Radio Wave Propagation in Potato Fields

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***Abstract*— Reliable communication is crucial for successful deployment of wireless sensor networks. Therefore, it is important to understand the impact of environmental conditions on the performance of the radios (Chipcon CC1000 transceivers) used in typical sensor nodes. This paper reports on an extensive set of measurements taken in a potato field, where the foliage has an important effect on the propagation of radio waves. The influence of the growth stage of the potato crop is significant. We observed a reduction of 15 dB in signal strength at 15 m between nodes, when a flowering crop is compared to a crop on its return. This effectively reduces the radio range from 23 m to 10 m. Another important result is that radio waves propagate better in conditions with a high humidity (i.e., at night and during rain). We attribute this to changes in the reflection coefficient of the top of the potato canopy.**

I. Introduction

Pervasive networks hold the promise of instrumenting the physical world with sensors to provide a level of detail that opens up a new class of applications [8]. Precision agriculture is one of the promising domains where wireless sensor networks could be exploited, for example, by observing the micro-climate within a field so that, ultimately, plant-specific farming can be realized. The LOFAR-Agro consortium [10] is carrying out a pilot project in which sensor nodes will measure the conditions in a potato field; this detailed information (1 reading per 150 m^2) will be used to improve the advice on how to fight the fungous *Phytophtora infestans* disease within a crop. Note that information about the micro-climate under the canopy of the potato crop cannot be accurately obtained by remote sensing, hence, the choice for a wireless sensor network. An important requirement that follows from this choice is the need for *reliable* multi-hop communication, since individual sensor readings need to be combined at a central place and low-power radios have only limited range. To reduce cost (i.e., minimize the number of nodes) it is important to know the maximum distance at which data packets can still be communicated reliably between neighboring nodes.

Wireless communication is affected by many environmental factors not foreseen by developers, not accounted for by simulators, and not considered by theoretical models [9, 11]. This is especially true for an arable farming environment in which growing crops (foliage) and ever-changing weather conditions have an unknown effect on the exact propagation of the radio waves. Therefore, this paper reports on a basic measurement study of the performance of the Chipcon CC1000 radio, part of the popular Mica2Dot sensor node, in a potato field during two months of a growing season (July and August 2004). The main findings are that

- radio range is limited to about 10 m when the potato crop is flowering, and that
- radio waves propagate better in conditions with a high humidity (i.e., at night and during rain).

As a consequence, the LOFAR-Agro pilot will use special relay nodes to ensure reliable communication during the whole growing season.

II. Background

In this section we briefly describe the (theoretical) background of signal propagation relevant to typical wireless sensor networks (WSN) deployment scenarios. In the case of outdoor deployment, the antennas are often mounted on, or just, above the ground, and the distance between the sensors is relatively small (up to 50 m). These settings fall outside the scope of most existing models that simulate radio wave propagation [6, 7], so we have to revert to analytical methods. Although these methods can only be applied in a few rather simple cases, they do give an insight into basic propagation mechanisms [13]. We will review both the analysis for propagation over a reflecting surface as well as the influence of foliage.

A. Reflecting surface

In WSN deployment, the distance between nodes is small, so it is permissible to neglect earth curvature [13]. Furthermore, in the scenario where nodes are deployed under the canopy of a potato crop, antenna heights are small compared to the transmission ranges of WSN hardware. In this case the *plane earth propagation equation* [13] can be applied, which reads in logarithmic form for isotropic antennas as follows

$$L_p(dB) = 40 \log_{10} d - 20 \log_{10} h_T - 20 \log_{10} h_R \quad (1)$$

where L_p is the propagation loss, d the distance in meters between receiver and transmitter, and h the antenna height in meters. Propagation loss follows the inverse fourth law with distance, which means that the path loss exponent is four. So received power falls by 12 dB when the distance is doubled [17].

In the derivation of Equation 1 it is assumed that the reflecting surface is the earth, in which case the reflection coefficient equals -1. In the beginning of the growing season the reflecting surface is the indeed the earth, but that changes over time. Determining the reflection coefficient is difficult

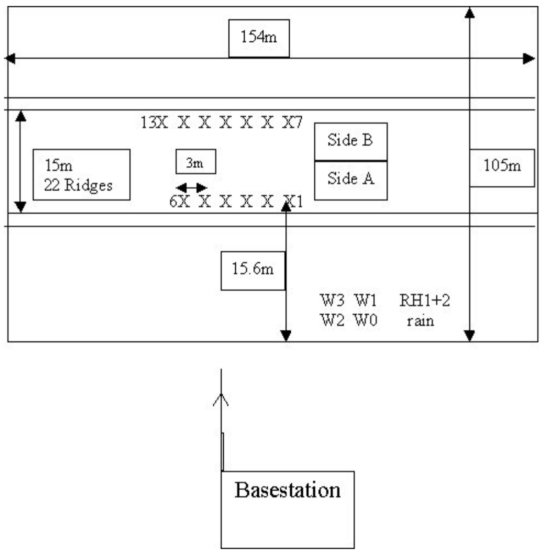

Fig. 1. Overview of the potato field.

