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Evaluation of Environmental Wireless Sensor Network - Case Foxhouse

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***Abstract*—Environmental monitoring in agriculture is an interesting and promising area of application for wireless sensor networks. Wireless sensor networks can deliver valuable information about environment, animals and their habitat. This paper describes a case where such sensing application was implemented by the authors together with biologists. The wireless sensor network collected data in hard outdoors conditions over a period of one year, during which luminosity, temperature and humidity were measured in a foxhouse. Evaluation of IEEE802.15.4 based communication used was one of the main subjects of the study. The throughput and the link quality statistics are presented and some factors related to link quality are analysed. In addition to reliability analysis, this paper describes the Foxhouse Case implementation, reports on its results, presents the power-consumption measurements and discusses the observations made during project.**

***Index Terms*—wsn implementation; environmental monitoring; reliability; link quality; power-consumption**

I. INTRODUCTION

Environmental monitoring, both indoors and outdoors, is one of the most promising application areas for wireless sensor networks. Compared to traditional sensing methods wireless sensor network (WSN) technology offers some important benefits: wide areas can be covered with inexpensive nodes, battery-powered devices with a self-configuration ability enable quick and easy system installation, the energy-efficiency of battery-powered devices makes long-term monitoring possible, and typically there is also a real time access to data. In addition, when monitoring animals, for example, human presence is unwanted and can distort the results or even cause damage to the subjects of monitoring. By using WSNs, measurements can be done without any other disturbance except that caused by the deployment of the network. Thus the results would also be free from any external impact.

In spite of the improvements in WSN technology there are not too many cases reported where WSN has been used in environmental monitoring. One such experiment was the Foxhouse case implemented by The Kokkola University Consortium Chydenius (later Chydenius) [1]. The other environmental wireless sensor networks have been built also, and valuable information about hardware and software has been obtained, see, e.g., [2], [3], [4], [5], [6], [7], and [8].

The Foxhouse project was undertaken jointly with the MTT Agrifood Research Finland. The wireless sensor network for environmental monitoring was implemented in the Fur Farming Research Station at Kannus. The reason for the WSN implementation was the need to get real time information about the habitat of foxes in a foxhouse. The amount of light received is presumed to be the key factor in stimulating reproduction of foxes, so measuring light intensity in different parts of the foxhouse was the focal point of interest. Measurement data for luminosity as well as temperature and humidity were gathered outdoors over a period of one year. We also observed the functionality and usability of the network, and some tools for network maintenance were developed during the project.

In addition to habitat monitoring we also wanted long-term information about WSNs in environmental monitoring as well as about the performance of wireless communication due to the IEEE802.15.4 standard. The amount of collected data was large in the Foxhouse project. A total of 1 707 758 received packets were stored in the database over a period of one year. This large database enabled us to evaluate the wireless sensor network's IEEE802.15.4 based communication. The performance of wireless communication is studied by analysing the throughput and the quality of links. The link quality is evaluated by using received signal strength indicator (RSSI) which indicates the strength of the radio signal at the receiver's position. Measurement data for temperature and humidity enabled analysis of the effects of weather conditions on link quality. Measurements to analyse the effect of angular orientation on link quality as well as to evaluate node's power consumption were performed also.

This paper is organized as follows. First we overview some related research where WSN has been used in agriculture and environmental monitoring. The Foxhouse case as a sensing application is described and the CiNet sensor network and node architectures are introduced. Resulting statistics about network reliability, like the throughput and the quality of links, as well as the application data are given. Some factors related to link quality are analysed and the power consumption measurements of a battery-powered sensing node are presented. Finally, the project experiences are discussed briefly.

II. RELATED WORK

WSN implementations have been used and reported in monitoring tasks during the past few years. In agriculture there have been applications where WSNs have delivered valuable information about environment, e.g., about soil moisture and microclimate [2], [3], and [6]. Also animals and their habitat have been monitored. A famous implementation of this kind was created by the project in Great Duck Island, where some researchers from the University of California, Berkeley, together with biologists from the College of the Atlantic, built a sensor network and collected data from a seabird habitat [7]. In that project the researchers discussed also the need and possibilities for network status monitoring and retasking.

In the implemented sensor network projects, performance of wireless sensor network has been one of the main concerns. The impact of environmental conditions on the link performance has been studied. For example, distance, height and angular orientation of devices have been reported to affect the received signal strength sensitivity [9]. Also the effect of foliage and weather conditions on the propagation of radio waves has been studied in [5], [10] and [11]. Reliability of sensor networks includes more than just error-free wireless communication. For example, validity of data is important, and, when problems occur, fault detection is needed. A fault detection system was tested in the project where groundwater quality was measured [12] and [13].

Typically, monitoring testbeds have included some tens of nodes. In some cases a network may include a few hundreds of nodes. Trio Testbed was a large network with 557 solar-powered nodes [14]. That network was functioning for quite a long time. The researchers of Trio Testbed discussed maintenance issues as well as middleware and system software challenges in outdoor sensing systems.

When monitoring environment, animals or their habitat, pure technical knowledge about sensor network technology is usually not sufficient; the implementations require also knowledge about the ecosystem.

III. FOXHOUSE CASE

Furbearing animals have been raised on farms from the 19th century. In the present housing system for foxes, rows of cages are placed in sheds. They provide a normal outside temperature while protecting against direct sunlight, wind and rain. In addition to the traditional sheds, also special halls have been tested as shelters. The goal of the scientific research has been to improve the health and welfare of animals as well as their productivity. From the economical point of view, successful breeding of animals is important. The amount of light received is presumed to be the key factor in stimulating reproduction. This has been studied in the Fur Farming Research Station at Kannus where, among other things, light intensity has been measured in different conditions in sheds and in a hall (foxhouse), and the results of fox breeding have then been compared [15].

Luminosity varies during the day and year. So the measurement should be more or less constant at least in the breeding season. Luminosity can also vary a lot in different parts of the foxhouse and many sensors are needed to cover the whole area. The measuring problem thus matched perfectly the potential for solution behind the idea of WSNs. By using the wireless sensor network the researchers could get real time data from the habitat all year round. Another reason for this experiment was to get practical experience about the reliability of communications in a CiNet network. The project was carried out cooperatively between Chydenius and MTT Agrifood Research Finland.

The Foxhouse project, funded by the Finnish Funding Agency for Technology and Innovations, started on April 11th 2006, and the wireless sensor network gathered data for over one year. A foxhouse is a large wooden building (approximately 15x75 meters in area) where fox cages are placed in four rows about 80 centimeters above the ground. The building has an asphalt floor and a part of the roof and the walls are made of transparent fiberglass. Luminosity in all areas of the foxhouse was the focal point of interest, but some of the nodes were equipped also with temperature and humidity sensors. There was no heating in the building.

