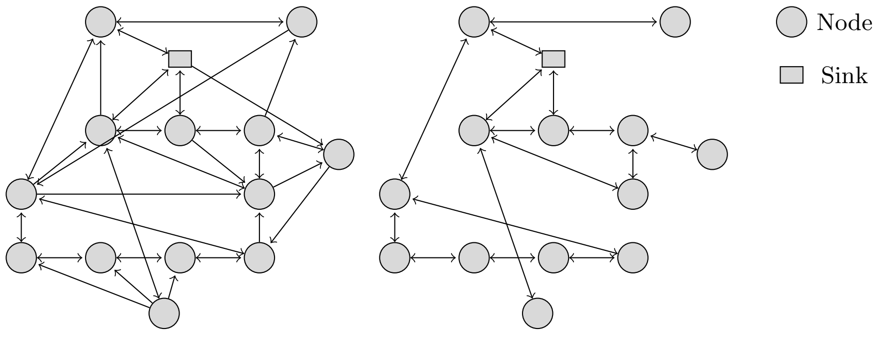
This paper is structured as follows: Related work, which gave us the idea that it would be worthwhile to investigate connectivity between nodes, is shown in section 2. Section 3 describes the sensor nodes from Texas Instruments we used for our experiments. The gathered connectivity information is shown in section 4. We finish with a conclusion in section 5.

2 Related Work

2.1 The Heathland Experiment: Results and Experiences

The authors of [10] describe an experiment they conducted in the Lüneburger Heide in Germany. The original goal was to evaluate a routing protocol, which is not characterized further in the paper. Rather, the observations they made concerning the properties of the wireless medium are described, focusing on the frequency of changes and the poor stability of links. These experiments were conducted using up to 24 Scatterweb ESB [9] sensor nodes, which were affixed mostly to trees or poles, and left alone for two weeks after program start. One of the duties of the network was the documentation of the logical topology (radio neighborhood of nodes), which was evaluated by building a new routing tree every hour, e.g. for use in a sense-and-send application. The neighborhood was evaluated using the Wireless Neighborhood Exploration protocol (WNX) [10], which can detect unidirectional and bidirectional links. All unidirectional links were discarded and only the bidirectional ones used to build the routing tree.

Figure 1(a) shows one complete communication graph obtained by WNX, while figure 1(b) shows the same graph without unidirectional links. Here, a lot of redundant paths have been lost by the elimination. In fact, one quarter of the nodes are connected to the rest of the network by merely one link when



(a) All Links (b) Only Bidirectional Links

Fig. 1. A Communication Graph (a) with and (b) without Unidirectional Links (taken from [10] presentation: [11])

unidirectional links are removed. If this single link breaks, the nodes become separated, even though there are still routes to and from them. Thus, the removal of unidirectional links increases the probability of network separation.

2.2 On Exploiting Asymmetric Wireless Links via One-Way Estimation

The authors of [8] propagate a similar opinion. They evaluate three kinds of links (asymmetric, unidirectional, bidirectional) using protocols like ETX (Expected Transmission Count) [2]. These protocols search for reliable connections, but most of them only focus on bidirectional links. This leads to the fact that a link with a reliability of 50% in both direction is chosen above one with 100% from node A to node B and 0% from B to A. If data needs to be transmitted only from A to B without need for acknowledgment, this choice is obviously wrong. To prevent this wrong choice, the authors of [8] propose a protocol called ETF (Expected Number of Transmissions over Forward Links), which is able to use unidirectional links. They also show that the reach of reliable unidirectional links is greater than that of reliable bidirectional links.

In experiments with XSM motes [8] 7 × 7 nodes were placed in a square, with a distance of about 1 meter between nodes. In four sets of experiments at different times of day each node sent 100 messages at three different power levels. Then the packet reception rate was recorded. It is defined for a node A as the number of packets A received from a node B divided by the number of messages sent (100). Afterwards, the packet reception rates of nodes A and B are compared. If the difference is less than 10%, the link is considered bidirectional. If it is more than 90% the link is considered unidirectional. The XSM nodes offer nine different transmission strengths, of which three were evaluated: the lowest, the highest and the third in between. Table 1 shows the results of the experiments.