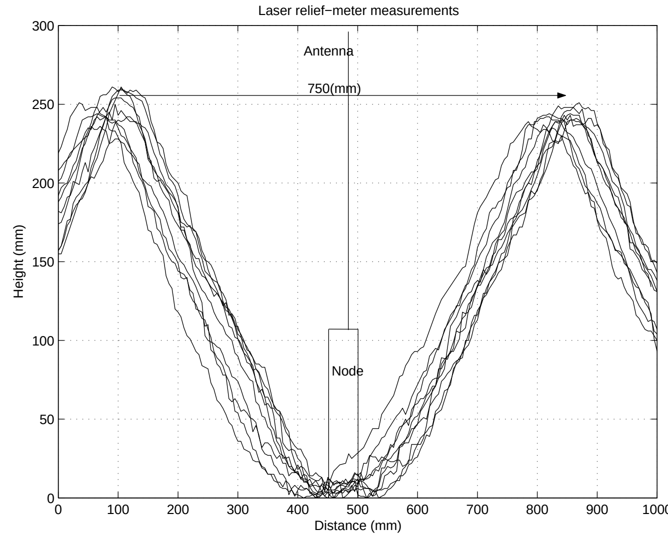

Fig. 2. The dimensions of the ridges with a node schematically drawn. Ridge height 25 cm, Ridge width 75 cm, Antenna height 11 cm and Total node height 29.5 cm.

since it depends on the carrier frequency of the radio signal, the grazing angle, and the constants characterizing the reflecting medium, in particular, the dielectric constant and the conductivity [13]. A study on the complex permitivity of the potato leaf has shown that there is a significant relationship between leaf thickness and reflection coefficient [4].

B. Foliage loss

Research on propagation loss due to foliage has focused mainly on forests [12, 6, 15] and on maize and soybeans [18]. The results show that when the height of the canopy is less than the distance between transmitting and receiving antennas, propagation is dominated by the lateral wave over the top of the canopy. The attenuation of the lateral wave depends on the reflection coefficient (surface roughness) of the top of the canopy [15]. In general, foliage loss increases as function of the carrier frequency [12, 15]. In the case of corn (maize and soybeans) it was determined that the loss as function of the moisture content of the canopy shows a rising exponential curve at frequencies above 5 GHz [18]. It is unclear to what extend these findings also hold for potatoes, which are grown on ridges, have different shapes, and make tubers.

III. Experimental setup

Since the literature provides little concrete information on the propagation of radio waves in potato fields, we conducted a long-running experiment with commercially-available hardware to determine the effects of the micro-climate on wireless communication in the LOFAR-Agro setting. This section reviews the field layout, the hardware, and the software used in our experiment.

A. Field layout

We deployed 13 Mica2Dot nodes (without sensors) in a 154×105 m potato field located in two separate lanes, see Fig. 1. The nodes are controlled from a base station located in an equipment shelter near the edge of the potato field. The distance between neighboring nodes in a lane is 3 m $\pm$ 5 cm. All nodes were placed on the bottom of the valley between two ridges of potato plants. The ridge dimensions were measured on 10 spots with a laser relief-meter, see Fig. 2. The potato plants reached a maximum height of about 90 cm during the growing season when flowering in July.

The experimental setup also includes three (large) sensors to measure the micro climate: temperature (T), relative humidity (RH), and rain. These sensors are located at the border of the field, so they would not disturb the communication measurements between the nodes, and to make them easily accessible. The information on the micro-climate was collected by a weather-station (data-logger), which was also housed in the equipment shelter.

B. Hardware

1) Nodes: For the field test, the Mica2Dot [5] platform was used. It represented at the date of purchase, the latest technology commercially available. The 433 MHz version was chosen, because of its high transmit power ensuring communication over long ranges. This node has a four channel Chipcon CC1000 [1] radio that uses frequency shift keying (FSK) and Manchester encoding. The highest transmit power is +10 dBm, and the receiver sensitivity is -104 dBm at 19.2 kbps. The CC1000 radio has a built-in Received Signal Strength Indicator (RSSI) giving an analogue output signal. The RSSI voltage is measured by the 10 bit A/D converter of the Mica2Dot's micro-controller. The reference voltage of the A/D converter is directly connected to the battery ($V_{ref} = V_{bat}$), which makes the readings unreliable at the end of the battery's lifetime. The RSSI readings (ADC counts) are converted to dBm according to the specifications in the manual.