The system architecture in the Foxhouse case is shown in Figure 1. The sensor nodes in the foxhouse send measurements to a sink, which is connected to a PC by a serial cable. All received information is stored into a SQL database in the PC. Data in the database can be browsed by a web application.

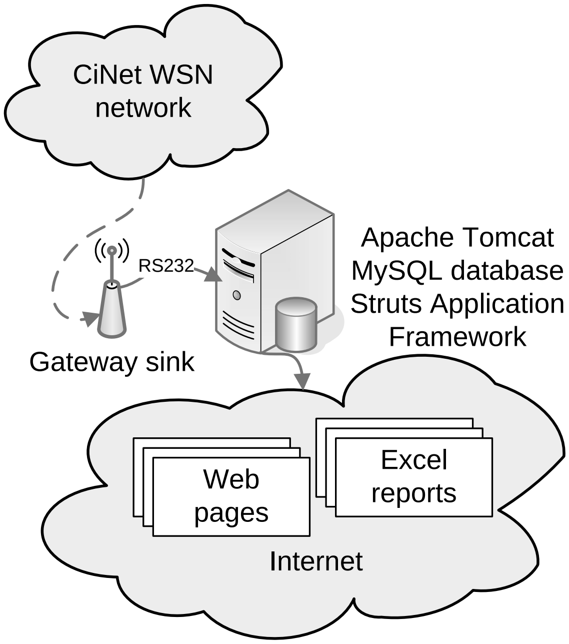


Figure 1. System architecture

Normally environmental monitoring networks require nodes with a battery supply. In this special case we could however use the main supply, because electricity was already available. This way we could also eliminate any effects of batteries' voltage variation on link quality. A battery powered node was included in the network for testing the real power consumption of the measuring nodes.

The nodes were attached about 1 meter above the metal cages as shown in Figure 2. Each wireless node was lightly encapsulated in a small plastic box while the sensors were left outside the box. The photodiode was shielded additionally with an aluminium tube.

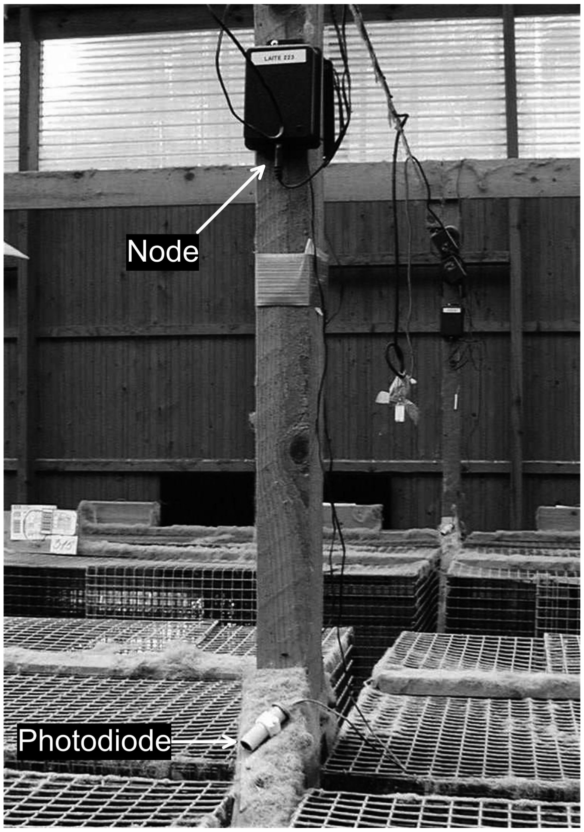
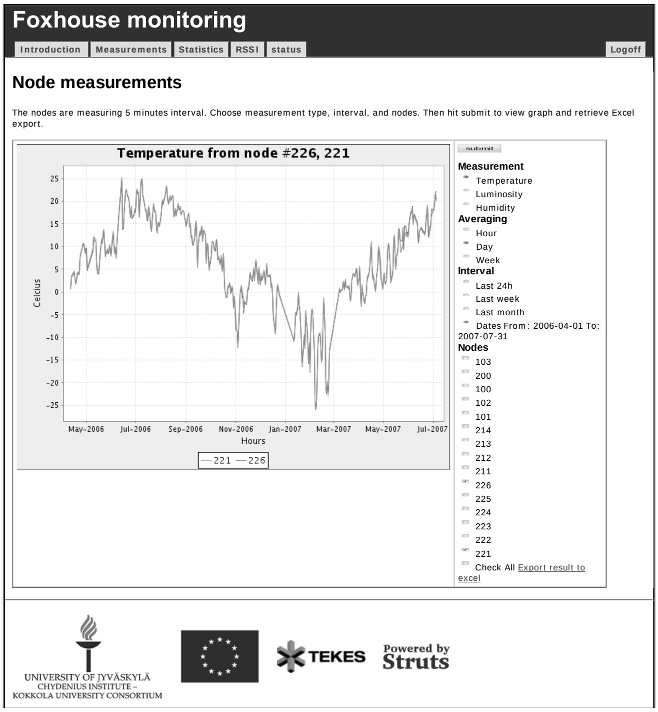


Figure 2. Node and photodiode placement

A. System Architecture

The system architecture is depicted in Figure 1. The wireless sensor network produces measurements data, which is delivered to the gateway (sink node). The sink node is connected to the server via a RS232 cable. The PC acts as a server in this system, running a Java program for reading packets from serial port. The Java program has the following functions: it reads data from the serial port, parses measurement data and adds timestamps, and finally stores the prepared data to a MySQL database. The Java program has no control functions, it only stores incoming packets. The system's database contains all information about the actual measurements (temperature, humidity, and luminosity) and also management data (RSSI, packet counts) for diagnostic purposes. The database includes basic information about nodes, nodes' location etc. A raw packet payload is also stored in the database.

The application is built as a 3-tier web application and it relies on freeware and open-source software. It consists of a Tomcat Java application server, Struts framework, and MySQL database server. The Tomcat Application server and Struts framework together act as a web server and the MySQL database server provides data storage.



Node measurements

The nodes are measuring 5 minutes interval. Choose measurement type, interval, and nodes. Then hit submit to view graph and retrieve Excel export.

