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Variable Rate Applications in Decision Agriculture

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Chapter 13
Variable Rate Applications in Decision Agriculture

Abstract In this chapter, the variable rate applications (VRA) are presented for the field of decision agriculture. The characteristics of VRA control systems are described along with control hardware. Di erent types of VRA systems are discussed (e.g., liquid VRA systems and dry VRA systems). A case study is also explored in this regard. Moreover, recent advances and future trends are also outlined. Accordingly, a sustainable variable-rate irrigation scheduling is studied where di erent hardware and software component of the cyber-physical system are considered. Finally, chapter is concluded with a novel sensor deployment methodology.

13.1 Introduction

Precision agriculture can be considered as a menu of numerous management techniques from which farmer can select one or multiple technologies, e.g., one farmer can choose variable-rate application (VRA) for nitrogen application and other can use VRA for application of all fertilizers. Irrespective of the chosen technology, PA can be view as a cyclic approach (see Fig. 13.1) which involves collecting data, developing plan to manage the farms, implementing those plans and finally evaluating those plans [38, 42]. VRA is one of the most popular PA method for adjustable application of fertilizer and chemicals for crop protection. Early VRA systems consist of adjusting flow rate through adjusting the speed of applicator [12] and provided a starting point for VRA systems.

13.2 Properties of VRA control systems

Fig. 13.3 shows a complex schematic of a VRA system. A typical VRA system includes data interpenetration, devising management plans, determining application rate and vehicle related task for application. It is important to note that not all VRA

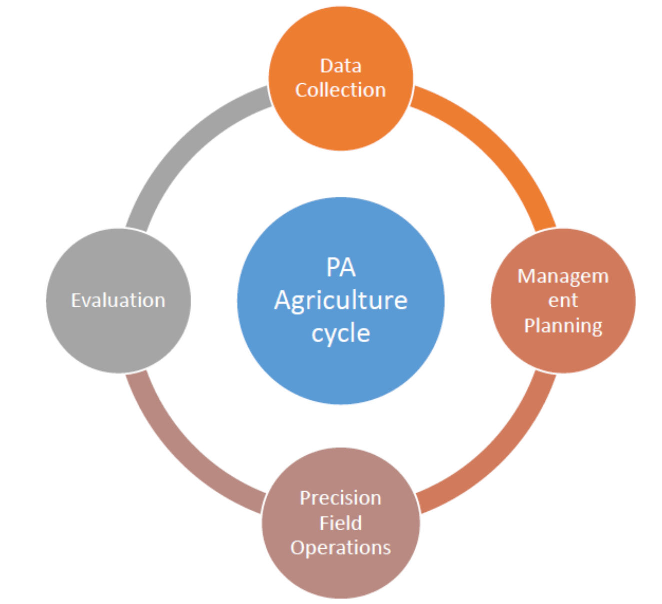


Fig. 13.1: The precision agriculture cycle

Table 13.1: Comparison of Sensor-based and Map-based systems [18]

Sensor Based Systems	**Map-Based Systems**
Human intervention is eliminated for data collection	Non-real data can be used
Reduced spatial interpolation errors with dense sensor data	Required amount is known before calculation
Suitable for applications with high temporal variability (soil nitrate level)	Gives more time between application and data collection allowing for intensive processing and analysis

system consist of all the elements shown in Fig. 13.3. Similarly, some VRA system may have functionalities of multiple elements combined into one.

Control decision for VRA system can be applied using map-based (also known as offline) or Sensor-based approach (also known as online). Sensor-based approach sense the data and use it immediately in real-time for automatic control. Map-based operation can be divided into two phases: Phase one includes gathering and storing the data and phase 2 includes the usage of information by controlled equipment

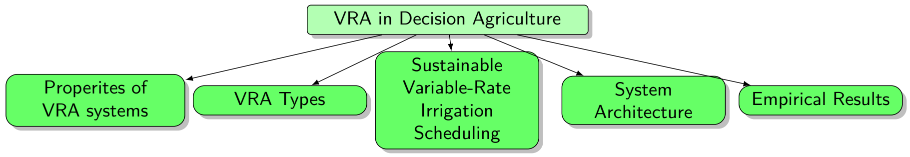


Fig. 13.2: Organization of the Chapter

in a separate field operation [25, 54]. Although, Map-based systems are popular now-a-days, however, real-time sensing systems are becoming mature and it is possible that sensor-based VRA may takeover in the future. Hybrid Systems consisting both of the technologies may also become popular. Benefits of both Map-based and Sensor-based systems are given in Table. 13.1.

Map-based technologies can use the historical agricultural and soil data collected from di erent states or region. However, this technique is often questioned because it is widely established that crop response may vary from site to site and sometimes it even changes within the field [19]. Therefore, integrated decision support systems (DSS) can be used with the combination of expert knowledge and data from di erent sources.

Sensing based technologies uses sensors on the applicator vehicle and determine the application rate. Most widely used sensing based technology is crop canopy reflectance sensing for the assessment and application of nitrogen. Various sensing technologies have been used for detection, identification and quantification fo weeds as an input to VRA systems. Other online senors, e.g., Soil Electrical Conductivity (EC_a) is also used to develop offline control maps fro VRA nematicide [39].

