(CPS)ˆ2: Integration of Center Pivot Systems with Wireless Underground Sensor Networks for Autonomous Precision Agriculture

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ABSTRACT

Precision agriculture (PA) refers to a series of practices and tools necessary to correctly evaluate farming needs and a high density of soil sensors is an essential part of this effort. The accuracy and effectiveness of PA solutions are highly dependent on accurate and timely analysis of the soil conditions. Traditional soil measurements techniques, however, do not provide real-time data and hence, cannot fully satisfy these requirements. Moreover, the use of wired sensors, which usually must be installed and removed frequently, impacts the deployment of a high density of sensor nodes for a certain area. In this paper, a novel cyber-physical system (CPS) is developed through the integration of center pivot systems with wireless underground sensor networks, i.e., $(CPS)^2$ for precision agriculture (PA). The Wireless Underground Sensor Networks (WUSNs) consist of wirelessly connected underground sensor nodes that communicate untethered through soil. A CP provides one of the highest efficient irrigation solutions for agriculture and the integration of WUSNs with the CP structure can provide autonomous irrigation capabilities that are driven by the physical world, i.e., conditions of the soil. However, the wireless communication channel for the soil-air path is significantly affected by many spatio-temporal aspects, such as the location and burial depth of the sensors, the soil texture and moisture, the vegetation canopy, and also the speed of the center pivot engine. Due to the high number of real-time parameters to be considered, a cyber-physical system (CPS) must be developed. In this paper, as a proof-of-concept, the results of empirical experiments with these components are provided. The main characteristics of a precision agriculture CPS are highlighted as a result of the experiments realized with a WUSN built on top of a real-life center pivot system. The experiment results show that the concept of $(CPS)^2$ is feasible and can be made highly reliable using commodity wireless sensor motes. Moreover, it is shown that the realization of $(CPS)^2$ requires non-trivial management due to stochastic real-time communication constraints. Accordingly, guidelines for the development of an efficient $(CPS)^2$ solution are provided. To the best of our knowledge, this is the first work that considers a CPS solution based on WUSNs for precision agriculture.

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Categories and Subject Descriptors

C.2.1 [**Computer-Communication Networks**]: Network Architecture and Design.

General Terms

Experimentation

Keywords

Cyber-physical systems, Cross-layer design and adaptation, Underground electromagnetic propagation, Wireless Underground Sensor Networks, Precision Agriculture.

1. INTRODUCTION

Precision Agriculture (PA) refers to a series of practices and tools necessary to correctly evaluate farming needs. It is based on the fact that even a small field presents strong variability of natural components, including topology, leaching, runoff, drainage, water content, nutrients, and soil components [5, 6]. Therefore, soil sensors are an essential part of this effort. The accuracy and effectiveness of the PA solutions are highly dependable on the accurate and timely analysis of the soil conditions. Unfortunately, traditional soil measurement techniques cannot provide real-time data and hence, cannot fully satisfy these requirements. Moreover, the use of wired sensors, that must be installed and removed frequently, increases the total cost of the solution and decreases the density of sensors for a certain area.

Wireless Underground Sensor Networks (WUSNs), which consist of wirelessly connected underground sensor nodes and communicate through soil, have recently been investigated [1, 4, 11, 12, 16]. WUSNs have the potential to impact a wide variety of novel applications including precision agriculture, environmental monitoring, border patrol, and assisted navigation. In the area of PA, the gap between the physical and the cyber worlds can be potentially bridged by the integration of WUSNs with irrigation technologies. The combination of WUSNs with the precision

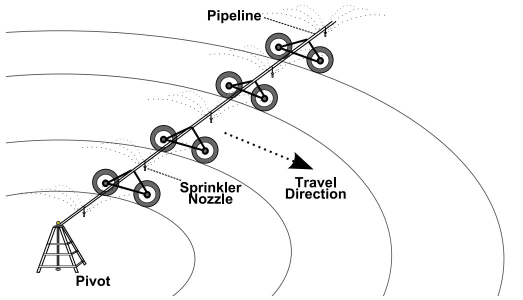


Figure 1: Basic components of a center pivot (CP) system.

agriculture techniques such as center pivot systems results in a cyber-physical system, i.e., $(CPS)^2$, not yet envisioned [10]. In addition to its monitoring capabilities, $(CPS)^2$ can provide automation for irrigation and application of chemicals. Moreover, a $(CPS)^2$ can also be used to evaluate the current irrigation methods and promptly alert for the need of optimization and/or maintenance tasks in a real-time manner.

In this work, we present a proof-of-concept for a CPS application, where an irrigation solution called center pivot system [8] is used as a physical mobile structure to send and receive soil condition data to/from buried underground sensors that form a wireless underground sensor network [1]. The empirical results related to the wireless communication are presented and critical research challenges for $(CPS)^2$ are discussed. The seasonal effects are also derived from the analysis of the effects of the soil moisture content and the canopy on the wireless communication. The experiment results show that the concept of $(CPS)^2$ is feasible and can be made highly reliable using commodity wireless sensor motes. Moreover, as will be discussed in Sections 4 and 5, several research challenges are yet to be effectively addressed.

The rest of this paper is organized as follows: In Section 2, the center pivot system and irrigation methods are explained. Moreover, the characteristics of a WUSN, its classification, and related work are provided. In Section 3, the methodology used in the experiments is described. The empirical results for the integration of CP system with WUSNs are discussed in Section 4. In Section 5, the main challenges for the development of a $(CPS)^2$ are discussed. Finally, the paper is concluded in Section 6.

2. BACKGROUND AND RELATED WORK

In this section, a description of center pivot systems is provided in Section 2.1. The characteristics of WUSNs and its classification are provided in Section 2.2. Finally, the related work in WUSNs is discussed in Section 2.3.