Measurement
- ● Temperature
- ○ Luminosity
- ○ Humidity

Averaging
- ○ Hour
- ● Day
- ○ Week

Interval
- ○ Last 24h
- ○ Last week
- ○ Last month
- ● Dates From: 2006-04-01 To: 2007-07-31

Nodes
- ☐ 103
- ☐ 200
- ☐ 100
- ☐ 102
- ☐ 101
- ☐ 214
- ☐ 213
- ☐ 212
- ☐ 211
- ☑ 226
- ☐ 225
- ☐ 224
- ☐ 223
- ☐ 222
- ☑ 221
- ☐ Check All Export result to excel

Figure 3. User interface in the Foxhouse monitoring system.

The user interface of the web application enables browsing and reporting of stored measurements. Data can be viewed as a graph on a web page or Excel report. An example of the user interface can be seen in Figure 3, in which the temperature from the 1st May 2006 until the 30th July 2007 is displayed. The measurement period can be defined by start and end dates. The period is also possible to choose from pre-entered values for day, week, or month. Also averaging is done by day, week, or month. In addition to physical quantities also statistical information about measurements as well as communication statistics can be monitored on the web site.

B. Network

The network was build to collect as reliable information as possible from the habitat of animals. It was likely that luminosity values would vary inside the foxhouse and nodes were situated in places that were interesting from the researchers' point of view. Cluster topology appeared to be the most suitable topology for this purpose. The network included two kind of devices: sensing nodes (RFD) and routing nodes (FFD). Some of the routing nodes worked as cluster heads also. The wireless sensor network in the Foxhouse case consisted of 14 nodes in two clusters: the front cluster and the rear cluster. Node 102 was the cluster head of the rear cluster (nodes 211-213) and node 101 was the cluster head of the front cluster (nodes 221-225). The placement can be seen in Figure 4. Nodes were programmed beforehand with fixed routing table as well as ID numbers, since the platform does not support hardware MAC address.

In figure 4 the nodes with RFD labels are sensing nodes that are extremely energy-efficient. They used the same mea-

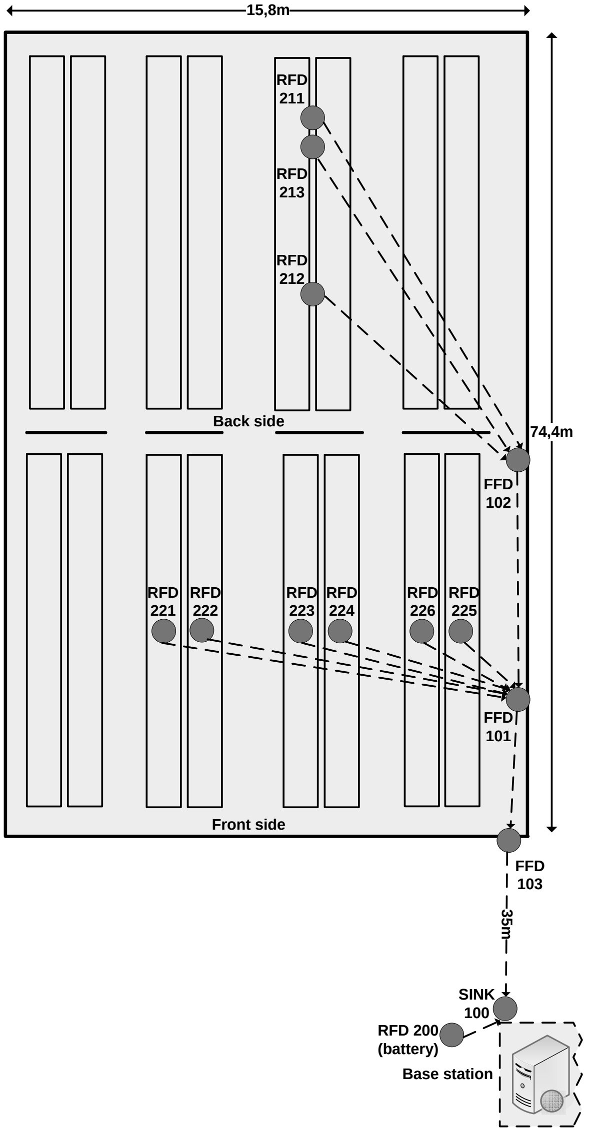


Figure 4. Node locations in the Foxhouse

surement interval and woke up in every 5 minutes to send measured values to cluster heads which forwarded packets through routing nodes to the sink. Rest of the time they were in deep sleep. Measuring in every 5 minutes produced more data than needed, but, because packet losses are likely in WSNs, a quite high measuring frequency was wanted. The current consumption of a sensing node during the measuring and transmitting period is explained in Subsection 4F.

The nodes with FFD labels are routing nodes, which take care of multi-hop communication and collect also statistical information about packet losses and link qualities. The network was not synchronized, and that is why routing nodes had to be active and listen to incoming packets all the time. Their energy consumption was higher than that of sensing nodes. Multi-hop communication was based on fixed routing tables, which means that each sensing node is sending packets to a sink via the same route, which minimizes control traffic. The solution was justified in this special case, because the network was both small and static and a predefinition of topology was possible.

The communication protocol used, IEEE 802.15.4, allows frames of 128 bytes, including the protocol overhead which is needed in every packet. Because all the messages have their starting cost, we aggregated management data cumulatively in each node, i.e., when a sensing node sends a message to a sink, each node in the communication path appends its own management data to the message. This method reduces the number of delivered packets. Thus, the light data aggregation used is cost-effective.

For studying the reliability of wireless communication two different communication methods were used. In the first phase (implementation and testing) from April 2006 to October 2006 all the communication links were unidirectional, so no acknowledgements were used. In the second phase (evaluation) from October 2006 to June 2007, acknowledgements and management data were required to ensure communication over link. In case of missing packets, there could be a maximum of three retransmissions.

C. Sensor Node

The nodes used in the Foxhouse network were CiNet nodes. CiNet is a research and development platform for wireless sensor network implemented by Chydenius. The hardware in the CiNet node is specially designed for WSNs and consists of inexpensive standard off-the-shelf components. The CiNet node includes all the basic components for wireless sensor networks. It has a microcontroller and a transceiver on board as well as one temperature sensor for testing purposes. In real monitoring more sensors are needed. These sensors can be placed on a special sensor board, which can be connected to the main board. The device is shown in Figure 5 and its architecture in Figure 6.