We copied the Mica2Dot enclosure designed for the Great Duck Island (GDI) deployment [14], which was proven to withstand harsh environmental effects. For ease of deployment the standard wire $\lambda/4$ monopole antenna was used. Due to the antenna height (18.5 cm), the antenna had to stick out of the enclosure. A lithium battery was chosen because of its stable discharge curve over time. The Tadiran C-cell, SL-770 version, has the same diameter as the Mica2Dot and a nominal capacity of 7200 mAh, at a discharge current of 3 mA. Before deployment the voltage of the 13 nodes was measured twice with a one hour time-interval. The mean voltage was 2.75 V with a standard deviation of 0.01 V.

2) Weather-Station: A Cambell Scientific CR10X datalogger was used to measure the relative humidity, temperature and rain each minute during the complete experiment. To measure the difference in temperature and relative humidity in and above the canopy, two sensors were placed. One at a height of 0.94 m the other at a height of 0.20 m relative to the bottom of the ridge. The rain sensor is of the tipping bucket principle; its funnel was placed at a height of 80 cm.

3) Base station: In order to have good contact between the base station and the nodes an omni-directional Diamond X400 antenna with 11.7 dB gain was used. The antenna was mounted on a telescopic mast to easily vary the antenna height; at 2.5 m the whole field could be covered. The base-station node (Mica2 with MIB510 programming board) was mounted in an aluminum box in the top of the mast and connected with the antenna trough a 69.3 cm (λ at 433 MHz) long coax cable. The programming board was connected by a 20 m RS232 cable to a laptop, which was located in an equipment shelter.

C. Software

The software used to perform the measurements consisted of two major components, brought together under the name Calamari and designed by Kamin Whitehouse [20]. The first component is the code running on the nodes, which was written in an open-source development environment called TinyOS. The code is designed to perform RSSI measurements between pairs of nodes for localization purposes. We used these RSSI measurements to examine radio wave propagation in the potato field. The second component, is the software to control the nodes in the field. It is written in Matlab and running on the base station, in our case a laptop. When running the application, Matlab commands node 1 to broadcast 30 packets at +10 dBm transmit power. There is no retransmission of lost packets. All other nodes listen for the packets. During packet reception, the RSSI value is sampled ten times, and the mean value is saved together with the packet ID number in the node. The base station also listens for the packets that are broadcasted, thus when node 1 finishes, the base station commands node 2 to start broadcasting 30 packets. When all nodes are ready with broadcasting, the base station asks all nodes in turn for the reports they made of all the packets they measured for RSSI. The small reports are put in one big file and saved with a time stamp. Matlab waits now for two minutes and repeats the whole cycle. The latest Calamari code can be downloaded from the Calamari project website [19].

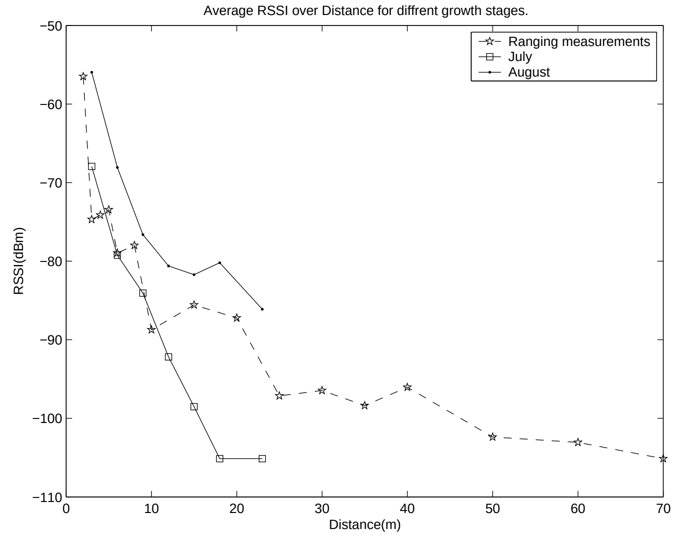

Fig. 3. Signal strength vs. distance.

D. Data processing

The raw data files of both the base station and the weather station were processed off-line in Matlab. For each pair of nodes the mean RSSI, max RSSI, min RSSI, standard deviation (STD), coefficient of variation (CV), and number of received packets ($N_{R.packet} \leq 30$) were calculated. These results, receiver number, transmitter number, and time stamp were saved to one file for each month. The weather-station measurements were also combined into one file for each month.