2.1 Center-Pivot System

Due to the need of reducing water loss, soil erosion, and energy costs, more efficient water application methods are necessary in modern agriculture practices. One of these methods is the sprinkler irrigation based on a center pivot (CP) system [5, 8]. A CP is a popular and large self-propelled sprinkler system [3, 5, 8]. As shown in Fig. 1, a sprinkler pipeline is used and one end of the pipeline is connected to a pivot element at the center of the irrigated area [8]. Usually, the irrigated area has a circular shape that is clearly visible from the air. Due to the fact that the cost of a CP is relatively high, it is best suited for large irrigated areas: from 3.5 to 65 ha [5, 8]. In Fig. 1, a CP for an area of 22 ha ($220,000m^2$), which is also used as a testbed for the experiments, is illustrated. Besides its primary use for water irrigation, a CP can also be used to apply chemicals to the soil and/or crop. An additional use of sprinkler irrigation systems, including the CP, is to provide emergence irrigation as a way to reduce or prevent frost hazard [5].

The amount of water to be applied by a CP can be determined by the travel speed of the pivot. For the same flow rate, a higher travel speed means a smaller amount of water applied to the field. Another possibility is to fix the travel speed and to adopt electronically-controlled nozzles to adjust the flow rate for smaller areas in the field. However, the simplicity, good accuracy, and low cost are significant advantages of the former option. In both cases, the soil monitoring is an essential part of the solution. The soil data sent from the underground sensors to the CPS can indicate the level of efficiency of the irrigation process. If the accuracy of the soil measurements is high enough, the irrigation process can be entirely automated to realize a cyber-physical system for precision agriculture.

One of the disadvantages of current CP solutions is the delay to detect problems with the system [3]. In addition to its agricultural impact, a $(CPS)^2$ can also significantly reduce the losses in such scenarios by generating warnings and alerts to the farmer in case of problems. In other words, emergence maintenance of the CP structure and errors in the irrigation plan can be promptly addressed without any delay. For instance, assume that one of the nozzles presents a problem and, before the passage of the pivot, the sensors of a non-irrigated region inform the value of 6% for the soil moisture. As expected, after the passage of the pipeline, a variation of the soil moisture must be reported by the underground sensors. If this is not the case, the CPS can generate a warning informing the farmer about the affected region.

The above PA challenges illustrate the importance of real-time soil measurement for an efficient PA solution. Consequently, a $(CPS)^2$ must employ an efficient solution for the communication with the underground sensors. To this end, a WUSN is used in this work to provide the communication infrastructure. In the next section, the WUSN technology is presented and its challenges are discussed.

2.2 Classification of Wireless Underground Communication Networks

Although a WUSN is mainly formed by underground sensor nodes, the network still requires aboveground nodes for additional functionalities such as data retrieval, management, and relaying. Therefore, considering the locations of the sender and the receiver, three different communication links exist in WUSNs, as shown in Fig.2:

- *Underground-to-underground (UG2UG) Link:* Both the sender and the receiver are buried underground and communicate through soil [11]. This type of communication is employed for multi-hop information delivery.
- *Underground-to-aboveground (UG2AG) Link:* The sender is buried and the receiver is above the

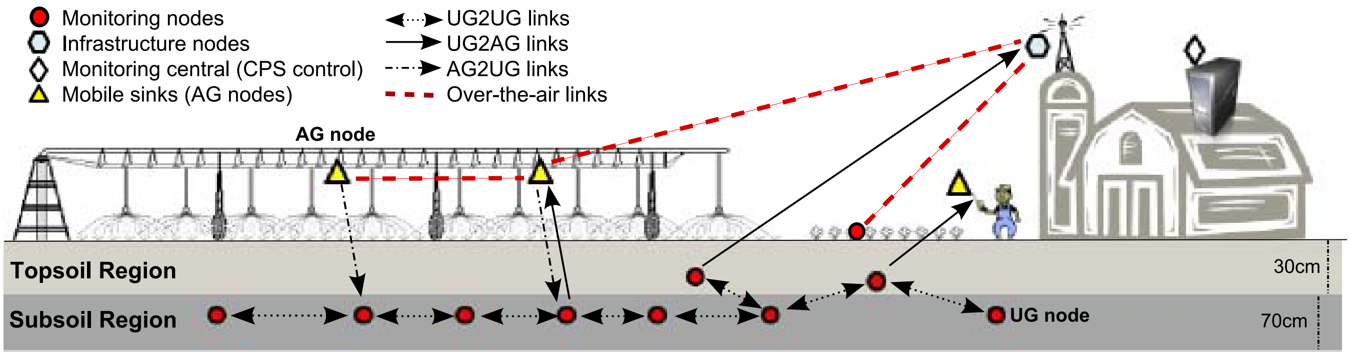


Figure 2: An example of a precision agriculture cyber-physical system $(CPS)^2$ based on Wireless Underground Sensor Networks (WUSNs). A WUSN can employ 3 kinds of communication: Underground-to-underground (UG2UG), Underground-to-aboveground (UG2AG), and Aboveground-to-underground (AG2UG).

ground [12]. Monitoring data is transferred to aboveground relays or sinks through these links.

- *Aboveground-to-underground (AG2UG) Link:* Aboveground sender node sends messages to underground nodes [12]. This link is used for management information delivery to the underground sensors.

For the realization of the $(CPS)^2$ described in this work, only the UG2AG and AG2UG links are necessary. Although the sensors may be buried at different regions of the soil, typical WUSN applications will require that the buried sensor be deployed at two specific regions: the topsoil and the subsoil regions. The *topsoil region* refers to the first 30cm of soil, or the root growth layer, whichever is shallower and the *subsoil region* refers to the region below the topsoil, i.e., usually the 30-100cm region [11]. Accordingly, both cases of the deployment of underground nodes are illustrated in Fig. 2.

Whenever possible, a shallower deployment (topsoil) is preferable due to the smaller length of the soil path and, thus, smaller signal attenuation. Unfortunately, for the PA scenario, plowing and similar mechanical activities occur exactly at the topsoil region and higher burial depths in the root range of crops are required. In other words, PA applications are mainly related to subsoil WUSNs. For instance, for our experiments with the corn crop, the 35cm-burial depth was defined as the best value to satisfy the application requirements. For the majority of crops, a burial depth of 40cm is the most secure and balanced option [11].