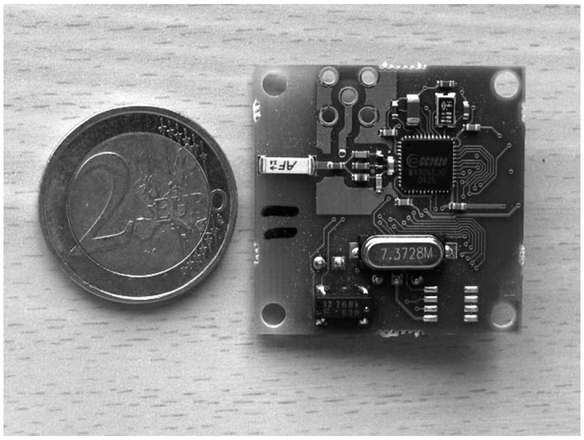


Figure 5. The CiNet main board

The processor in the CiNet main board is an inexpensive 8-bit controller ATmega128L. It is highly integrated, and as a low-power CMOS controller it is suitable for battery-powered

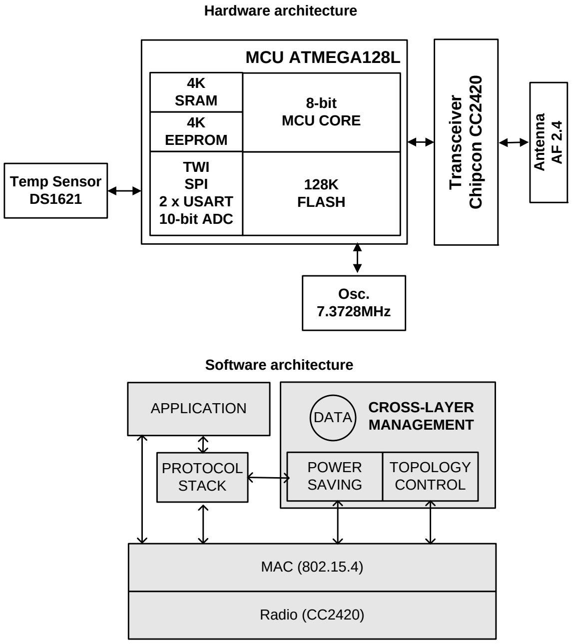


Figure 6. The CiNet software and hardware architectures

devices. It has good power saving features and enough internal memory. The AVR RISC architecture supports efficient C programming and is able to execute most instructions in a single clock cycle. The RF transceiver CC2420 is connected directly to the controller with an SPI connection.

In addition to the main board, a sensing node in the Foxhouse network included a sensor board. The sensor boards were equipped with photodiodes (Osram BPW21), and some of the nodes have also temperature/humidity sensors (Sensirion SHT7x). A measurement period could take a relatively long time, in the worst case 380ms. To save energy, the sensing nodes use a short duty cycle, i.e., they are in a sleep mode approximately 99.8% of time depending on the sensors connected.

The software in nodes was implemented according to the cross-layer architecture [16]. The cross-layer approach seemed to offer good performance in devices with reduced resources and it appeared to be a working solution. The software architecture used in a node is shown in Figure 6. The main idea in this model has been to implement the wireless sensor network's basic tasks, such as topology management and power saving functionalities, as separate protocols in a cross-layer management entity. These modules can control directly both the application and protocol stack. Data structures, which are in shared use, are also implemented in the cross-layer management entity. The biggest advantage of the cross-layer implementation is its reduced computational and memory requirements - not all the information need to be transmitted between the application interfaces and protocol layers.

Wireless communication between two neighbour nodes takes place according to the 802.15.4 protocol, and these layers are implemented in the RF transceiver. All other modules are implemented in the microcontroller. The application takes care of communication with sensors. If a node has several sensors connected, data from all used sensors is added to the same payload. The protocol stack routes packets according to the IP protocol by using routing table information. The modules in cross-layer management are in common use or control both the protocol stack and application. The power saving module controls the functionality of other modules. Topology control in the cross-layer management gathers some statistical information from the received packets. The measured statistics were link quality and number of received packets in each node. Link quality was estimated in practice by measuring the signal strength from each received packet. These statistics are presented in more detail in Chapter IV.

IV. RESULTS

The amount of collected data in the Foxhouse project was large. A total of 1 707 758 received packets were stored in the database. Based on this material, the researchers were able to analyse the physical circumstances of the foxhouse, the reliability of the network, and the quality of links. The effects of weather conditions and angular orientation of devices on the link quality are analysed also as well as the power consumption of the battery-powered sensing node.

A. *Environmental Monitoring*

The WSN in the Foxhouse collected luminosity, temperature and humidity values for one year. Typically, luminosity measurements were done manually a few times each day. The WSN reduced the need for manual measurement and recording in the database and made constant real-time data available for the biologists of MTT Agrifood Research Finland. Moreover, the network increased the number of measurements manyfold and, therefore, the network gave more information about the physical circumstances in the foxhouse. The measurements were stored in a SQL database, and are thus easily available for further studies. In this respect the sensor network can be regarded as a working solution for environmental monitoring.

For the biologists the most important information was the luminosity inside the foxhouse. They were especially eager to know how light conditions varied in different parts of the foxhouse and also how luminosity values change during winter and spring. In Figure 7 there is an example of luminosity values in the foxhouse depicted graphically. From the figure it is easy to get an overall understanding of how luminosity begins to increase after winter and of the related differences between nodes. In the figure, luminosity is averaged by week, and a rising trend is clear. Differences between trends show that the amount of light varies in different parts of the foxhouse. By using other filters, more variations in daytime luminosity values can be observed. In Figure 8 luminosity values are averaged by day. Measurements are available also in the SQL database and in an Excel format. Similar statistics are also available about temperature and humidity conditions.

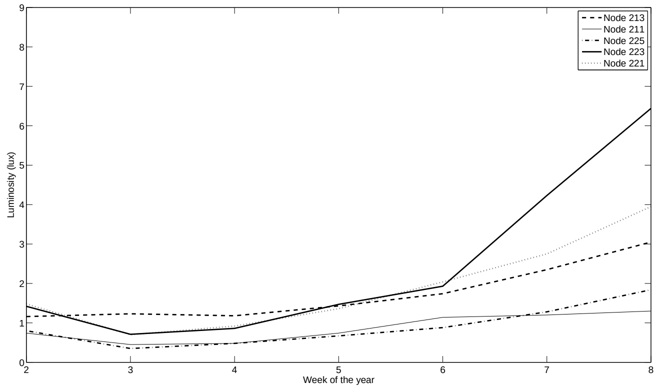


Figure 7. Averaged luminosity values during two months from the 11th of January in 2007.