The results show that even when using the maximum transmission strength, 12% of the links would have been discarded by ETX and similar link quality evaluation protocols that focus only on bidirectional links.

The observations of [8] are concluded in three points:

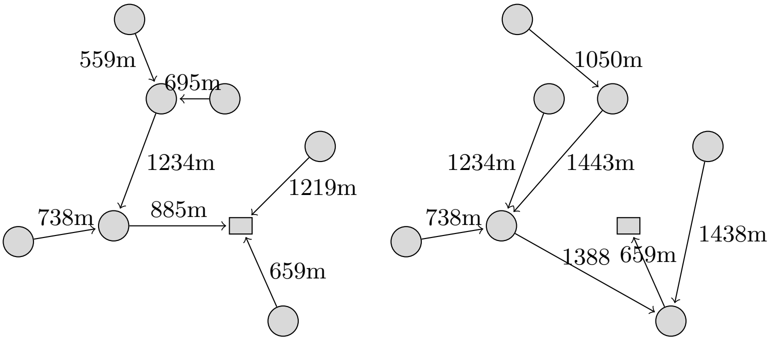
1. Wireless links are often asymmetric, especially if transmission power is low
2. Dense networks produce more asymmetric links than sparse ones
3. Symmetric links only bridge short distances, while asymmetric and especially unidirectional ones have a much longer reach. A conclusion drawn from this is that the usage of unidirectional links in a routing protocol can increase the efficiency of a routing protocol considering energy and/or latency.

Table 1. Link Quality versus Transmission Strength (taken from [8])

link quality	bidirectional	asymmetric	unidirectional	number of links
power level 1	50%	43%	7%	500
power level 3	65%	22%	13%	1038
power level 9	88%	6%	6%	1135

2.3 Design and Deployment of a Remote Robust Sensor Network: Experiences from an Outdoor Water Quality Monitoring Network

A sensor network which monitors water pumps within wells is described in [3]. The sensors were used to monitor the water level, the amount of water taken and the saltiness of the water in a number of wells which were widely distributed. The necessity for this sensor network arose because the pumps were close to shore and a rise in saltiness was endangering the quality of the water. The average distance between wells was 850 meters and the range of transmission was about 1500 meters. Communication was realized using 802.11 WLAN hardware both for the nodes as well as for the gateway. For data transmission between nodes *Surge_Reliable* [13] was used, which makes routing decisions based on the link quality between nodes.



(a) A Normal Connectivity Graph (b) A Strange Connectivity Graph

Fig. 2. Two Communication Graphs (taken from [3])

During the experiments, it could be seen; that the (logical) topology of the network changed dynamically, even though all nodes were stationary. The authors claim that these changes were probably due to antenna size and changes in temperature and air moisture. In this context it is important to remember that the distance of nodes was far below the range of the transmitters (about 50%). While about 70% of the routing trees observed followed the theory (figure 2(a)), there were a lot of strange topologies. In one case the average distance between connected nodes even rose to 1135 meters, as nodes that should have been able to communicate directly with the gateway were connected to nodes on the far side instead. In one of these routing trees (figure 2(b)), a single node had to take care of all communication with the gateway, even nodes that were on the other side were using it as next hop.

2.4 Taming the Underlying Challenges of Reliable Multihop Routing in Sensor Networks

The main focus of [13] is link quality estimation. The authors measured link quality for a sensor network deployment consisting of 50 MICA motes from Berkeley.

Figure 3 shows the results they obtained. All nodes within a distance of about 10 feet (about 3 meters) or less from the sender received more than 90% of the transmitted packets. The region within 10 feet of the sending node is therefore called the effective region. It is followed by the transitional region. Nodes in this region can not be uniformly characterized as some of them have a high reception rate while others received no packets at all. In the transitional region, asymmetric links are common. The last region is the clear region and contains only nodes that did not receive any transmissions.