13.2.1 Control hardware

Following hardware enables the operation of a VRA system:

- *Application rate processor.* Application rate processor and the associated software is the core part of a VRA system. It combines the speed, position, and sensed data with the application rate map, and issues the rate command to application rate controller.
- *Application controller.* It receives the instruction from the application rate processor and controls the actuators on the applicator based on those commands. It compares the desired application rate with actual application rate and adjust the control signal based on the error rate to minimize the rate. This is a closed-loop control operation [27].
- *Operator interface.* It is a very important part of VRA system. An e ective operator interface must quickly communicate the complex and continuously changing information to the driver. This requirement comes important especially

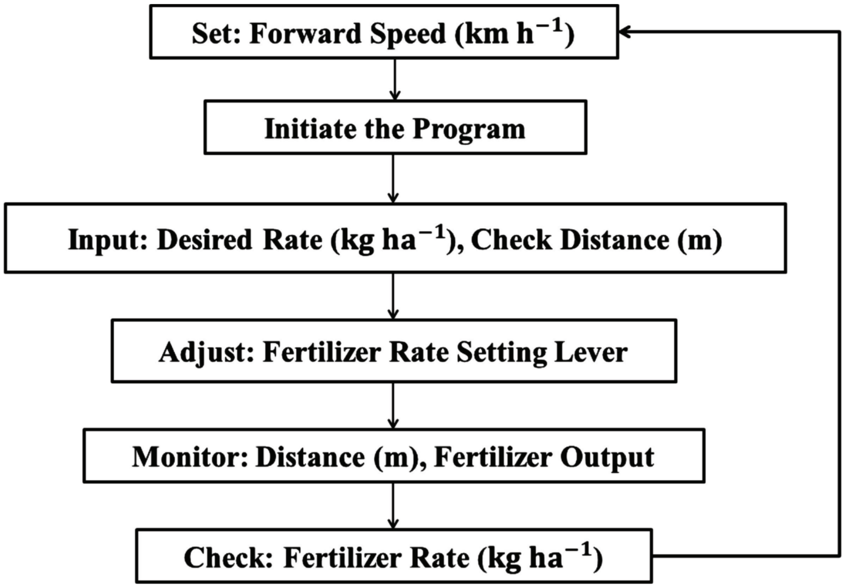


Fig. 13.3: A generalized schematic of data flow in VRA system [4]

when the VRA system is being used in multiple area simultaneously. It must allow the operator to dynamically change the operating parameters, fix any detected fault and override the default parameters. The information can be provided in the form of readable, audible audio alarms, and graphical interface. Similarly, data can be entered using touchscreen [36].
Some systems also combines the all or multiple components (application rate processor, operator interface, or application controller) into one box and connect them with sensor and actuator [33].

- *Equipment actuators and sensors.* Most of the equipment works on the hydraulic and electric motors. Liquid fertilizers are pumped through hose and dry fertilizers from a holding tank. Application controller controls the delivery rate by taking the input signal from the actuator motor speed. In some cases, delivery rate can also be controlled by adjusting the size of flow passage.
- *Documentation of application: as-applied maps.* The application rates maps generated by the VRA systems can be logged with time, distance intervals, GPS position and current rates reported by the controller. This documentation can be used to keep record what and how much of it was applied, check compliance with environmental regularities for chemical and fertilizer application [20, 30].

13.3 Types of VRA Systems

In this section, two di erent types of VRA systems are explained.

13.3.1 Liquid VRA systems

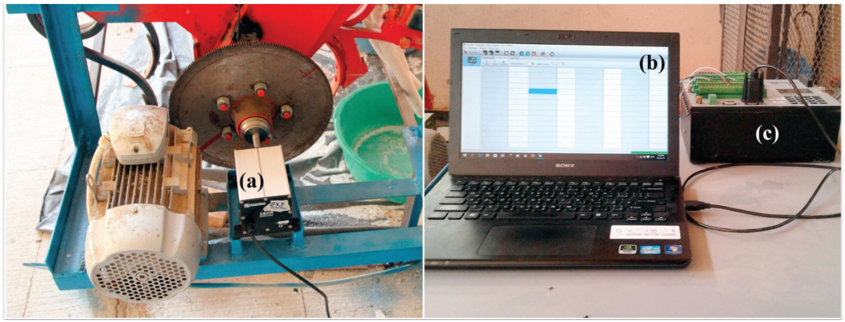
This section discuss following liquid-based VRA systems.

- *Flow Control Methods.* There are two ways of controlling flow for VRA. One includes varying the concentration of an active ingredient (a.i) and is known as *Variable Concentration Method*. Second method includes varying the whole solution, i.e., a.i + carrier solution and is known as *Total Output Control Method*. A comparative study of both method is given in [15, 34].
  Historically, total output method is implemented by controlling the pressure at the nozzle which then transformed to electronic spray providing closed-loop flow control using pressure and flow sensors and sometime ground speed sensor to compensate for variations in travel speed.
  Variable Concentration Method were first reported in mid-70s [15, 46, 50] and [69] tested a laboratory system for injecting concentrated pesticides. However, disadvantage of such is system include a non-uniform application of pesticides and frequent transient error due to operating speed.
- *Section Control.* Section control method involves division of applicator into multiple sections and maintaining the input for each individual section through application rate processor. This gives much more independence and control over regions within the field. The primary goal of the method is to avoid 1) overlapping application in irregular shape of the area and 2) spraying on the non-target area, e.g., grassed waterway. This method provide good spatial resolution of control, therefore, resulted in 15-17% reduction in spray [21, 65]. However, it may result in large variations from desired application rate while turning nozzle on and o [44, 58].

13.3.2 Dry VRA systems

This section discuss following liquid-based VRA systems.

- *Flow Control Methods.* There are two ways of controlling flow for VRA. One includes varying the concentration of an active ingredient (a.i) and is known as *Variable Concentration Method*. Second method includes varying the whole solution, i.e., a.i + carrier solution and is known as *Total Output Control Method*. A comparative study of both method is given in [15, 71].
  Historically, total output method is implemented by controlling the pressure at the nozzle which then transformed to electronic spray providing closed-loop flow



(a)

Fig. 13.4: VRA Case Study of a variable rate granular fertilizer [4]: (a) The shaft encoder, (b) Software program and (c) Data Logger

control using pressure and flow sensors and sometime ground speed sensor to compensate for variations in travel speed.
Variable Concentration Method were first reported in mid-70s [15] and [35, 69] tested a laboratory system for injecting concentrated pesticides. However, disadvantage of such is system include a non-uniform application of pesticides and frequent transient error due to operating speed.