2.3 Related Work

Wireless underground communication has been investigated in many contexts recently. The concept of WUSNs and their challenges have been introduced in [1]. In [2, 7], we develop a theoretical channel model for UG2UG links at the 300-900MHz frequency range and empirical evaluations of UG2UG communication are reported in [11], where Mica2 motes [21] are used.

However, few WUSN experiments have been performed to date. In [13], the challenges for realizing WUSN experiments are discussed and some of the aspects to be considered when developing a WUSN testbed are provided. In [4], a WUSN, which is based on customized sensor nodes (SoilNet) that operate at 2.4GHz, is developed for real-time soil water content monitoring. A 5-9cm burial depth is considered and a theoretical model for the UG2AG link for this burial depth is developed. In [17], an ultra wideband elliptical antenna [9] is proposed for the underground communication and the advantages of this scheme are highlighted. An UG2AG theoretical model is proposed in [18] and experimental results are provided. Communication ranges of 30 and 150m are reported for the burial depths of 40cm and 25cm, respectively. However, only long range (>20m) UG2AG communication links are considered.

While the above results illustrate the feasibility of WUSN applications, a solution for PA applications involving both UG2AG and AG2UG links are not provided. In [12], we performed experiments with UG2AG and AG2UG links using short-range communication and the effects of the antenna design, burial depth, and soil moisture are discussed. However, the use of an aboveground node attached to a mobile device, such as a center pivot, is not considered. In this work, we provide a proof-of-concept for such a solution with subsoil deployment, i.e., burial depth higher than 30cm. We also show that such a center pivot system solution requires non-trivial management due to stochastic real-time communication constraints. Accordingly, guidelines for the development of an efficient $(CPS)^2$ are provided.

3. EXPERIMENT SETUP

The experiments with 433MHz Mica2 [21] sensor nodes are carried out in South Central Agricultural Laboratory (SCAL) of the University of Nebraska-Lincoln, located at Clay Center, NE. The analysis of the soil texture, particle density, and bulk density of the site, where the center pivot is located, is shown in Table 1 according to laboratory analysis [22].

Table 1: Soil parameters used in the experiments.

Depth	Texture	Sand	Silt	Clay
0-20cm	Silt Loam	17	55	28
20-60cm	Silt Clay Loam	16	46	38

Part. density	Bulk density	$VWC_{exp.A,B}$	$VWC_{exp.C}$
$2.66g/cm^3$	$1.3g/cm^3$	22.7%	16.6%

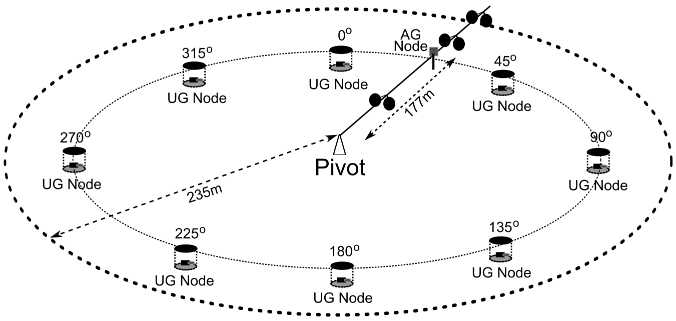


Figure 3: Testbed for the experiments: An aboveground (AG) node is installed on the center pivot and 8 underground (UG) nodes are buried along its path.

As shown in Fig. 3, the experiment involves one aboveground node (AG node) installed on the center pivot's structure, which is located on a corn field. The height of the AG node from the soil is 2.5m. The UG nodes are installed at the gaps between the roots of the corn. The mentioned gaps are about 10cm below the level of the corn. Therefore, the $35cm$-burial depth used in the experiments corresponds to the depth of 40cm when the soil is plowed.

3.1 Hardware Architecture

In the experiments, a special antenna scheme is used: a Full-Wave (FW) antenna for the AG node and a Single Ended Elliptical Antenna (SEA) for the UG nodes [12]. The FW antenna is a commercial magnetic 433MHz, full-wave (FW), 3dBi-gain antenna, and it is shown in Figs. 4. In Fig. 4(a), the FW antenna attached to the Mica2 mote is shown. In Fig. 4(b), both mote and antenna are properly encapsulated. This encapsulation is critical because the AG node is exposed to irrigation water. The final installation of the AG node is shown in Fig. 4(c).

A customized ultra wideband single ended elliptical antenna (SEA) [9] is used in the UG node, as shown in Fig. 4. The antenna dimensions are illustrated in Fig. 4(d) [12]. In Fig. 4(e), a Mica2 mote attached to a SEA is shown. The SEA antenna is placed in the vertical position, with its minor ellipsis pointing in the direction of the center pivot (before its passage). This orientation favors a larger communication range before the passage of the center pivot compared to the range after its passage. The advantages of this antenna orientation will be explained in Section 4.

3.2 Communication Module

For the experiments, a TinyOS 1.1x application is developed to enable carrying out several experiments without reprogramming the sensor nodes and without the use of cables connecting the sender-receiver pair of nodes. Transmit power level of +10dBm is used for all experiments. Due to the long distances between the UG nodes, it is not possible to have more than one UG node communicating with the AG node at the same time. The software is developed considering the concept of *transaction* and it is modeled according to a modified version of the Virtual Finite State Machine (VFSM) [19]. In Fig. 5, a simplified VSFM diagram for the application is shown, where the UG node can have the states 0, 1, ..., 8 and the AG node the states 0, 11, ..., 18. The