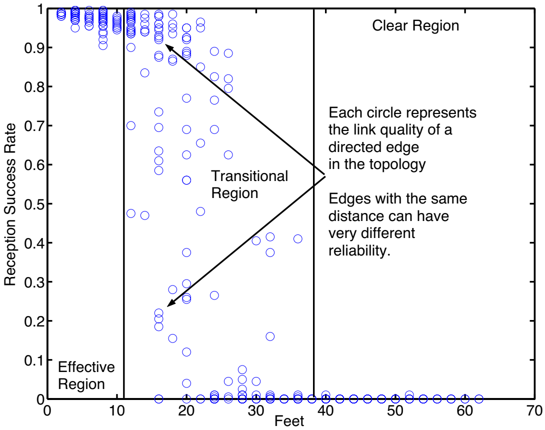


Fig. 3. Effective, Transitional and Clear Region (taken from [13])

2.5 Understanding Packet Delivery Performance in Dense Wireless Sensor Networks

The authors of [14] measured the properties of wireless sensor networks on the physical and medium access control layers. These measurements were conducted using up to 60 MICA motes, which were placed in three different environments: An office building, a parking lot and a habitat. The experiments for the physical layer were realized with a single sender and multiple receiver nodes and have shown the existence of a *grey area* in reception which can consist of up to one third of the network. In this grey area, the reception quality of nodes varies a lot, both spatial as well as in time. This observation is similar to the *transitional region* described in [13](see section 2.4). Another result described by the authors is that in the parking lot and indoor environments nearly 10% of links are asymmetric. Please note that what the authors call asymmetric links is otherwise referred to as unidirectional links in this paper: *"Asymmetry occurs when a node can transmit to another node but not vice versa"* [14].

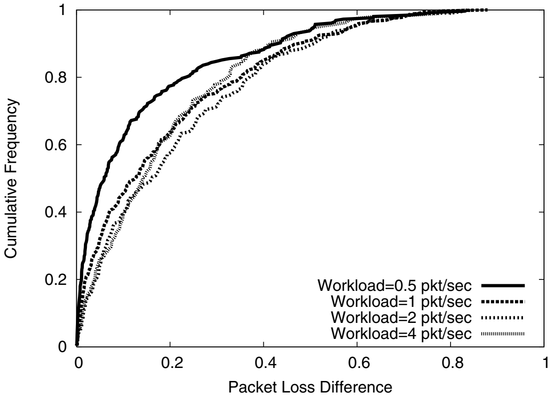


Fig. 4. Packet Loss Difference for Pairs of Nodes (taken from [14])

Figure 4 shows the results obtained by the authors of [14]. They have defined the packet loss difference for two nodes as the difference between the packet delivery efficiency of both nodes. The figure shows that asymmetric (unidirectional) links are quite common: More than 10% of the surveyed links have a difference of more than 50%.

The final claim the authors make is about asymmetric (i.e. unidirectional) links: *"The fraction of asymmetric links is high enough that topology control mechanisms should, we argue, carefully target such links"*.