- *Spinner Spreaders.* They use spinning disc to spread the dry granular fertilizer (dropped on the disc) in the wide area. They are not used for banded operation and are mostly used for the broadcast application. They relatively cover large per unit area as compared to other VRA systems and are suitable for the application where large volume of application is required. These VRA systems are commonly used in the application of fertilizers and pH balancing products during harvesting and planting season [28, 45, 53, 72].

13.3.3 A Case Study

A conventional spray application uses a huge amount of pesticides in horticultural crop production system to e ectively control the pesticides. This problem was solved by an automated sprayer shown in Fig. 13.4(a). It uses sensor technology to apply pesticides as per the crop needs and requirements. The sprayer uses the size and shape, presence and foliage density of target area to apply the optimum amount of pesticide that too with minimum human involvement. It consist of the following components: a laser scanning sensor, a travel speed and nozzle flow control sensor, a touch screen, an embedded computer, 40-variable rate nozzles and a switch box. It significantly reduced the over-spray of pesticides while benefiting the environmental ecosystem and saving time by fewer refill [48, 55].

A system is developed by modifying a commercial self-propelled sprayer (Spra-Coupe 3640, Melroe Co., Bismarck, ND, USA). It has following design requirement: 1) Fast rate change, integrated sensing and associated algorithm for online N-rate determination and application and 3) ability of using offline data. Moreover, system uses a flow feedback system which changes the application rate based on pressure of the nozzle to achieve high turn-down ration. System is controlled by a Visual Basic program. This system has hugely evolved by including advanced sensors and efficient algorithms for in-season VRA application. it is being used by many research projects and is involved in many on-farm research projects [47, 49].

13.4 Sustainable Variable-Rate Irrigation Scheduling

Increasing food demand has given rise to popularity of new generation farming technique: Precision Agriculture (PA). The main focus of PA techniques are the variable amount of natural components (nutrients, water content, drainage, runo , chemical leaching, and soil components) present in the field [11, 13]. The main purpose of PA is to accurately analyze the field variations using modern day technologies such as GPS, aerial & remote sensing, satellites and sensors. As a result the farming methods (irrigation and fertilizer management, sowing) can be scheduled and applied autonomously [31, 45].

The success of PA-based farming systems depends upon the e ective real-time evaluation of field which is then used to make timely decisions. For example, it is important to have complete knowledge of *quantity* and *time* of applying water in Irrigation scheduling. A successful irrigation management demands accurate monitoring of water status for the field under observation. In order to obtain optimum crop yield, water in the crop root-zone must be maintained at a certain desirable level. A good and accurate irrigation management systems can help in avoiding financial losses which otherwise may occur because of over- or under-irrigation, pesticides, nutrients movement, and other water bodies etc. Hand-feel method is the qualitative method and soil sensor is the quantitative method for estimating soil moisture levels. If there is no cost-e ective soil moisture sensor available, then hand-feel method is used for irrigation management purposes. However, hand-feel method rely on the person ability of feeling and perceiving the soil. This method is prone to human-error and can sometimes be less accurate causing financial loss. Therefore, a quantitative method is needed for reporting soil moisture status for accurate irrigation management [17, 24, 46].

A proper irrigation management is needed to decide the timing and quantity of irrigation to mitigate the farmers loss which may occur due to water stress. An accurate irrigation can result in increased yield response to other management technologies. The farmers profitability is increased by adopting these practices. Other advantages of proper irrigation management includes: reduced runo , soil erosion and pesticides in surface and ground water. To summarize, combination of a irrigation management systems and in-situ water monitoring through sensors has great advantage over unmanaged system in that it can prevent water wastage while increasing crop yield [16].

Traditional soil sensing techniques involves installation of sensor at the start of season and are needs to be removed before harvesting begins. These techniques are not considered e ective for real time in-situ soil sensing in PA. To deal with this situation, Wireless Underground Sensor Networks (WUSNs) have become popular recently for such unattended soil monitoring [1, 5, 28, 53, 59, 60, 66]. WUSN can be considered as the wireless network of underground sensors nodes communicating through soil. A WUSN-based cyber-physical system (CPS) can be considered as an efficient solution for the PA which provides detailed soil information in timely manner [25, 32, 57]. WUSN proved to be better than satellites and aerial remote sensing because of their cost-efficient methodology of providing accurate information. Another advantage of WUSN is that they do not interfere with the farming operations (planting process and machinery operations) while deployment which is a significant improvement over the wired networks which are frequently installed/removed while planting process..

This chapter discuss a Wireless Underground Sensor-Aided Center Pivot (WUSA-CP) irrigation system. This system is an application of cyber physical system and presented here as a proof-of-concept. This application uses a center pivot system [22, 26, 35]. Center pivot system is a physical system that move through the field and collect soil moisture data from the sensors buried in the ground. To that end, some of the challenges faced in implementation of such irrigation system are presented. An important challenge is the di erence between underground (UG) channel and aboveground (AG) channel as communication in UG channel is e ected by the soil properties. A WUSN channel model is analyzed and two antenna designs are evaluated for verification of the model and WUSA-CP. Moreover, analysis for burstiness of the packet error rate and range of communication is also analyzed.

13.4.1 Central Pivot System

Cost-efficient and productive methods are constantly being developed in an e ort to improve the agricultural crop yield. To that end, irrigation with center pivot (CP) system [11, 22] is being used to efficiently use and apply water to the fields. Fig.13.5 shows the di erent components of CPS system. It consist of segmented pipes with sprinklers mounted on the wheels [3, 11, 22, 37, 40]. The pipe is connected to a pivot which is placed at the center of the irrigation field and is known as pivot point. The water is sprayed through sprinklers as the machine moves in circular pattern.