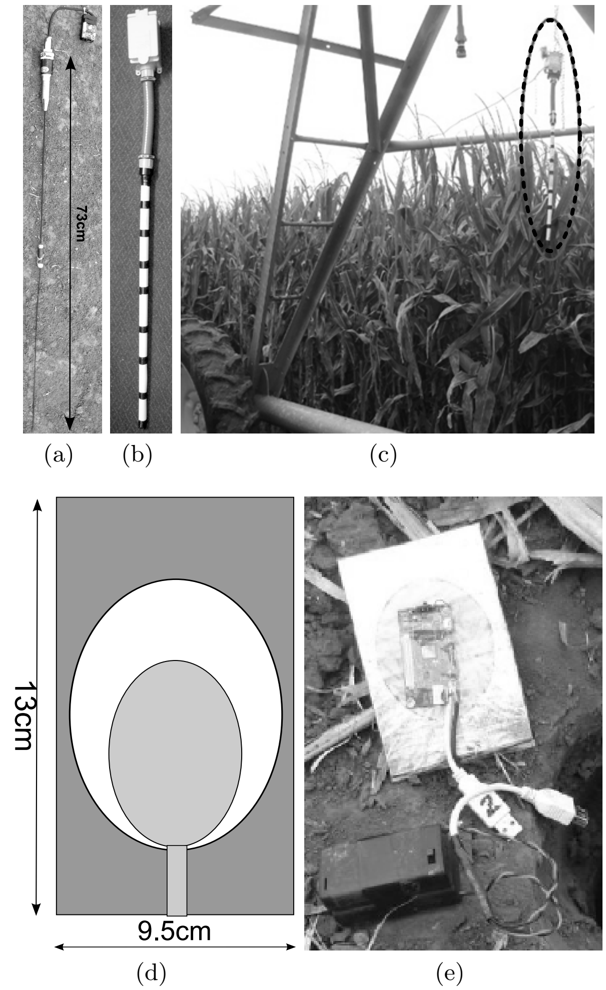


Figure 4: Antenna used at the aboveground (AG) and underground (UG) nodes: (a) 433MHz full-wave (FW) magnetic antenna attached to a Mica2 mote, (b) FW antenna in its final encapsulation, (c) final installation of the AG node (2.5m-height); (d) Single ended elliptical antenna (SEA) [9], (e) 433MHz Mica2 mote with the SEA antenna near a 50cm-depth hole.

UG node continuously sends HELLO messages (state 2) to find the AG node. If the AG node responds (state 12), a *transaction* is initiated and the AG node sends 100 packets to the UG node (states 3 and 13). The size of each packet is 37 bytes and a 100 ms delay between each packet transmission is configured. The UG node evaluates the quality of the communication in terms of packet error rate (PER) and received signal strength (RSS) for each packet. A summary containing the PER, the maximum RSS, the minimum RSS, and the average RSS for that transaction is sent to the AG node (states 4 and 14) .

The second part of the transaction starts when the UG node sends the sequence of 100 packets to the AG node (states 6 and 15) and similar steps are repeated. When a transaction is completely finished according to the mentioned steps, its status is recorded as *successful*. On the other hand, if some steps are not realized and timeouts oc-

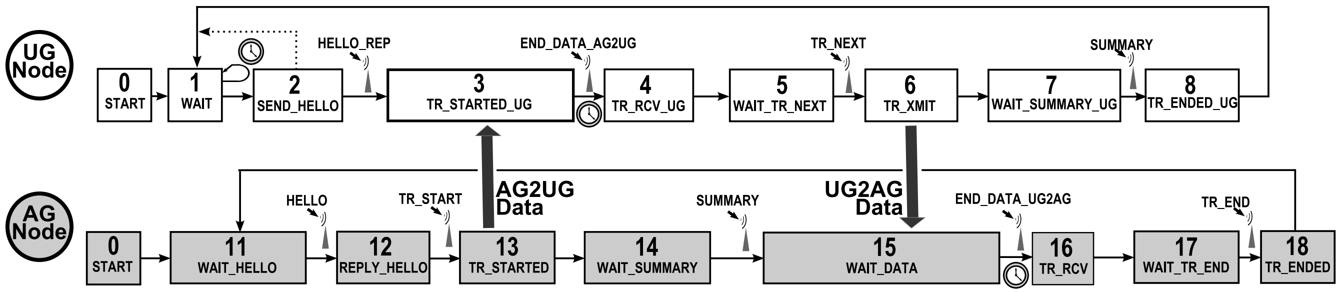


Figure 5: Virtual Finite State Machine (VFSM) for the transaction-based application developed for the experiments.

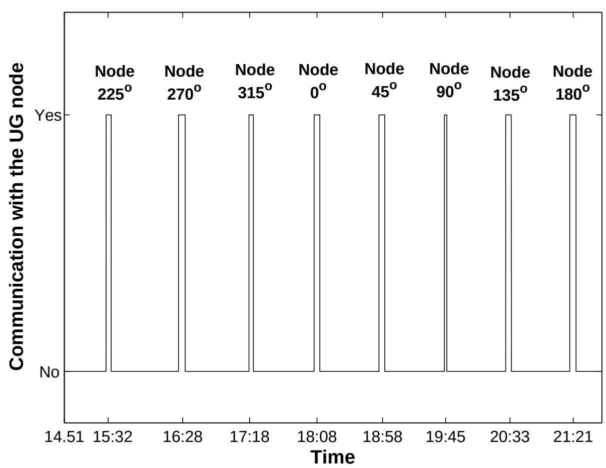


Figure 6: Timeline for a complete travel of the center pivot. Only 7.4% of the total time is being used for communication with the UG nodes.

cur, the transaction is recorded as *incomplete* and the reason is also recorded. After finishing the first transaction, the same process is repeated until the communication range reaches its limit. Both AG and UG nodes record the summaries into the Flash memory for future retrieval of the experiment results. All transactions are time-stamped with a global clock reference given by the AG node. Based on the time-stamp and the travel speed of the pivot, it is possible to determine the physical position of the AG node at any transaction. The measured total location error for an entire pivot travel is found to be 2.28m. Therefore, for each node location an error of +/- 29cm must be considered.

3.3 Experiment Procedure

To prevent the effects of significant differences related to the transceiver/antenna of each individual Mica2 node, *qualification tests* have been performed before each experiment [13]. Accordingly, *through-the-air* tests, which consists of 200 packets of 30 bytes, are performed to (1) determine compliant nodes and (2) confirm that the battery level of a node is above a safe limit. A node is labeled compliant with a given set of nodes if (1) its PER varies within 10% of the average PER calculated for the set of nodes and (2) its RSS average varies, at maximum, +/- 1 dB from the average RSS for the set of nodes. The safe limit for the battery level has been determined as 2.5V.