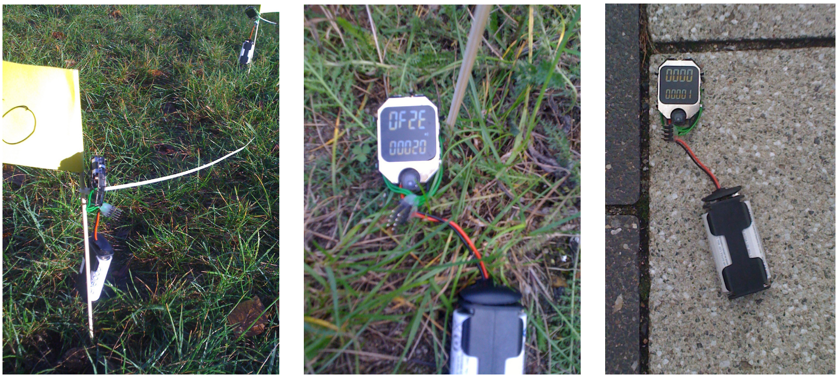
3 Hardware and Application

The eZ430-Chronos from Texas Instruments [4] is an inexpensive evaluation platform for the CC430. It features an MSP430 microcontroller with integrated CC1100 sub-gigahertz (868MHz) communication module [1]. The evaluation board is delivered as a compact sports watch containing several sensors, e.g. a three-axis accelerometer and 5 buttons which are connected through general purpose I/O pins. The sports watch casing has been removed in order to use the eZ430s as sensor nodes.

Figure 5 shows the used eZ430-Chronos sensor nodes in three different placements (see below). An external battery pack has been soldered to the nodes, which replaces the internal coin cells. This enables the usage of freshly charged batteries for each experiment.

To get a feeling for the behavior of the real hardware and to keep the possibilities of application errors to a minimum, the first experiments were made using a fairly simple application. 36 sensor nodes were deployed on the lawn outside of the university's main building, spaced one meter from each other.

As only the connectivity should be measured, the "application" consisted only of a flooding with duplicate suppression. Node 0 was connected to a laptop via USB and transmitted 50 messages containing a sequence number (increased every round) and the ID of the last hop, with a one minute pause between messages.



(a) affixed to poles (b) placed on the lawn (c) on a stone pavement

Fig. 5. A modified eZ430-Chronos Sensor Node

Each node that received a flooded message first logged the neighbor from which it received the message. After that the node checked if it had already handled a message with this sequence number. If it had, the message was discarded, otherwise the node changed the field *last hop* to contain its own ID and rebroadcast the message. This change of the last hop in the message enables the detection of all incoming links by each node. The decision whether a link was unidirectional or bidirectional was made offline, once all connectivity data had been gathered and combined. If node A had an incoming link from node B for sequence number X and node B had an incoming link from node A for that same sequence number X, the link is considered bidirectional at time X.

Even this simple application ran into two problems: The CC430 uses a so-called CCA Medium Access Control, which is basically a CSMA/CA scheme. A node that wants to transmit a message waits for a random time (backoff) before sensing the medium. If it is free, the message is transmitted. Otherwise, the radio waits for a random time before trying again. The used hardware was not able to receive messages during the backoff, which meant that even in an experiment with 3 nodes (0, 1, 2) node 2 was never able to receive messages from node 1, because it was still in its backoff when node 1 transmitted. To solve this problem for the connectivity evaluation, a software delay was introduced. The software waited between 1 and 13 milliseconds before passing the message to the hardware. This delay could be tolerated, because application knowledge was available (node 0 transmitted a new packet only every minute).

Retrieval of data was induced by sending a message to a node, telling this node that it should transmit its gathered neighborhood information. But the nodes were not able to receive any messages after a seemingly random time. Sometimes, nodes functioned only for a couple of minutes, sometimes nodes ran for more than a day and still responded. The influence of stray messages on the application can be ruled out due to precautions in the software. The problem seems to exist in the state machine of the radio. To remove this problem, a watchdog timer was introduced which resets the radio every 5 minutes if the application did not receive any messages during that time. If it did receive a message, the watchdog was restarted. While this could lead to problems if the nodes radios failed during the experiment, it was mainly used to gather the results, once the sensor nodes were collected and returned to the office.

4 Results

Four different placements were evaluated: On a lawn, on a stone pavement, affixed to poles and taped to trees. The first three placements were also evaluated on two different radio channels.

4.1 Lawn Experiment, Channel 0, Sink (Node 0) Connected to Laptop

The first experiment was conducted on the lawn in front of our university.

Figure 6 shows the connectivity graph obtained for the first of the 50 messages that were flooded into the network. One of the nodes, node 30, had a defective contact and did not participate at all. Four other nodes, nodes 12, 27, 28 and 33 suffered a complete reset during transportation, leading to loss of the connectivity data they gathered. Still, this had no effect on the network load at runtime, and a lot of information could be gathered.