IV. Results

Our field setup was used to perform two series of measurements, one in July and the other in August. Each series spans a time frame of about two weeks. In both cases the canopy was closed, which makes the lateral waves the dominating factor. Due to irregular planting material, the crop was not uniformly developed in the regions where the nodes were located. Unfortunately, we were not able to account for these differences. In August the potato crop was already on its return, crop height and bio mass is reduced compared to July.

First we will present the results on how the radio signals are attenuated according to distance. Next we will zoom in on the results with low signal-to-noise (SNR) ratio values since WSN deployment focusses on saving energy by making the largest hops possible (or by reducing the transmit power to the lowest possible level). In particular, we will report the effects of the micro-climate only for long-distance links.

A. Propagation loss versus distance

Figure 3 shows how received signal strength drops when the distance between nodes increases. According to theory (cf. Section II) the signal strength curves decrease logarithmically

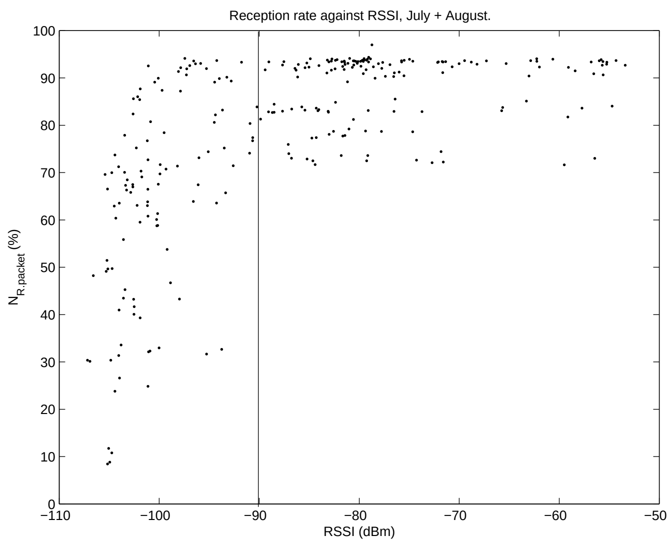

Fig. 4. Reception rate vs. RSSI.

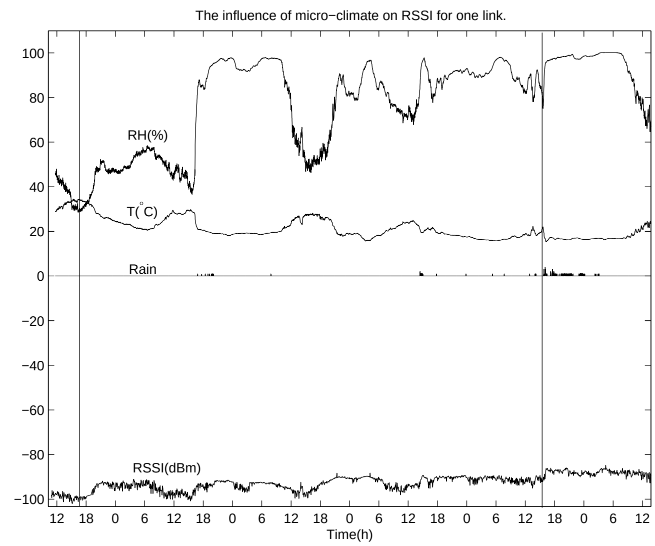

Fig. 5. Influence of the micro-climate on RSSI against time, for receiver 1 and transmitter 13 (23 m apart, low SNR regime).

with distance. Until 15 m the path loss exponent is four, which matches with other measurements of sensor network communications [6]. After 15 m there were not enough channels to obtain reliable RSSI values. For reference, Figure 3 includes an additional set of ranging measurements obtained with two nodes exchanging messages within a lane over a wider range of distances (up to 70 m). In these ranging measurements the potato canopy was still open, therefore there was a clear line of sight between the nodes. These measurements, however, only cover a time frame of a few minutes each, so we do not include them in any other graph.

We observe that the maximum distance for reliable communication (RSSI $>$ -90 dB, see below) is much shorter than the plane earth propagation equation indicates. (The maximum path loss for the CC1000 radios is equal to transmit power - receiver sensitivity = 114 dB, the antenna height is 11 cm, so the maximum distance is 78 m.) The reduced range is mainly caused by the foliage of the potato plants, which explains why August (reduced crop) does better than July (flowering crop). At a distance of 23 m the difference in conditions causes a 19 dB difference in received signal strength. At 15 m the difference in attenuation is 16.8 dB. The impact of foliage loss is thus significant.