Three different experiments are realized with different conditions of soil moisture and vegetation canopy, as listed below. To avoid the effects of additional factors, the same nodes are used. For these experiments, the horizontal internode distance between the AG and UG nodes is 3m. Also, the AG node is installed on the structure of the center pivot, and the UG node is buried (35-cm burial depth) at the position 0^o shown in Fig. 3.

- ***Experiment A***: Realized on December 7, 2009. This experiment is related to the UG node located at the position 0^o. The corn crop had been harvested and the effects of the vegetation canopy can be neglected. The soil moisture is measured and the volumetric water content (VWC) [5] is found to be 16.6%.

- ***Experiment B***: Realized on September 9, 2009. The experiment is realized at an area of the crop field where no vegetation canopy is present. Therefore, the canopy effect can be neglected. The soil moisture is measured and the VWC is found to be 22.7%.

- ***Experiment C***: The same scenario as the Experiment B, but it is realized inside the corn crop where reached its maximum height, 285cm. Therefore, the wireless communication is performed subject to the effects of the canopy.

If not explicitly stated, any experiment mentioned in this paper is related to Experiment A. The travel speed of center pivot is fixed at 2.78m/min, related to the circumference where the sensors are located. This speed is the maximum speed of the center pivot and represents the most critical scenario for communication due to the smallest available time window.

4. EXPERIMENT RESULTS

In this section, the effects of the inter-node distance between the AG and UG nodes on the UG2AG and AG2UG communication performance are discussed. Also, the effects of the vegetation canopy and the soil moisture on the communication are analyzed.

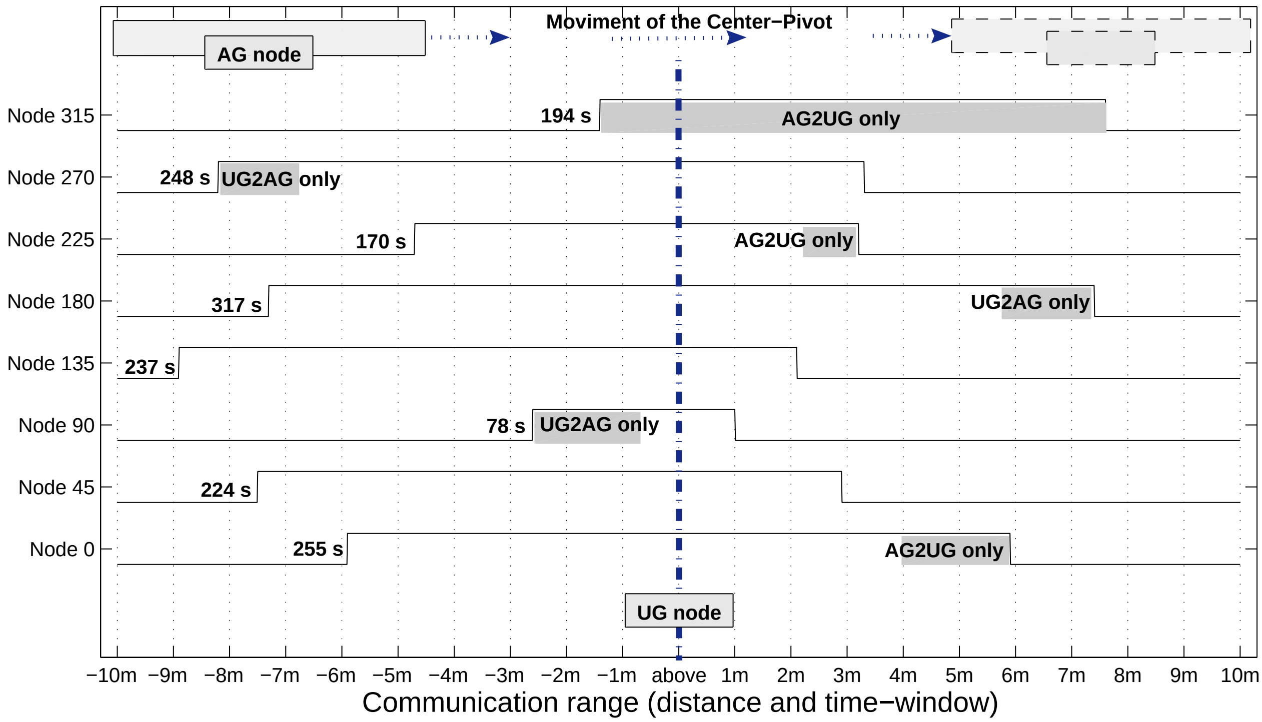


Figure 7: Communication between the AG node, installed on the center pivot, and the UG nodes: range in terms of horizontal inter-node distance and time-window.

4.1 Real-time Operation

To illustrate the effects of the horizontal inter-node distance between the AG and UG nodes on the real-time communication performance, experiments are realized and the results are shown in Fig. 6, where the x-axis represents the timeline for a complete travel of the center pivot and the y-axis shows the success of the communication between the AG and UG nodes. This result highlights the criticality of the communication channel for this application: only 7.4% of the total travel time is available for communication with the UG nodes.

In Fig. 7, the communication range values in terms of horizontal inter-node distance and communication duration are shown as a function of the location of the UG nodes, where each angle is the position denoted in Fig. 3. A negative distance represents the distance of the AG node *before* passing over the UG node and a positive value is related to the distance *after* passing over the UG node. For each location of the UG node, two values are observed: the low value means no communication and the high value represents a *communication window*. For each communication window, the corresponding duration in seconds is also shown. This time-window is related to the opportunity for the CPS to send and receive data to/from the UG node. The gray area in some communication windows indicates an asymmetry in the communication, as also indicated in [12]. In other words, within the gray area, only one link is available: UG2AG or AG2UG link.