Node 0, which was connected to a laptop using an USB cable, was heard by lots of nodes, even those far away like node 11, node 29 or node 31. This shows that the transmission strength of the nodes, while it was set to 0 dBm for all nodes, still depends on the power supply of the nodes, i.e. the batteries. In deployments where a sink node connected to a fixed power supply such as a computer should be used, the longer reach of the sink node might well be a problem. This problem

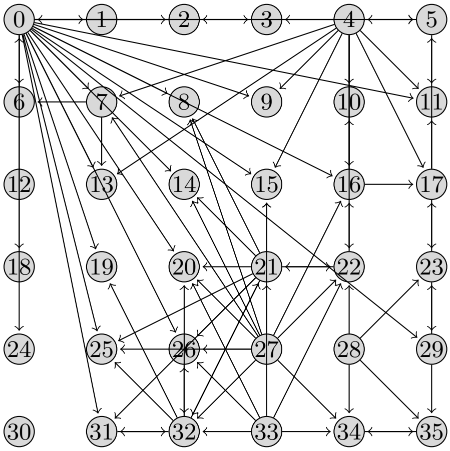


Fig. 6. First Connectivity Graph obtained on the lawn, channel 0

would for example manifest, when a tree routing approach is used, and the sink floods a message through the network to establish initial parent and child nodes, as most of the nodes would assume node 0 as their parent, but be unable to transmit directly to it.

Also, the results show that even though the nodes were only one meter apart from each other, bidirectional links are rare and unidirectional links are common. If all links are counted, 3018 unidirectional and only 403 bidirectional links have been recorded during the 50 minute deployment. If the unidirectional links from the nodes that have failed during transport are deducted (560 seemingly unidirectional ones), the ratio is still 2458 unidirectional links against 403 bidirectional ones. 7019 link changes occurred.

To remove the influence of the higher transmission strength of the "sink" (node 0), all links to and from node 0 can be removed from the equation. But even then, the result seems pretty obvious: 1477 unidirectional links stand opposed to 355 bidirectional ones (ratio 4.16 : 1).

4.2 Lawn Experiment, Channel 0, Sink (Node 0) Connected to Batteries

To remove the influence of the USB cable connected to node 0, the experiment was repeated. This time, and in all subsequent experiments, node 0 used a normal battery pack like all the other nodes. Even though precautions were taken, one node (node 25) still suffered a reset before the gathered data could be retrieved. The application was the same, with 50 flooded messages. 4039 unidirectional links as well as 818 bidirectional links were recorded this time, if the links from node 25 are removed that still leaves 3912 unidirectional ones opposing 818 bidirectional links (4.78 : 1 ratio) with 7019 link changes over the length of the whole experiment. The first connectivity graph is presented in figure 7.

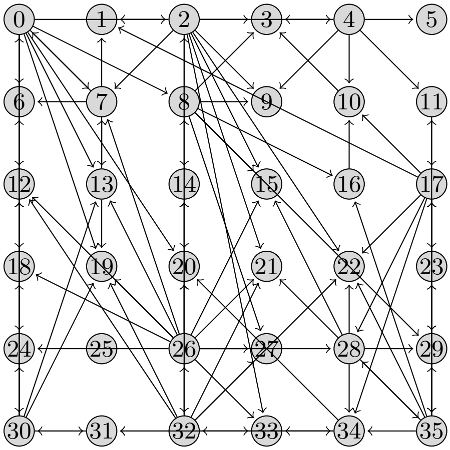


Fig. 7. First connectivity graph obtained on the lawn with node 0 connected to batteries, channel 0

4.3 Stone Pavement Experiment, Channel 0

To evaluate the influence of the ground on which the sensor nodes were placed, the experiments were repeated again, but this time the nodes were placed on the stone paved yard of the university. Figure 8 once again shows the first connectivity graph obtained.