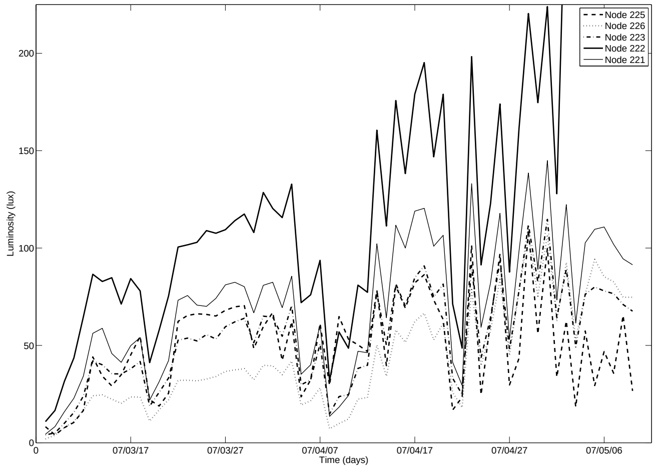


Figure 8. Development of averaged luminosity from March to June 2007.

B. *Reliability of Communication*

Reliability of IEEE 802.15.4 based wireless communication was one of the research subjects in this project. The plan was to relate it to the number of packet losses. Due to collisions and external disturbances, packet losses are possible.

Table I shows the received packets from the sensing nodes from the 12th of January until the 8th of February 2007. The throughput of the rear cluster was very good and that of the front cluster was almost 100%. The period was free from device failures and the throughput of the routing nodes 101, 102 and 103 was 100%. Thus the results in Table 1 show also the ratio of received packets to delivered packets at the cluster heads. Table II shows the longest continuous break and the number of consecutive missed packets for each sensing node during the break. The results of the front cluster were very good, at most only 8 consecutive packets were missed. Nodes 212 and 213, the sensing nodes of the rear cluster, had minor problems: node 212 missed 501 consecutive packets and node 213 missed 171 consecutive packets. This can be seen in the throughput statistics also. The short breaks of a single node had no effects on the environmental monitoring application. It can be concluded that wireless links were very reliable. The statistical calculations were based on 69 014 received packets.

Table I
THROUGHPUT STATISTIC BETWEEN 12TH JAN AND 8TH FEB

Node	**Throughput %**
Rear cluster	
211	99.85
212	93.42
213	97.81
Front cluster	
221	99.59
222	99.29
223	99.95
224	99.77
225	99.95
226	99.28

Table II
THE LONGEST BREAK AND THE NUMBER OF CONSECUTIVE MISSED PACKETS BETWEEN 12TH JAN AND 8TH FEB

Node	**Packets**	**Break start**		**Break end**	
Rear cluster	#	Date	Time	Date	Time
211	3	25.01	20:52	25.01	21:07
212	501	16.01	05:06	17.01	22:53
213	171	16.01	07:56	16.01	22:53
Front cluster					
221	7	24.01	04:27	24.01	05:02
222	8	02.02	08:04	02.02	08:44
223	3	13.01	09:05	13.01	09:20
224	6	24.01	05:32	24.01	06:02
225	3	02.02	08:04	02.02	08:44
226	8	02.02	06:59	02.02	07:39

Table III presents the corresponding figures as Table I from the 12th of January until the 1st of May 2007. The throughput of the nodes of the front cluster is good (excepting node 224), but not as good as in Table I. The reason is that the cluster head, node 101 in the front cluster, had a severe two weeks failure between the 24th of February and the 8th March. Similarly, the throughput of the rear cluster was not good and was basically due to two longer periods when node 102, the cluster head of the rear cluster, was dead and the communication from the rear cluster was disabled. The throughput of the rear cluster was also affected by the failure of node 101. The statistical calculation in Table III was based on 203 494 received packets.

The results show clearly that the network used could not guarantee reliable communication whenever there were problems in some critical nodes, like cluster heads. The poor results were basically due to device failures and the topology used. On the other hand, a failure of a single node is not necessarily a big problem in environmental monitoring. For example, a sensing node, node 224, broke during the spring 2007, and it shows in the statistics as a poor throughput. In any case, only the measurements of that node were lacking; the other nodes in the front cluster gave enough information for the needs of the environmental monitoring application. Thus, it can be concluded that the network of sensing nodes was dense enough for the application but the network of routing nodes was too sparse for reliable communication. Reliability of communication can easily be improved by increasing alternative communication paths to the sink.

Table III
THROUGHPUT STATISTIC BETWEEN 12TH JAN AND 1ST MAY

Node	Throughput %
Rear cluster	
211	58.14
212	57.81
213	59.76
Front cluster	
221	88.93
222	88.66
223	89.01
224	28.62
225	89.02
226	88.78

C. Link Quality

The significance of sufficient link quality came apparent at the beginning of the project when the network was installed. Distributing the nodes was difficult because of the unpredictable radio range. As it is well known, soil and other surfaces considerably affect the radio range by emitting signals and causing reflections. Also devices' angular orientation as well as variable weather conditions affect wireless communication. For that reason, radio range is difficult to predict beforehand. The average radio range inside the foxhouse was only 30-40m with the maximum transmission power of 0 dBm. Some nodes did not necessarily have a line of sight. Outside with the same transmission power the nodes have about 100m radio range.

Link quality can be evaluated by using the Received Signal Strength Indicator (RSSI), which indicates the strength of the radio signal at the receiver's position. The observed good throughput statistics indicate that there are no problems with the quality of links. However, during the project the received RSSI values varied significantly in time. An example of the received RSSI variation is shown in Figure 9.

The noticed RSSI variation forced us to ensure an adequate signal level. We added some functionalities which helped us to monitor the quality of links. The cluster heads measured the strength of the received signal from each sensing node and included this information to the end of data frame. The received RSSI values appeared to be especially useful when distributing nodes. Finding the positions for each node in a static network was easy and quick when the quality of link was known.

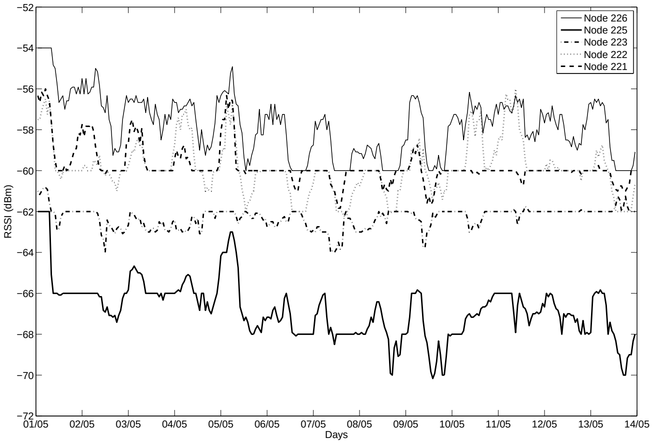


Figure 9. RSSI of the front cluster between 1st May and 15th May.