As shown in Fig. 7, there is a significant variation in the communication duration. The best range is obtained by the node 180^o, with a symmetric communication that starts 7.3m before the passage of the AG node above the UG node and finishes 5.9m after. In this case, the UG2AG link is available for 1.5m or 32.5s more. On the other hand, the node 315^o cannot finish a bidirectional transaction and only AG2UG communication is possible during a time-window of 194s. Similarly, the node 90^o has a time-window of 32s (10% of that of node 180^o) predominantly used for an unidirectional link (UG2AG). Moreover, in Fig. 7, several gray areas are shown. These areas are observed at the beginning and at the end of the communication window and represent incomplete transactions. As explained in Section 3, a transaction is successful if both UG2AG and AG2UG links are successfully used. Therefore, an incomplete transaction indicates the presence of an unidirectional link as shown by the gray areas in Fig. 7. A high variability of the gray areas as a function of the UG node location is also observed. For instance, all the communication window of the node 315^o is formed by a gray area, that is, the channel is unidirectional all the time for the AG2UG link. The node 90^o has 55% of its communication area formed by a gray area, but, in this case, the unidirectional link is the UG2AG. On the other hand, the node 135^o does not present gray areas.

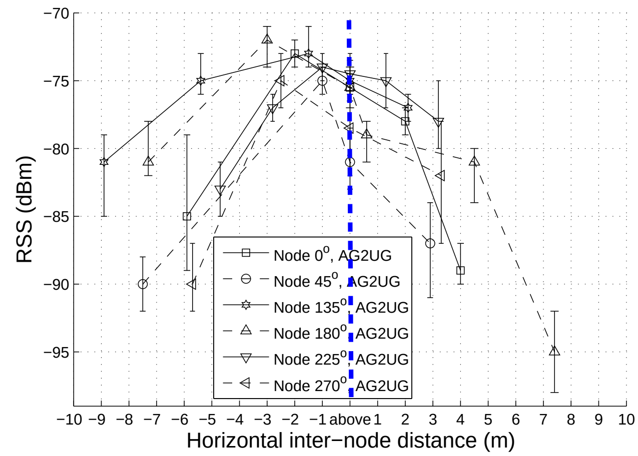
The asymmetry between the UG2AG and AG2UG links agree with our previous empirical results with the same FW/SEA antenna scheme [12]. However, due to the mobility of the AG node, the variation in the communication window is also observed when different locations for the UG node are used, as predicted in our theoretical model [7, 2].

In [12], a special attention was given to the surrounding area where the UG node is buried to avoid soil irregularities or areas with plant roots and/or rocks with significant sizes. However, for the new $(CPS)^2$ experiments reported here, the burying process is done in a real-life crop field without any care related to the location of the UG node. With this procedure, the experiments are closer to the real application scenarios.

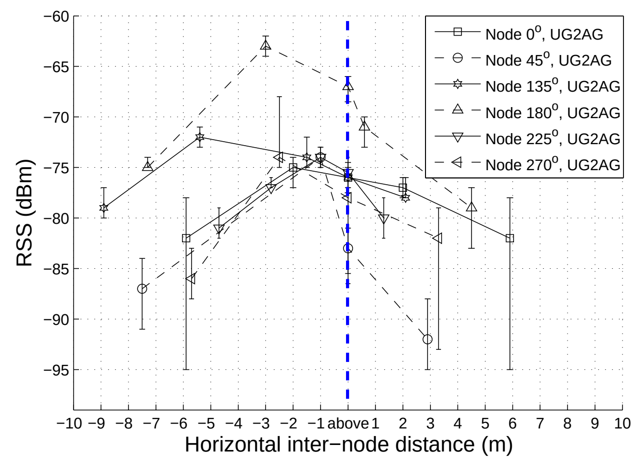
A careful observation of the locations of each UG node reveals that the irregularity of the soil surface is one of the reasons for the spatio-temporal variation observed in Fig. 7. Such irregularity can significantly affect the communication performance due to the dispersion level of the signal, which is reflected/refracted at the soil-air interface. The variations on the soil surface are naturally created by the plowing process and the crop growth. Even the burial depth can be altered depending on how much soil is left above the UG node after the plowing process. Even with a careful installation of the nodes, a change on the soil surface above an UG node can still occur as a result of the activities of the agricultural machinery, which results in a random process. Another potential reason for the mentioned differences of the results is the interference caused by the existence of plant roots and/or rocks in each location where the UG node is buried. In this work, we use the term *soil irregularity* to refer to these impacts.

In Figs. 8(a) and 8(b), the average RSS values for AG2UG and UG2AG links, respectively, are shown as a function of the horizontal inter-node distance for different UG nodes. The PER values for these results are not shown due to the fact that they are below 6.5% in all cases, with the exception of the node 315^o. For clarity, the results of the nodes 90^o and 315^o are also omitted in this figure since these nodes do not present enough empirical data for a non-biased comparison with the other nodes. Comparing the Fig. 8(a) with Fig. 8(b), one can observe that the AG2UG and UG2AG links present similar performance. Moreover, the AG2UG link performs slightly better for positive values of distances, which reaches a higher inter-node distance of 7.4m. Also, it is observed that the distance -1m is the point where both AG2UG and UG2AG links present the maximum and very similar RSS values of -75.3dBm, on the average. It can be observed that on the average, the communication range is 39.2% longer before the UG node than after the UG node. This is important since most of the communication occurs before the CP passes over an UG node to control the amount of water to be applied. These results are expected because, as explained on Section 3, the orientation of the antenna was previously investigated to favor a higher communication range before the passage of the center pivot.