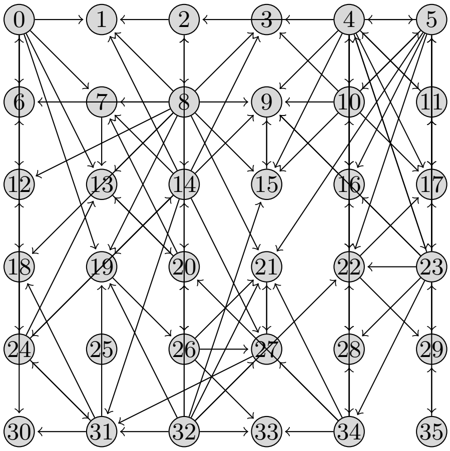


Fig. 8. First Connectivity Graph obtained on the stones on channel 0

Altogether 3570 unidirectional links and 851 bidirectional ones were measured, resulting in a ratio of 4.19 : 1, which is nearly the same as the ratio obtained in the first row of experiments and only a little bit different from the results of the second row of experiments. The average ratio seems to be between 4 and 5 to 1, even though individual values vary between 2.40 to 1 and 11 to 1. 6589 link changes occurred.

4.4 Pole Experiment, Channel 0

The previous three rows of experiments were all conducted with sensor nodes that lay on the ground, which is a safe assumption for many deployments. However, if the nature of radio communication is taken into account, the nodes should be placed with a certain distance from the ground; to increase the communication range and reception. Therefore, the 36 sensor nodes were connected to wooden poles and placed about 20 cm above the university lawn in these experiments.

Figure 9 visualizes the first obtained connectivity graph.

Altogether 5150 unidirectional links and 492 bidirectional ones (ratio 10.47 : 1) with a total of 7146 changes were measured. Interestingly, the better radio characteristics increased the number of unidirectional links far more than the number of bidirectional ones. The ratio of unidirectional ones to bidirectional ones increased up to 18 : 1.

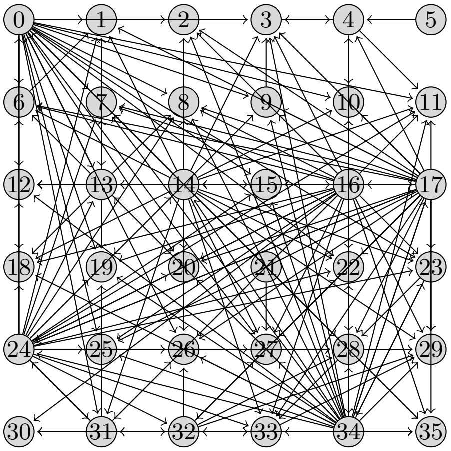


Fig. 9. First connectivity graph obtained on the poles on channel 0

4.5 Tree Experiment, Channel 0

To evaluate the connectivity at an even higher altitude, the sensor nodes were next fitted to a 5 × 5 tree arrangement on the campus of our university. Please note that the absolute values for links naturally decreases, as only 25 nodes are used in this scenario, instead of 36. Figure 10 shows the initially measured connectivity.

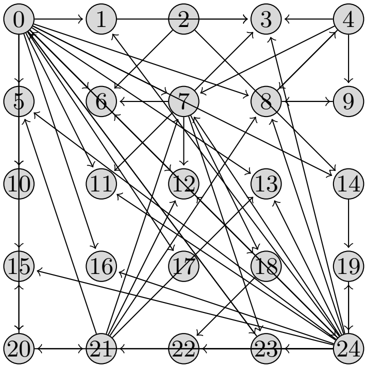


Fig. 10. First Connectivity Graph obtained on the trees on channel 0

A total of 2977 unidirectional links and 330 bidirectional ones were measured (ratio 9.02 : 1) with 3329 link changes occurring during the 50 minutes runtime of the experiment.

4.6 Lawn Experiment, Channel 3

To evaluate the influence of the chosen channel on the connectivity, the experiments on the poles, the lawn and the stone pavement were repeated on channel 3.

The initial connectivity graph is shown in figure 11.