A well managed CP irrigation systems di er from traditional surface irrigation systems in that they reduces surface runo and deep percolation, and requires less water application (e.g., up to 40%). Saving water makes more water available for crop transpiration while increasing the productivity of the crop. Using chemigation [11, 41, 42], CP irrigation system can also apply the nutrient to crop canopy. Chemigation, in contrast to ground application, enhances the absorption of nutrients,

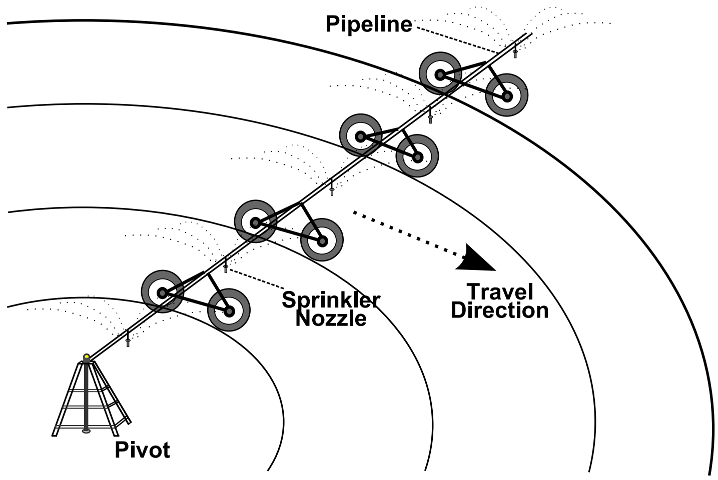


Fig. 13.5: Center Pivot System (CPS) [9]

fertilizers, herbicide, pesticide and insecticides by the crop leaves which consequently increases the productivity of applied chemical and nutrients.

CP cost prevents it t be used in small irrigation areas and is used in larger areas of 3.5 - 65 ha [11, 22, 27, 30]. A testbed of 22 ha is developed at the South Central Agricultural Laboratory (SCAL) for experimentation to analyze CP system.

CP water application can be controlled by either 1) controlling its traveling speed, or 2) electronically controlling the application rate of sprinklers. First method is preferred because of its simplicity, accuracy and low-cost as there is no requirement to change sprinklers. For a given flow rate, high speed of CP applies less water to the field. Furthermore, water applied through CP system can be adjusted by reading the real-time soil moisture data from the field through soil moisture.

WUSN can be used for failure detection in CP irrigation systems. Normally it takes tome to detect the failure in the system which can cause sprinkler to stop irrigating. One method is to measure the sprinkler rate at discharge point to determine the rate at which water is being discharged. however, this requires very expensive and sophisticated small sized flow meters which is impractical for the real-life implementation. To this end, sensors can be used to generate alert if soil moisture level of a region doesn't rise to a particular level when CP passes through that region. Farmers can use these alerts to mitigate the e ect of reduced irrigation. To that end, an efficient communication system is required for communicating real-time data from UG sensors. Next section discuss the one such option for implementing communication infrastructure [54].

Table 13.2: Characteristics of soil used in the experiments [9]

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

Particle density	Bulk density
2.66 g/cm^3	1.3

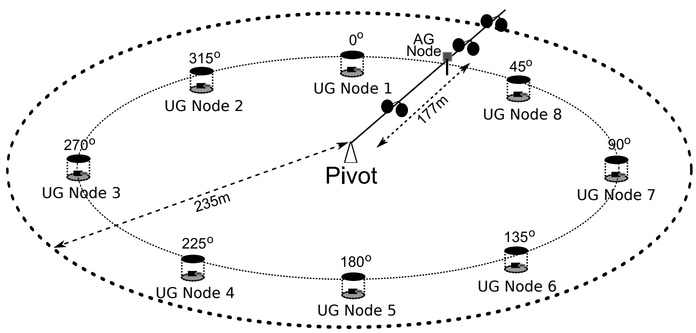


Fig. 13.6: CPS Testbed with one central AG node and eight buried UG nodes [9]

13.5 System Architecture

Experiments are conducted at South Central Agricultural Laboratory (SCAL), Clay Center, Nebraska, using 433 MHz Mica2 [2] sensor nodes. The purpose of the experiment is to provide proof-of-concept of autonomous irrigation system and investigate the associated challenges. Table 13.2 shows the data (bulk density, particle density and soil texture) of the site, gathered from laboratory analysis, where center pivot is located [29].

Fig. 13.6 shows the experiment setup for central pivot irrigation system in the corn field. AG node is deployed on the system's arm at 2.5m along with UG nodes buried at the depth of 35cm in circular arrangement around the field. This depth keeps the UG nodes safe from farming machinery. For AG and UG nodes communication, CP has to be within communication range. CP operates in both clockwise and counter clockwise direction.

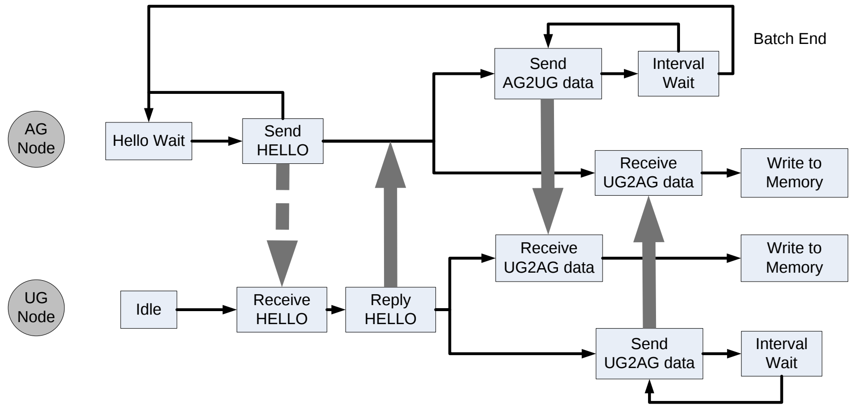


Fig. 13.7: The program structure for the experiments [9]

13.5.1 Hardware Architecture

Soil decreases the signal strength (attenuation) and wavelength of the signal [17, 24]. Phase shifting constant β in equation is related to wavelength λ as: $\lambda = 2\,\pi/\beta$. This relation between λ and soil properties requires an antenna designed specifically to underground communication. the e ective soil permittivity ϵ define phase shifting constant β and attenuation constant α. It is highly e ected by the di erent soil properties such as soil type, soil structure and moisture, and salinity. Peplinski model this property for the frequency range of 0.3 - 1.3 GHz [12]. The operating frequency of Mica2 nodes is 433 MHz. Maximum and minimum values for VWC of site is observed for the experimental site. Given this frequency and VWC values, UG antenna works between 30-69cm wavelength. The frequency range for free space is 1-1.8 GHz. Therefore, operation frequency of an underground antenna must be in the range fo 1 - 1.8 GHz in order to communicate with Mica2 nodes in air. AG node uses the antennas with high-gain [33].