In Figs. 9, the RSS and PER values are shown, respectively, as a function of the location of the UG node. These results are detailed versions of the results shown in Fig. 7. In each figure, the results for both UG2AG and AG2UG links are shown. As shown in Fig. 9(a), in general, the UG2AG links have similar mean and variance in RSS compared to the AG2UG links. It is important to highlight stronger variance of RSS in all cases, varying from 4 to 22dB and with an average of 14.3dB. This result can be explained by the fact that different inter-node distances are considered together and it agrees with our experiments in [12]. However, the range of the RSS values also varies as a function of the UG node's location. For instance, the RSS variations for the nodes 0^o



(a)



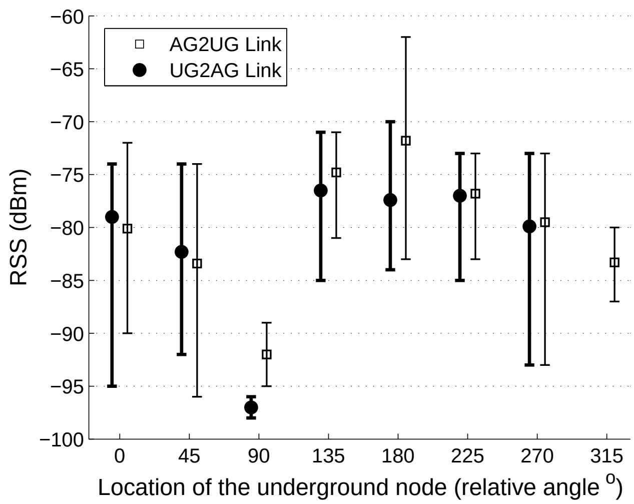
(b)

Figure 8: Effects of the horizontal inter-node distance on RSS: a) AG2UG link, (b) UG2AG link.

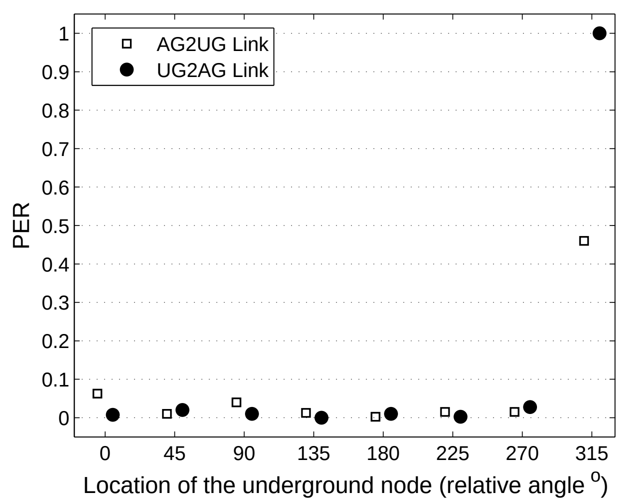
and 225^o are different for both AG2UG and UG2AG links. As observed in Fig. 9(a), the RSS values of the node 0^o varies from -72 to -95dBm and the RSS values for the node 225^o varies from -73 to -85dBm. As already explained, a potential reason for these differences is the irregularity of the soil at the region where the UG nodes are buried.

The high variance in RSS values do not necessarily imply bad channel quality as shown in Fig. 9(b), where both UG2AG and AG2UG links result in PER <6.5%, with the exception of the node 315^o. Based on these results, we observe that besides the high variance of the RSS, the communication channel presents high quality. Moreover, the transitional region [20] is extremely small compared to typical WSN scenarios. As shown in Fig. 9(b), when the link is symmetric (UG2AG and AG2UG links are both operational), a high quality communication is observed. These results agree with previous experiments in [12], provided that the RSS value is not very close to the receiver sensitivity, i.e., RSS >-90dBm for Mica2.

The above results suggest that error detection/correction



(a)



(b)

Figure 9: (a) RSS and (b) PER for different UG node locations.

schemes can be avoided in symmetric regions to save energy and network bandwidth. However, for the small portion of the communication ranges, where the channel is unidirectional (gray areas), a significant increase in errors occur. As observed in Fig. 7, the gray areas in the experiments represent 21.4% of total communication range. In this portion of the communication window, error control schemes are necessary. These results are especially important for the design of communication protocols for WUSNs.

4.2 Effects of Canopy and Soil Moisture

The growth of the crop causes an increase in the vegetation canopy and can affect wireless communication [15]. Also, previous studies show that the soil moisture can affect the communication [1, 11, 14]. In this section, the results of experiments related to these two important aspects are discussed.

As explained in Section 3, 3 experiments are performed.

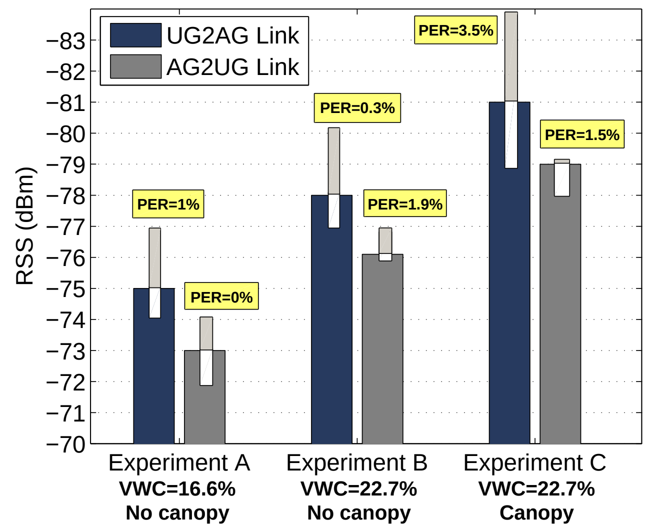


Figure 10: Effects of the vegetation canopy and the volumetric water content (VWC) for a horizontal inter-node distance of 3m.

The experiments B and C are realized with a higher soil moisture than the experiment A. The experiments A and B do not have the effect of the canopy. Hence, intuitively, a smaller signal attenuation is expected to be associated with the experiment A (no canopy effect and a smaller soil moisture effect), followed by the experiment B (soil moisture effect only), and finally the experiment C (canopy and soil moisture effects).

In Fig. 10, these results are presented in terms of RSS and PER values for both AG2UG and UG2AG links. The average RSS, the RSS variance, and the PER values are shown for each experiment. For the horizontal inter-node distance of 3m for all experiments A, B, and C, the PER values are very small, below 5% and no meaningful comparison can be done using the PER values. However, the values of RSS show the expected attenuation differences for the 3 scenarios. As shown in Fig. 10, the experiment A has the results with the smallest signal attenuation because the soil moisture is smaller (16.6%) and the vegetation canopy effects can be neglected. The experiment B is an intermediate scenario, without the canopy effects, but with a higher soil moisture (22.7%). Finally, the scenario C is the worst case because both canopy and soil moisture effects are contributing for the signal attenuation.