Tables IV and V present the statistics of RSSI values from the 12th of January until the 8th of February 2007. For each node the average of RSSI is above -80dBm and the standard deviation of RSSI varies between 0.76dBm and 2.90dBm. From Table IV it can be seen that the RSSI value of a single node can vary as much as 18dBm. However, Tables IV and V show that on average the link quality of nodes is good apart from the sensing node 211, which had the RSSI value below -75dBm for most of time. The minimum RSSI value was -83dBm, which in our experience can indicate unreliable communication. On the other hand, the throughput between sensing node 211 and sink was very good, which implies that the link quality was good enough for reliable communication. In spite of significant variation of the received RSSI values it can be concluded that the link qualities of the sensing nodes were very good on average.

Table IV
LINK QUALITY STATISTIC BETWEEN 12TH JAN AND 8TH FEB

Node	Mean RSSI	Std RSSI	Min RSSI	Max RSSI
Rear cluster	dBm	dBm	dBm	dBm
211	-77.2	1.7	-83	-73
212	-69.5	2.9	-75	-62
213	-71.1	1.0	-73	-68
Front cluster	dBm	dBm	dBm	dBm
221	-59.9	1.6	-64	-55
222	-65.4	2.5	-78	-60
223	-54.9	1.9	-63	-54
224	-55.1	1.0	-57	-53
225	-64.4	1.0	-67	-61
226	-54.5	0.8	-58	-53

D. Effects of Angular Orientation on Link Quality

During the project there seemed to be also variations between apparently similar devices; the link quality seemed to be better in some devices than others. Variations of the distance

Table V
RELATIVE FREQUENCY DISTRIBUTION FOR RSSI BETWEEN 12TH JAN AND 8TH FEB

Node	**Relative frequency %**		
Rear cluster	$[-83, -75]$ dBm	$(-75, -65]$ dBm	$(-65, -57]$ dBm
211	85.7	14.3	0
212	0	89.8	10.2
213	0	100	0
Front cluster	$[-83, -75]$ dBm	$(-75, -65]$ dBm	$(-65, -57]$ dBm
221	0	0	100
222	0.1	54.1	45.8
223	0	0	100
224	0	0	100
225	0	13.3	86.7
226	0	0	100

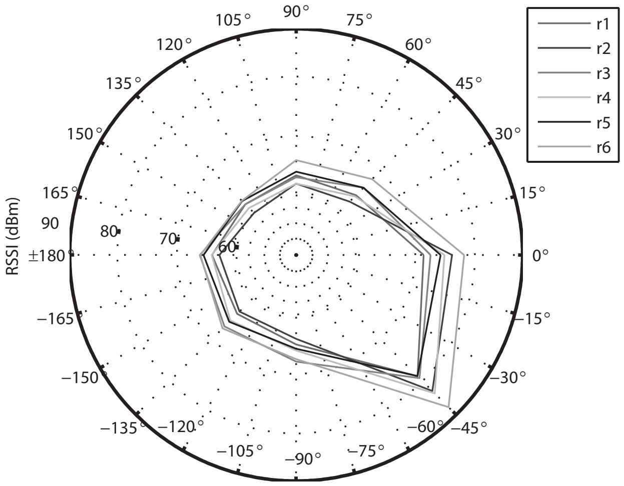


Figure 10. Variation of RSSI with angular orientation

between nodes could not alone explain the variations of the link quality. The angle of a device was also significant. Minor changes in positions were able to destroy the communication link between two devices. The effect of antenna's angular orientation has been reported in [9] also.

We designed the measurement procedure such as to obtain knowledge about how the received RSSI depends on a device and angular orientation. The measurements were done inside a large football hall in spring 2006. One transmitter device and six similar receiver devices were used. The transmitter and each receiver were attached to one-meter high wooden poles. The distance between the transmitter and a receiver was 4 meters. The transmitter was transmitting packets at -10dBm while in 8 different orientations (0, 45, 90, 135, 180, 225, 270, and 315 degrees) The transmitter was configured to send 20 packets per transmission period. When calculating the mean of RSSI, the maximum and minimum values were dropped in order to eliminate possible outliers. Figure 10 shows that there exist variations of RSSI values between different devices, but the impact of the angular orientation on the received RSSI is clearly more significant. In the worst case, the effect of the angular orientation on the received RSSI can be over 20dBm. Thus, the angular orientation clearly affects the received RSSI.

E. Effects of Weather Conditions on Link Quality

The weather conditions in the foxhouse were comparable to typical Scandinavian outdoor weather conditions. The lowest temperature during the measurement period was $-33.6\,^{\circ}\mathrm{C}$ and the highest $32.4\,^{\circ}\mathrm{C}$. The relative humidity inside the Foxhouse varied between 14.3% and 93.1% . The temperature and the relative humidity outside the Foxhouse were approximately the same as inside. A very low temperature and a high relative humidity make the conditions demanding for WSN.

While the network seemed to work well one day some of the static links could some other day prove unreliable. The link quality statistics show that the standard deviation of RSSI could be as high as 2.9dBm and RSSI of a single node could vary as much as 18dBm. The observed anomalies in the link performance of a single node can be explained by multipath propagation and dynamic environmental factors, such as the presence of people, movements, and weather conditions. These factors can interfere with the radio signal propagation, varying the received RSSI. On the other hand, most of the nodes had the line of sight and there was very little changes in environmental factors except in weather conditions. Since the radio frequency of 2.4GHz is also the resonant frequency of water, variation in air's moisture content can interfere with the received RSSI. An environment with a high humidity tends to absorb more power from the radio signals than when the humidity level is lower.

Figure 11 shows the average of relative humidity and RSSI from the 12th of January until the 8th of February. The values are averaged each hour. The effect of the relative humidity on the RSSI values can be seen in Figure 11. When the relative humidity increases, RSSI values decrease. Similar negative correlated results have been observed by others as well [17] and [5]. On the other hand, opposite effects of relative humidity on the RSSI values have been observed by [10]. When the relative humidity increases, the received signal strength increases. We observed similar positively correlated results also. Figure 12 shows the average of relative humidity and RSSI from the 14th of June until the 30th of June. The values are averaged each hour. The figure shows that the RSSI values are clearly positively correlated with relative humidity. The results are contradictory to each other in this matter.