As much as 4411 unidirectional links and 757 bidirectional ones (ratio 5.83 : 1) with 7103 link changes were measured.

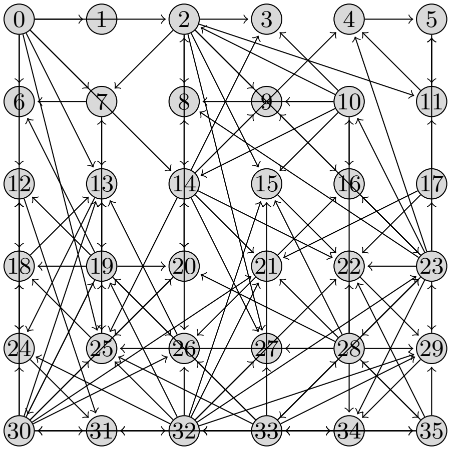


Fig. 11. Initial Connectivity on the Lawn, September 23rd, 2011

4.7 Stone Experiment, Channel 3

The initial connectivity graph obtained on the stone pavement is shown in figure 12. A total of 3508 unidirectional links and 712 bidirectional ones were detected (ratio 4.93 : 1), with 5528 link changes occurring.

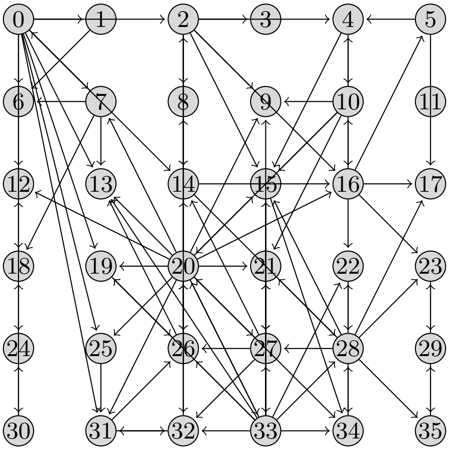


Fig. 12. Initial connectivity graph on the stone pavement

4.8 Pole Experiments, Channel 3

The first connectivity graph obtained is visualized in figure 13.

Altogether 4761 unidirectional links and 225 bidirectional ones (ratio 21.61 : 1) with 5541 changes were measured.

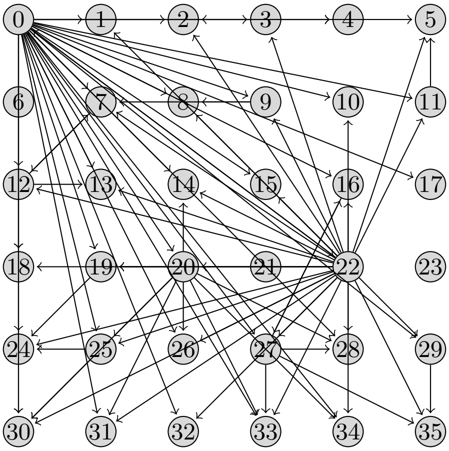


Fig. 13. First connectivity graph, obtained using poles

4.9 Summary

The connectivity measurements have shown that unidirectional links occur even more often than literature suggests and that the height of the placement does influence the communication range. More specific, the number of unidirectional links increases stronger than the number of bidirectional ones.

Figure 14 shows the results of the lawn experiments on channels 0 and 3 in detail. Each round represents one flooded message, with one minute passing