The attenuation caused by the vegetation canopy can be investigated by comparing the results from the experiments B and C in Fig. 10. For both AG2UG and UG2AG links, this difference is 3dB. This result agrees with previous studies [6, 15] and it is important for the development of a $(CPS)^2$. As the crop grows, the signal attenuation slightly increases due to the canopy effects and the overall $(CPS)^2$ must dynamically react. One possibility is to have the CP command the UG nodes to increase their transmit power levels.

The attenuation caused by the variation in the soil moisture can be investigated comparing the results from the experiments A and B in Fig. 10. The volumetric water content (VWC) of the soil varies from 16.6% (experiment A) to 22.7% (experiment B). Comparing the results from the experiments A and B, for both AG2UG and UG2AG links, the RSS difference is 3dB. More specifically, the increase of 6.1% in the VWC causes an increase of 3dB in the signal attenuation for the scenario of these experiments.

The soil moisture is one of the most important parameters to be considered in the wireless underground communication. Depending on the length of the soil path which the signal must traverse, the mentioned negative VWC effect is very strong, as demonstrated in our previous experiments [11, 12]. The impact of these results on the $(CPS)^2$ design is also critical. Compared to many environment parameters considered in this work, the VWC can change very quickly. It can occur, for instance, as the result of rainfall or the irrigation realized by the CP. Again, the UG nodes must dynamically change their behavior in the network when the VWC significantly increases or decreases. For instance, the communication can be temporarily suspended to save energy of the UG nodes. Also, it is possible to increase the transmit power level of the UG nodes in order minimize the negative effects of the VWC [11]. The results of the experiments reveal several important challenges for the realization of $(CPS)^2$ as discussed in Section 5.

5. RESEARCH CHALLENGES

In this section, the main design challenges and guidelines for the realization of a $(CPS)^2$ are discussed.

Real-time Operation: Due to the movement of the CP system, the communication availability is significantly limited in $(CPS)^2$. Moreover, the communication range with the UG nodes has a high variability as a function of the location of the UG node. We observed that the irregularity of the soil is a potential cause for this variability. However, this aspect cannot be controlled because the soil is subject to successive plowing and machinery activities. Therefore, stochastic communication tools are required to provide guarantees in communication availabilities as well as minimizing energy consumption of each node. One possible way to minimize the effects of this potential risk is the use of more than one UG node for the same monitored area. In this case, the $(CPS)^2$ will choose the node with the best performance and/or with the best level of remaining energy. Moreover, stochastic scheduling solutions are necessary to improve the lifetime of the $(CPS)^2$. The development of real-time opportunistic protocols that adopt to the environment and seasonal conditions according to real-time communication constraints are required.

Soil Irregularity: As discussed in Section 4, the soil irregularity is an extremely complex parameter to be controlled. Consequently, the $(CPS)^2$ application must be developed considering these random soil effects to treat each node individually and exploit the historical communication performance data of each node. For instance, an UG node which presents good communication performance in one year can have poor communication behavior only because of physical changes of the soil surrounding this node. Moreover, the existence of the mentioned gray areas, i.e., the regions of time and space where the channel is unidirectional, must be efficiently exploited. Due to the small time-window communication, the strategic use of the temporary unidirectional link, if available, is important. Considering the typical small amount of information to be transmitted between the UG and AG nodes, some seconds of an unidirectional channel can still be successfully used by the $(CPS)^2$. The use of historical data and theoretical communication models to forecast the communication channel conditions are also required. A similar approach can also be used for the soil measurements as the spatio-temporal soil measurements correlation becomes evident for the specific field where the $(CPS)^2$ prototype is installed.

Error Control: It is observed that the symmetry of the communication channel within communication windows potentially indicates high quality of communication. If the RSS is not very close to the receiver sensitivity and the channel is symmetric, error detection/correction schemes can be potentially avoided, thus saving network bandwidth and power-consuming resources. However, if the channel is unidirectional, error detection/correction schemes are highly recommended.

Soil Moisture: The soil moisture strongly affects the communication performance. The environment can potentially change the characteristics of the communication channel, for instance, due to the rainfall or after an artificial irrigation. The application data, the soil moisture measurement, can be also used by the low-level network protocols, to adapt the communication channel to the environment. This cross-layer approach can be optimized with the real-time control performed by a $(CPS)^2$. For instance, the $(CPS)^2$ can command the UG node to temporarily increase its transmit power level when the soil moisture is above a certain limit.

Energy-efficient Operation: A low-power solution for the UG nodes must be developed for $(CPS)^2$. To provide a lifetime of more than 3 years for the UG nodes, some additional aspects not covered in our work must be addressed. Due to the long periods of inactivity - weeks to months - of the irrigations system, a mechanism to put the UG nodes into *hibernation* mode is necessary. In this mode, the UG node must have a very small power consumption, such as $\leq$ 0.5mW. Moreover, depending on the PA application, smaller communication windows can be allowed and smaller transmit power levels can be used.

6. CONCLUSION

In this work, we propose a novel cyber-physical system (CPS) through the integration of center pivot systems with wireless underground sensor networks, i.e., $(CPS)^2$, for precision agriculture (PA). The two main components of the $(CPS)^2$ is the center-pivot (CP) system, a popular and efficient irrigation solution, and the WUSNs, a recent extension of the WSNs to the underground environment. As a proof-of-concept, empirical experiments with these components, CP and WUSN, are provided. The experiments are realized in a real-life corn field and many challenges related to this novel integration are discussed. Based on the results of our experiments, a set of guidelines is provided for the development of an efficient $(CPS)^2$. To the best of our knowledge, this is the first work that provides insight to the integration of a PA irrigation solution and WUSNs.

Through empirical analysis, we show that an efficient PA solution is feasible using commodity wireless sensor nodes. However, such solution also requires an intelligent control for providing the balance between efficient PA decisions and a low energy solution for the underground nodes. Due to the criticality of real-time communication constraints, the realization of $(CPS)^2$ depends on several research challenges, as discussed in the paper.

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