Relative humidity is dependent on the temperature. Figures 13 and 14 shows temperature and relative humidity from the 12th of January until the 8th of February and from the 14th of June until the 30th of June, respectively. The values are averaged each hour. When the temperature changes, the relative humidity will change. However, as in the case of RSSI, the Figures 13 and 14 show clearly that relative humidity

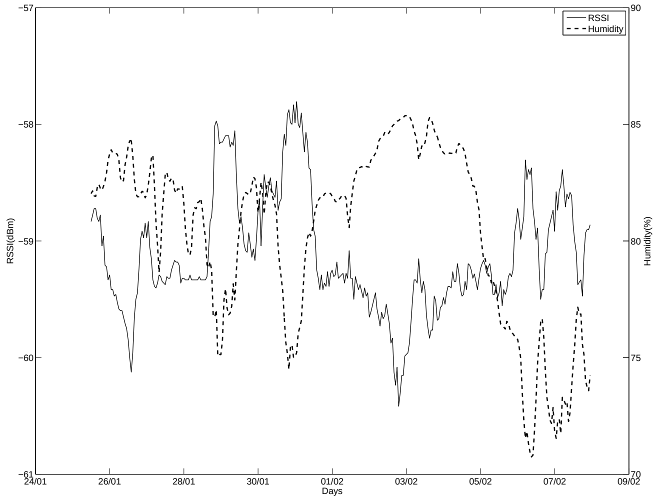


Figure 11. Relative humidity and RSSI between 12th Jan and 8th Feb

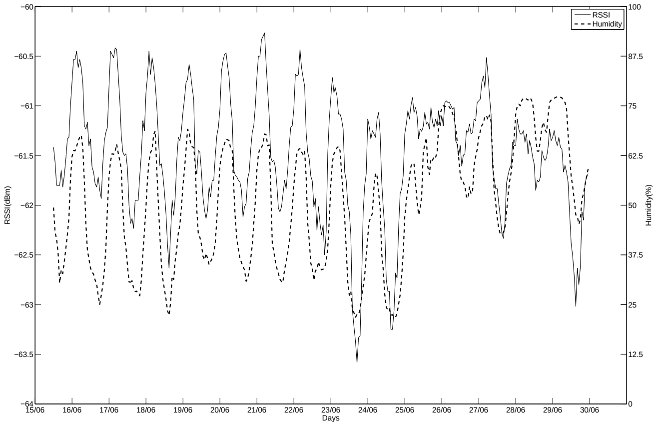


Figure 12. Relative humidity and RSSI between 14th June and 30th June

correlates both positively and negatively with temperature. On the other hand, relative humidity and temperature are associated with the dew point. If the temperature T and the relative humidity R are given the dew point T_d can be approximated by

$$T_d \approx \frac{bf(T,R)}{a - f(T,R)},$$

where

$$\begin{aligned} f(T,R) &= \frac{aT}{b+T}\ln R, \\ a &= 17.27, \\ b &= 237.7\,^{\circ}\mathrm{C}. \end{aligned}$$

When the dew point remains constant and temperature increases, relative humidity will decrease. At a given barometric pressure, independent of temperature, the dew point indicates the mole fraction of water vapor in the air, and therefore determines the specific humidity of the air. Thus, the dew point can be a better "absolute" measure of the air's moisture content than relative humidity.

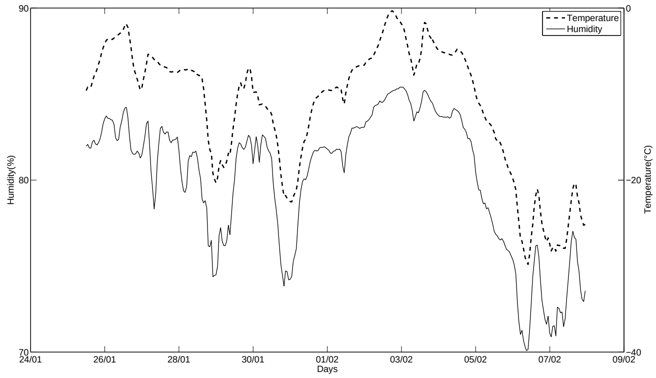


Figure 13. Relative humidity and temperature between 12th Jan and 8th Feb

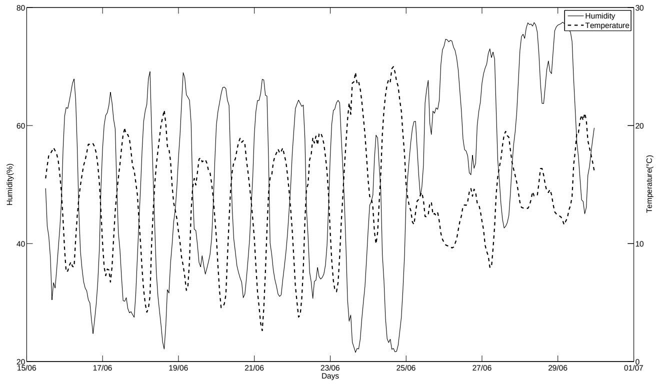


Figure 14. Relative humidity and temperature between 14th June and 30th June

Figures 15 and 16 show the dew point and relative humidity from the 12th January until the 8th of February and from the 14th of June until the 30th of June, respectively. The values are averaged each hour and the dew points are calculated by using the above equation. Both Figure 15 and Figure 16 show that RSSI values are negatively correlated with the dew point. We can conclude that the main part of the observed variation of the received RSSI of a single static node can be explained by the variation of weather conditions.

F. Power Consumption of Sensing Nodes

Normally environmental monitoring networks require battery-powered nodes. In this special case we could, however, use the main supply. In spite of main supply, the protocols of the used nodes supported energy-efficiency. The power consumption of a sensing node was measured by adding a 8.2Ω resistor next to the power supply. We measured the voltage over the resistor and calculated the current using the Ohm's law. Similar methods have been used in [18] and [19]. In order to indicate the different phases, an output pin is triggered when there is a phase transition.