Two di erent schemes are used for both AG and UG node. In first scheme, AG node uses Full-Wave (FW) dipole antenna and UG node uses Ended Elliptical Antenna (SEA) [14, 17]. The gain for the dipole antenna is 3 dB. In second scheme, AG node uses Yagi antenna and UG node uses a circular planar antenna. The gain for the Yagi antenna is 3 dB. The operational range of SEA and circular planar antenna is customized as per the application requirement.

13.5.2 Software Architecture

In order to avoid the reprogramming of the sensor node for every experiment, an application, TinyOS was developed and all experiments were performed with the transmit power of 10 dBm. Each transaction involves transmission of 100 packets, with 100 ms interval between each packet, in both direction (UG-AG nodes and AG-UG nodes). Size of each test packet is 37 bytes.

Fig 13.7 shows the program structure. UG and AG nodes send and receives packet from each other. For each received packet, UG node extract the timestamp, id of the AG node which sent the packet, and RSS of the signal, and stores it in the flash memory. Similarly, for each packet received by AG node, it extract the timestamp using its own clock, id of the UG node which sent the packet, and RSS of the signal, and stores it in the flash memory. Experiment data is read from the flash memory of each node. An important thing to note is that timestamp of only AG node is used for the experiment. As the speed of the CP is very slow (0.704m/min), hence, all 100 packets can considered to be sent from same location. Therefore, the timestamp is used to determine the location of AG node [72].

13.6 Empirical Results

The di erence between the antenna and transceiver of each Mica2 node is significant, therefore, a qualification test is performed before every experiment [18]. For this purpose, a *through-the-air* test with 200 packets of 30 bytes are sent. The test identifies the complaint nodes and check if the battery level of a node is above the safe threshold. A node will be considered compliant if it satisfies the two conditions: 1) node's packet error rate (PER) is within the 10% of average PER calculated for all nodes, and 2) the node's RSS varies ± 1 dB from average RSS of all nodes. The safety threshold for battery level is set as 2.5V.

A total of five di erent experiments were performed. Each experiment considered di erent soil moisture conditions and vegetation canopy as given below:

- **Static-Dry:** For this experiment, CP was not used and corn field was used with VWC[6] of 16.6%. As the crops were recently harvested , therefore, impact of vegetation canopy can be neglected.
- **Static-Wet:** For this experiment, corn field was used with VWC of 22.7%. As field was wet, therefore, no vegetation canopy was there.
- **CP-Crop-SEA-Vert:** For this experiment, CP was used and corn field was used with VWC of 22.7%. In this case, the crops reached their maximum height of 2.85m, hence, wireless communication had impact of vegetation canopy can be neglected. SEA and FW antennas were used for the experiment and vertical placement of SEA.
- **CP-Crop-SEA-Hori:** For this experiment, corn field was used with VWC of 32% and SEA antenna was placed horizontally.
- **CP-Circular-Yagi:** Second antenna scheme, with Yagi and circular planar antenna, was used for this experiment. Experiments were considered right after

Table 13.3: Channel model parameters [9]

	node	η^*	$\mathcal{K}^*$	MSE
CP-Crop-SEA-Hori (UG2AG)	**Approaching**			
	2	4.67	34.27	2.32
	5	4.21	29.52	5.94
	7	2.68	48.11	1.33
	Departing			
	2	4.05	29.7	1.52
	5	5.25	34.19	3.70
	7	3.30	47.42	1.51
CP-Crop-SEA-Hori (AG2UG)	**Approaching**			
	2	5.11	23.87	1:54
	5	4.48	24.43	5.94
	7	3.15	44.38	3.10
	Departing			
	2	3.53	31.52	2.03
	5	5.58	27.35	3.57
	7	3.84	42.43	4.47
CP-Circular-Yagi (UG2AG)	1	5.10	72.06	4.69
	3	4.91	60.65	3.22
CP-Circular-Yagi (UG2AG)	1	5.62	73.02	4.60
	3	5.34	63.91	3.34

harvesting with horizontal placement of circular planar antenna and VWC of 32%.

First two experiments were used to analyze how soil moisture e ect the communication. Last three experiments were used CP arrangement similar to shown in Fig. 13.6. In order to observe the worst-case scenario, the maximum speed of CP was used, i.e., $43°$ / hr.

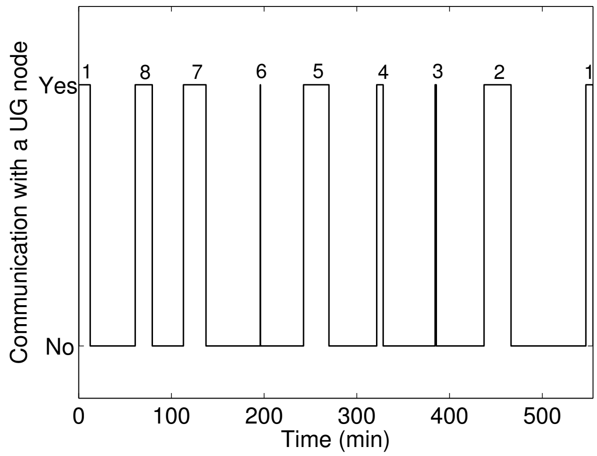


Fig. 13.8: Travel timeline for CP-Crop-SEA-Hori experiment in clockwise direction [9]