B. Low signal to noise ratio

In general when the signal strength drops below a critical threshold the chance of receiving a corrupted packet increases rapidly. The TinyOS communication stack automatically filters out packets with an incorrect CRC checksum, so the $N_{R.packet}$ numbers recorded can be used to determine the critical distance beyond which reliable communication can no longer be guaranteed.

Figure 4 shows the packet reception rate ($N_{R.packet}$) for different RSSI values observed in our field setup. Each dot represents the average RSSI between a pair of nodes obtained in one measurement session (i.e. July or August). Note that the packet reception rate is never 100%, not even for the highest RSSI values. This is probably due to the absence of a direct line of sight between nodes, better known as a Rayleigh fading link [16]. The data in Figure 4 shows that good links with an RSSI above -90 dBm obtain a packet reception rate of at least 73%. This finding roughly corresponds with the -100 dBm value reported by Alippi and Vanini, who also performed measurements with Mica2Dots [2]. Below the -90 dBm threshold, the reception rate fluctuates heavily, rendering RSSI an inaccurate indicator for link quality. This so-called gray-area effect is observed by others as well [21, 22].

The influence of the micro-climate on RSSI is shown in Figure 5, where the two vertical lines indicate interesting points. The RSSI values suggest day-night regimes with RH and T. When other low SNR links are compared, the same regime is found. Further it is shown that RSSI values are positively correlated with RH and negative with T. That means, when RH increases, RSSI also increases. Even when RH is already high and it starts raining, RSSI increases, as shown at the last line. The first line shows the end of a dry period with temperatures above $30°\mathrm{C}$. After the first line RSSI starts increasing again, because of different weather. A comparison of low-SNR links with high-SNR links suggests that for small values of RSSI, fluctuations tend to get higher. An overnight test on concrete supports this finding. The nodes were deployed in a closer grid with a minimum distance of 0.5 m, At these distances the RSSI values were very stable over time, only fluctuations in the 0.1 dB range. These fluctuations are therefore induced by the environment and not by the temperature dependence of V_{bat}, the diode or the rubber antenna enclosure.

A plot of RSSI against RH suggested a linear relationship. In order to quantify and validate the relationship between RH and RSSI, linear regression was performed. Quantification of this relationship is interesting, because moist field conditions are often related to a higher chance on fungous diseases in potato crops. However none of the assumptions for linear regression hold, so the performed quantification was not valid. This is in line with the observation that relative humidity is not a parameter in the calculation of the reflection coefficient [13]; apparently the effect is indirect.

V. Discussion

For the Mica2Dot hardware, the plane earth propagation model predicts a communication range of 78 m (-104 dBm receive power threshold). In practice, however, we observed that a careful indication for reliable communication (-90 dBm receive power threshold) in our potato field would be 10 meter for a flowering crop and 23 meter when the crop is on its return.

In our setup, radio waves propagate better with high humidity (i.e., at night and during rain). In literature no information could be found that confirms this phenomena. On the contrary, Anastasi et al. who use similar hardware (Mica2Dots, but transmitting at 868 MHz), report that the transmission range of the nodes decreases significantly in the presence of fog and rain [3]. Since they did not specify the outdoor environment and operate at another carrier frequency, it remains unclear what is causing the difference with our findings.

For now, we attribute the positive impact of humidity on transmission range to changes in the reflection coefficient of the top of the potato canopy, but additional experimentation is needed to verify our beliefs. An interesting consequence would be that in outdoor WSN deployment energy can be saved by delaying traffic until moist conditions appear.

VI. Conclusions

This paper reported on an experimental study of the propagation of radio waves in a potato field as part of the LOFAR-Agro project investigating the use of wireless sensor networks in phytophtora control. We found that it was possible to communicate reliably with the popular Mica2Dots under the canopy of a potato crop. We determined that the path loss exponent was four irrespective of the growing season. The radio range, however, is reduced to 10 m when the potato crop is flowering. Therefore the distance between nodes for precision-agriculture applications should be at most 10 m when the micro-climate must be sensed during the whole growing season. The influence of the potato foliage is at least 17 dB when nodes are at a distance of 15 m (flowering crop vs. a crop on its return). A second remarkable result is that radio waves propagate better in conditions with a high humidity (i.e., at night and during rain). We attribute this to changes in the reflection coefficient of the top of the potato canopy. In the next growing season (2005) we plan to carry out additional measurements in a larger field, over a longer period to confirm and refine the results obtained so far.

Acknowledgments

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