A sensing node works periodically and each cycle has two main modes: a sleep mode and a work mode. During a sleep mode the radio module is turned off and the microcontroller wakes up every second which takes at most 5ms and the power

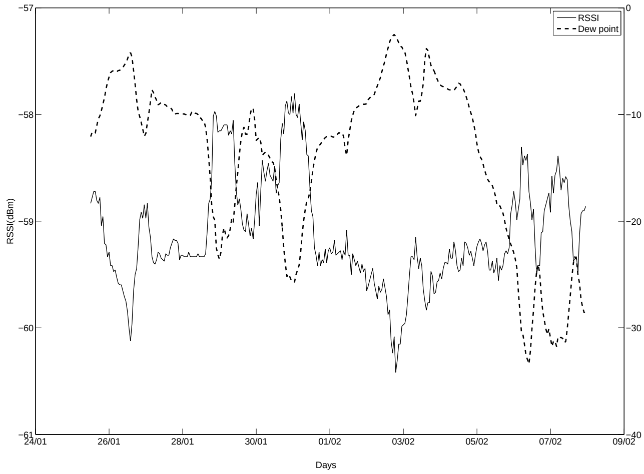


Figure 15. Dew point and RSSI between 12th Jan and 8th Feb

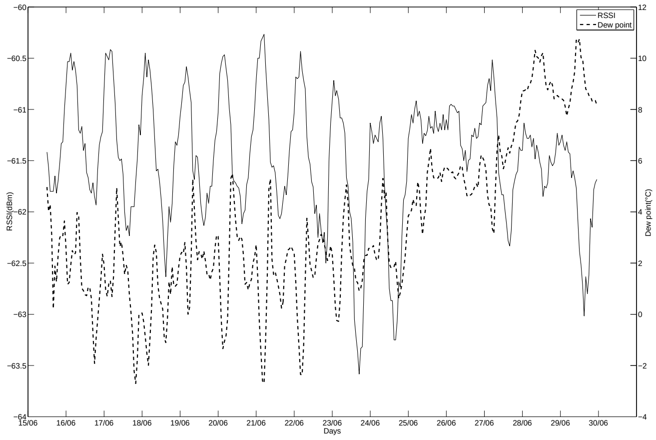


Figure 16. Dew point and RSSI between 14th June and 30th June

consumptions stays below $6mA$. The entire sleep mode takes 300s and the power consumption is below $30\mu A$ on average.

The work mode can be divided into 5 phases, which are depicted in Figure 17. The phases t_1, t_2, and t_3 are the temperature, relative humidity, and luminosity measuring phases which take approximately $216ms$, $62ms$, and $102ms$, respectively. The power consumption is approximately $12.4mA$. The phase t_4 is the message preparing phase which takes about $81ms$, and the power consumption is about $13.2mA$. During the phases $t_1 - t_4$ the microcontroller is turned on and the radio module is turned off. In the phase t_5, the transmitting phase, both radio module and microcontroller are turned on, and the duration of this phase depends on the number of retransmissions. In case of missing acknowledgements, there are at most three retransmissions. The phase takes at most $95ms$, and the power consumption stays below $30.6mA$. The entire work mode takes at most $556ms$, and the power consumption is $15.6mA$ on average.

The duty cycle of the sensing node is very short. Sensing nodes are in a sleep mode about 99.8% of the time. In average the power consumption of the entire cycle is at most $59\mu A$.

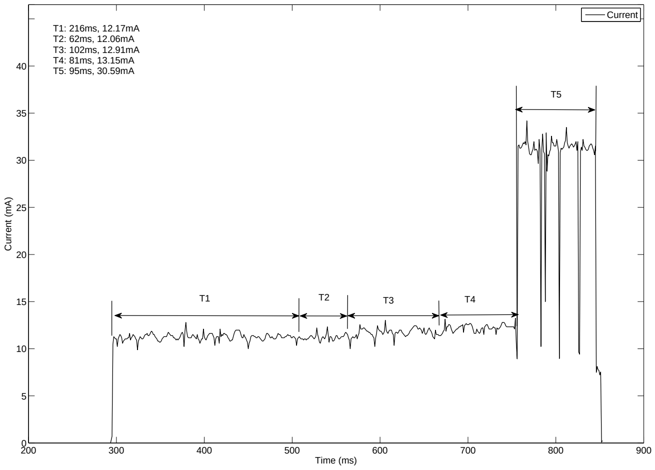


Figure 17. Power consumption of a sensing node

In the project a typical AA-type battery with voltage of $3.6V$ and capacity of $1000mAh$ was used. It can support the sensing node $1000mAh \cdot 1/0.064mA \approx 17014$ hours, which is about 708 days.

During the project battery duration in a low temperature was tested also. A battery-powered node measured temperature, humidity and luminosity during 10 months from October 2006 onwards. The lowest temperature during the measurement period was $-33.6\,°\mathrm{C}$ and the highest $32.4\,°\mathrm{C}$. The node function was 100% reliable in all weather conditions. The node was still working in July 2007 when the test period ended. Thus, the test of battery powered node supports the above calculations.

V. DISCUSSION

Although the application in the Foxhouse case was quite small, we believe that it is actually quite a typical sensing network with its typical problems and features. The implemented network met the requirements. The biologists from MTT Agrifood Research Finland got desired information about habitat of animals, and the network reduced the need for manual measurements.

From the network developers' viewpoint the Foxhouse case was twofold. The tested IEEE802.15.4 wireless communication links proved very reliable in hard outdoors conditions. However, during the project the received RSSI of the static nodes could vary significantly in time, which could be explained by the variation of weather conditions. In spite of some variations of the received RSSI, the quality of links proved to be very good on average. Also the battery-powered node worked fine in spite of cold weather and the protocols proved to support energy-efficiency. On the other hand, the sensor nodes appeared to have some problems and the cluster topology could not guarantee reliable communication whenever there were problems in cluster heads. Alternative communication paths would have been needed. Also, it is important to recognize possible communication problems soon after malfunctioning.

During the project we added some functionalities which helped us to monitor network status. Information about quality of links together with information of successful packet delivery gave an idea about the network status and also helped to evaluate possible reasons for malfunctioning. It is however obvious that, in the future, network management in the CiNet network needs more attention, and we are going to focus our work on this question. Improvement of both diagnostics and reconfiguration is essential when thinking of usability and reliability of the CiNet network.

VI. CONCLUSION

The environmental monitoring system in the Foxhouse case proved that WSN using the IEEE802.15.4 communication protocol is reliable. The quality of links proved to be good on average in spite of some observed anomalies in link performance. The project showed also the technology used is relatively easy to implement in an environmental monitoring application. The use of WSN made constant real-time data available for biologists, and it also reduced manual measurements. To that extent, the WSN in the Foxhouse case was successful. There were nevertheless problems in functionalities of some routing nodes, which together with the fixed topology caused unnecessary packet loss. Reliability of communication can be improved by using a dynamic routing protocol. Design and implementation of a dynamic routing protocol will be future work. The Foxhouse case made it clear that IEEE802.15.4 based communication is suitable for environmental monitoring applications, but more attention must be paid to network management issues in the future.

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