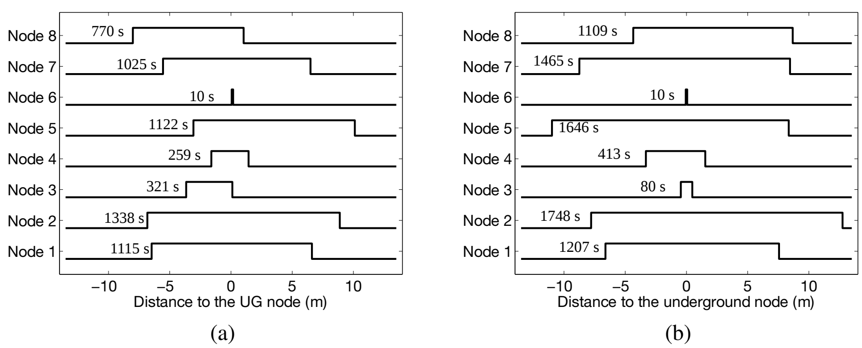


Fig. 13.9: AG and UG node communication in both clockwise and anti-clockwise direction for CP-Crop-SEA-Hori experiment [9]

This section discuss the experiment results to provide proof-of-concept for autonomous irrigation system. It also discuss the e ect of distance between the sending and receiving on UG2AG and AG2UG communication link.

Table 13.4: Comparison theoretical model computations and measured results [7]

	node	η^*	$\mathcal{K}^*$	**MSE**
CP-Crop-SEA-Hori (UG2AG)	3.16	40.78	5.41	48.59
CP-Crop-SEA-Hori (AG2UG)	3.29	38.46	5.84	55.50
CP-Circular (UG2AG)	5.01	66.36	7.24	48.59
CP-Circular (AG2UG)	5.48	68.47	6.33	55.50

13.6.1 Communication Range

A communication window is defined as the time duration in which AG and UG nodes communicate with each other and is analyzed first. Fig. 13.8 shows the results from CP-Crop-SEA-Hori experiment. With traveling speed of $43°$, CPS travel the complete field in 8.37 hrs. It can be observed in Fig. 13.8 that nodes communicate for 1.33 hrs and which is 16% of total traveling time. Communication time also varies significantly with longest time being 29 minutes and shortest is 10 seconds only.

Figs. 13.9 shows the communication windows for each of the AG and UG node in experiment. For UG node, communication range is shown as horizontal distance and time of AG node while moving. AG approaching UG is indicated by negative distance and positive distance represent AG moving away from UG node [50].

It can be observed that communication window varies significantly. In Fig. 13.9(b), best case scenario occurs when node 2 communicates for a total of 20.6m by starting the communication when AG node is 7.8m away from UG node and continues the communication 12.8m after the AG node has passed the UG node. Similarly a worst case scenario is just 0.5% of best case and occurs when node 6 communicates for only 0.11m. The average communication distance in Fig. 13.9(a) and Fig. 13.9(b) is 8.75m and 11.27m with standard deviation of $\delta_{CCW} = 5.73$ and $\delta_{CW} = 8.19$, respectively.

For both cases, CCW and CW, the communication distances are quite similar which shows that communication quality is independent of the CP movement and related to specific location. The variations could be because of irregular soil surface which may occur due to farming activities (e.g., plowing) on the ground a ecting the EM waves dispersion. Even if the nodes are installed carefully, the soil surface above the UG nodes can change because of working of agricultural machinery. UG nodes are buried so that AG node can be right above them. This deployment may result in some nodes (e.g., node 2) being close to crop canopy and some being farther (e.g., node 7). The irregularity can also be seen in the results since crops hinders the EM waves propagation. The phenomena is known as canopy e ect and empirically analyzed in coming sections.

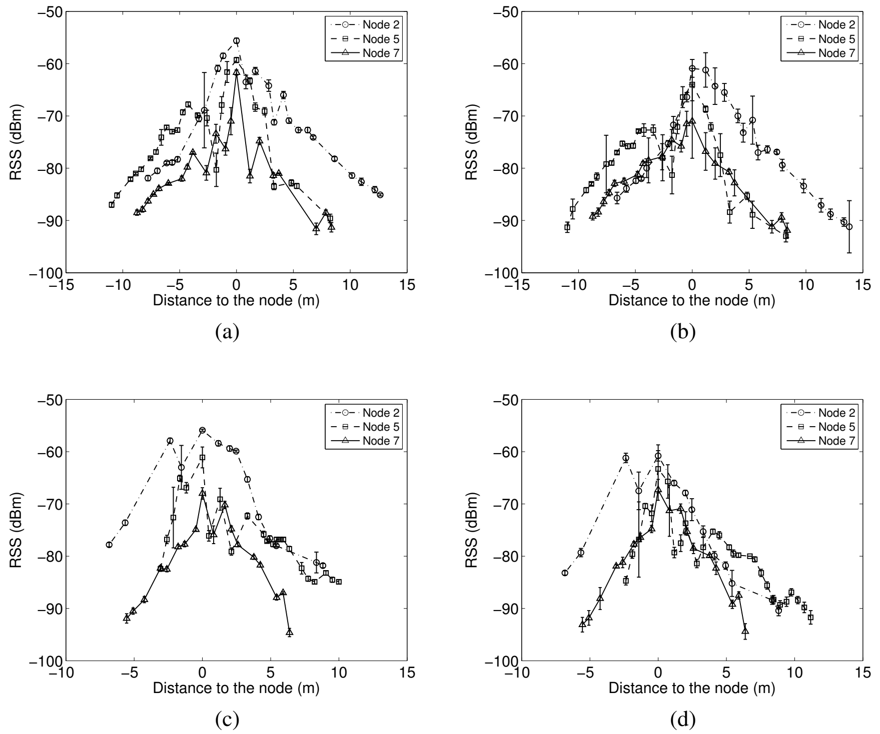
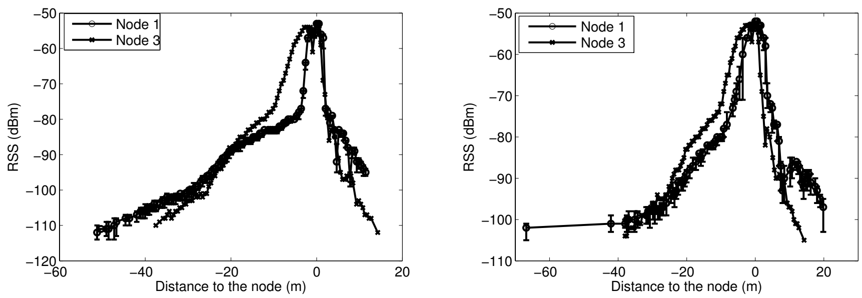