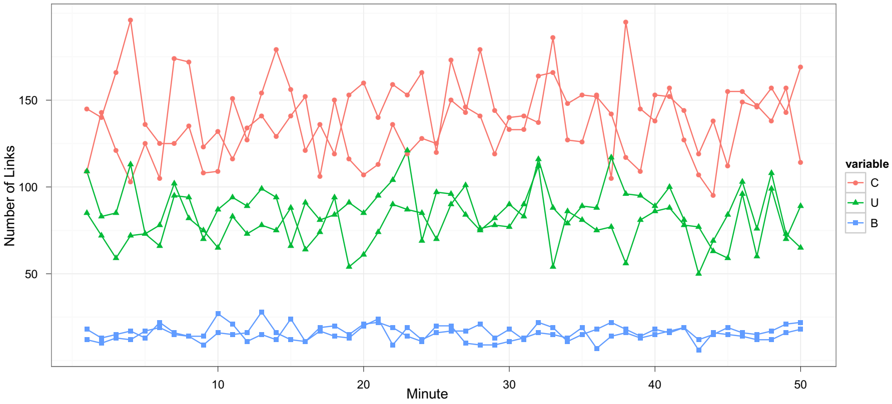


Fig. 14. Measured Links on the lawn for Channels 0 and 3: (C)hanges, (U)nidirectional ones, (B)idirectional ones

between rounds. The figure shows the number of unidirectional (U) and bidirectional (B) links as well as the number of changes between the previous round an the current one (C). Each change of a single link is counted separately, meaning that a unidirectional link that appears or disappears counts as one, a bidirectional one that turns unidirectional is also counted as one but a bidirectional link that appears or disappears counts as two changes, one for each directed link contained therein. It can be seen that the number of link changes is often higher than the number of unidirectional links. This is due to the fact that when one unidirectional links disappears and another appears, two changes occurred.

Figure 15 shows a box plot of the number of changes per round for each environment and channel. It can be seen that apart from the tree environment which only featured 25 nodes instead of 36, the number of changes seems to be fairly independent of the environment.

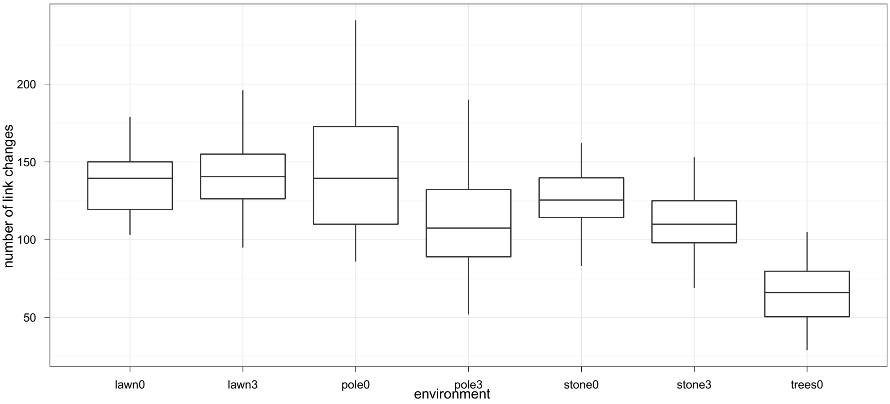


Fig. 15. Link Changes per Round

The ratio of unidirectional links compared to bidirectional ones changes a lot, but there are always far more unidirectional than bidirectional links present. The ratio varies between 3 : 1 and 91 :1, with an average value of 8.69 : 1 over all presented experiments. This high number of unidirectional links makes it necessary to rethink the strategy of ignoring unidirectional links in routing protocols.

When considering the networks consisting of 36 nodes, an average number of 108 link changes per round can be recorded. This high number of link changes in a very short time makes it highly improbable that paths that have been measured at one point in time will exist long enough to transmit a high number of application messages over this exact path. Other forwarding mechanisms are required, which can react to such changes implicitly, without creating route error messages and repetition of route request flooding.

5 Conclusion

In this paper we have presented the results of connectivity measurements we conducted using real sensor network hardware. The experiments were conducted in four different locations and on two different channels. The results show, that unidirectional links are far more common than previously assumed, and link stability does basically not exist. This makes usage of traditional routing protocols in wireless sensor networks hard, to say the least. New protocols need to be devised, that can deal with the influence of an ever changing environment.

Complete connectivity graphs in visual form as well as simulation matrices for OMNeT++ [12] were also generated for all experiments, but are not included here. Complete sets of connectivity data, presented as graphs or connectivity change lists that can be used for simulations, e.g. using OMNeT++, are available upon request.

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