Fig. 13.10: RSS v/s Horizontal inter-node distance using SEA & FW antennas [9]: (a) AG2UG-Clockwise, (b) UG2AG-Clockwise, (c) AG2UG-Anticlockwise, (d) UG2AG-Anticlockwise

Figs. 13.10 plots the RSS results from CP-Crop-SEA-Hori experiment for AG2UG and UG2AG link. Figs. 13.10(a) and 13.10(c) shows results for AG2UG link in CW and CCW direction, respectively. Similarly, Figs. 13.10(b) and 13.10(d) shows results for UG2AG link in CW and CCW direction, respectively. Figs. 13.11(a) and 13.11(b) plots the RSS results from CP-Circular-Yagi experiment. for AG2UG and UG2AG link, respectively [43].

The Yagi and circular planar antenna pair achieves a maximum of 65m communication range and that of FW and SEA antenna pair achieves maximum of 14m communication range. Hence, the Yagi and circular planar relatively increases the communication range by 364-400%. In worst case scenario the communication range for Yagi-circular pair is 40m and that of SEA-FW pair is 8m. This high di erence is because of two facts: 1) The return loss of planar antenna (-10dB) is less than that of SEA antenna (-3dB) in UG deployment, and 2) the antenna gain of Yagi is also higher. The communication distance for Yagi-circular pair is also not symmetrical



(a) (b)

Fig. 13.11: RSS v/s Horizontal inter-node distance using Circular & Yagi antennas [9]: (a) AG2UG, (b) UG2AG

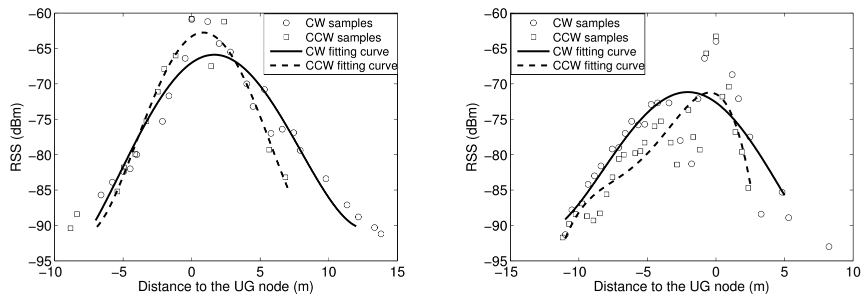
because of directivity of Yagi antenna and asymmetry for circular planar is analyzed in Section 13.6.2

13.6.2 Numerical Analysis of the Channel Model

This section analyze the model developed from the results. Minimum mean square (MMSE) is used empirically calculate the air attenuation η^* and soil-dependent component $\mathcal{K}^*$. [1] $\mathcal{K}$ is compared with the model developed. The values for constant c is 13.57 dB and 3.57 dB for CP-Crop-SEA-Hori and CP-Circular-Yagi experiment, respectively. Table 13.3 and Table 13.4 shows the results for UG2AG and AG2UG links. Model comparison is shown in Table 13.4. $\mathcal{K}$ is calculated from Peplinski model.

It can be observed in Table 13.2 that attenuation model shows the UG2AG and AG2UG link with very low error with max MSE = 5.94. However, large variations can be seen based on location. Attenuation coefficient η varies because of plants and $\mathcal{K}$ varies because of variations in α, β and $L_{R,\rightarrow}$ due to di erent locations. E ective soil permittivity ϵ mainly determines these values. These variation shows how soil characteristics even within the field. It can be observed in Table 13.4 that $\mathcal{K}$ predicted by model is similar to empirical results obtained in CP-Crop-SEA-Hori experiments but its accuracy is limited for CP-Circular-Yagi experiment. Yagi antenna gain G_r becomes dependent on distance with moving CP because of its high directivity. Moreover, the model results are focused for only one point in the field. The error in the values predicted by the model is due to spatial variance in soil. To summarize, the results from the channel model are accurate enough but also underscore the

[1] For rest of the discussion, empirical estimates are represented by * superscript.



(a) (b)

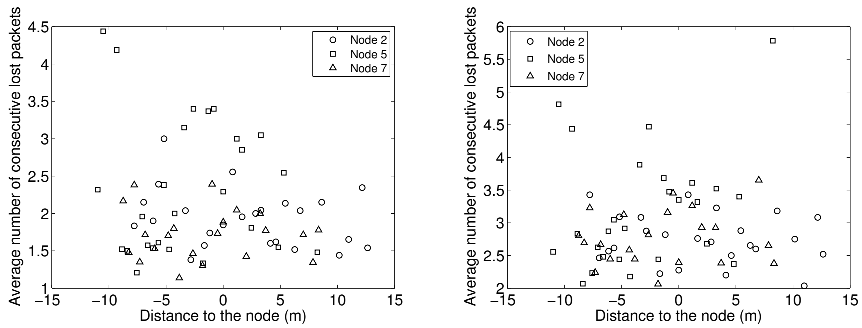
Fig. 13.12: Comparison between communication of two nodes with AG node (UG2AG link) in both directions [9]: (a) Node 2, (b) Node 5

importance of semi-empirical models because of uncertainty due to soil properties [51, 52].

13.6.3 Asymmetry of the Communication over Distance

With same horizontal distance, RSS value changes depending on the fact that AG node is approaching or departing from the UG node. For Yagi-circular pair results in Fig. 13.11(a) and 13.11(b), it happens because of high directivity of Yagi antenna. However, for SEA-FW pair results in Fig. 13.10(a) and 13.10(d) has symmetric propagation pattern, hence, generating symmetric RSS results. Figs. 13.10(c) and 13.10(d) further analyses this phenomenon of SEA-FW pair for UG2Ag and AG2US links, respectively, by experiments while CP is moving in opposite direction A asymmetric communication quality is observed for both AG2UG and UG2AG cases. For example, in Figs. 13.10(c) and 13.10(d), communication between node 5 and AG nodes start 3m before the AG node approaches node 5, however, both keeps on communicating till 11m after AG node departs from the UG node. Furthermore, RSS values can be di erent when absolute distance between AG and UG node is same but side is di erent. For example, for a distance of -5.65m and 5.4m, RSS is -73.6dBm and -78 dBm, respectively in Fig. 13.10(c) (CCW). Similarly, for a distance of -5.65m and 5.4m, RSS is -78.9dBm and -72.7 dBm, respectively in Fig. 13.10(a). A comparison of CW and CCW results is performed to determine the reason for this asymmetry [31, 32].

Figs. 13.12 shows RSS values for UG2AG links of node 2 and 5. it can be observed that node 5 communicates better when CCW direction when Ag is approaching it and, in CW direction, it is better when AG is departing it. Hence, it can be concluded that asymmetry is mainly because of the environment conditions (soil surface and



(a) AG2UG communication (b) UG2AG communication

Fig. 13.13: E ect of distance on average burstiness of packet error in clockwise direction [9]

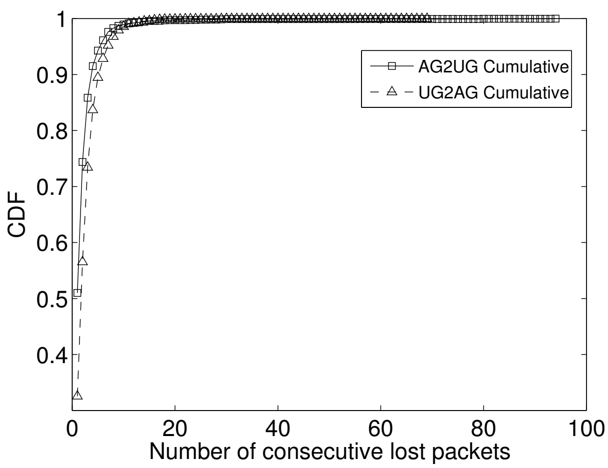


Fig. 13.14: lost packet percentage v/s burstiness of packet error[9]

crops), antenna placement, and asymmetric propagation patterns, rather than the AG node movement[26].

13.6.4 Burstiness of the Packet Error

In an attempt to understand the communication characteristics completely, a CP-Crop-SEA-Hori experiment is performed to understand the burstiness of packet error. This experiments sends a burst of 100 packets after the communication is established between the nodes. The time interval is kept 100ms between each packet within the burst. The number of packet loss between the two successfully received packet is selected as the metric for burstiness of the packet error and average error is shown in Figs. 13.13.

In th figure, average length of the consecutive packet errors is represented by a single point. It is observed that there is no relation between the burstiness of the packet error and the distance which confirms the findings of [17] about the transitional region of UG communication being very small from over-the-air communication. Hence, the error rate is stable while nodes are communicating. Fig. 13.14 shows the distribution of the burstiness of the packet error. It can be observed that with the increase in continuous packet loss, a decrease is seen in probability of high burst error. Both UG2AG and AG2UG observes one packet loss of 33% and 50%, respectively, between two successfully received packets. The maximum size of burst error is 94 packets. Fig. 13.14 concludes that AG2UG communication link performs better than the UG2AG communication with average number of consecutive packet loss of 2.25 which 2.89 in case of UG2AG [40, 41].

13.6.5 Effects of Canopy and Soil Moisture

Wireless communication is highly e ected by the crop growth (increased vegetation canopy) [22] and soil moisture [1, 16]. This section discuss how communication is e ected by these parameters by performing the three experiments explained in Section 13.5, i.e., Static-Dry, Static-Wet, and CP-Crop-SEA-Vert experiments. Only Static-Dry experiment uses dry soil whereas other two uses wet soil. Static-Wet, and CP-Crop-SEA-Vert experiments are performed with and without canopy present whereas Static-Dry experiment without canopy.

Fig. 13.15 shows average RSS, RSS variance and PER for AG2UG and UG2AG links in each experiments. The horizontal inter-node distance is kept at 3m. It is observed that PER values are very small to make any meaningful comparison but RSS values confirms the expected attenuation di erences for all experiments. Static-Dry soil su ers the least attenuation because of least amount of soil moisture (16.6%) and almost no canopy e ect. Second least attenuation is seen in Static-Wet experiment with no canopy e ect but high soil moisture (22.7%). CP-Crop-SEA-Vert is the worst case with most attenuation (6 dB decrease in the RSS) because of soil moisture and canopy e ect contributing towards attenuation [29, 37].

To understand the e ect of vegetation canopy on signal attenuation, the results from CP-Crop-SEA-Vert and Static-Wet are compared. It can be observed that there is an attenuation increase of 3 dB in both AG2UG and UG2AG communication links which confirms the results from [7, 22] and is important for developing environmental-aware networking solutions. Similarly, to understand the e ect of soil moisture on signal attenuation, the results from Static-Dry (VWC = 16.6%) and Static-Wet (VWC = 22.7%) are compared. It can be observed that for an increase of 6.1% in VWC there is an attenuation increase of 3 dB in both AG2UG and UG2AG communication links.

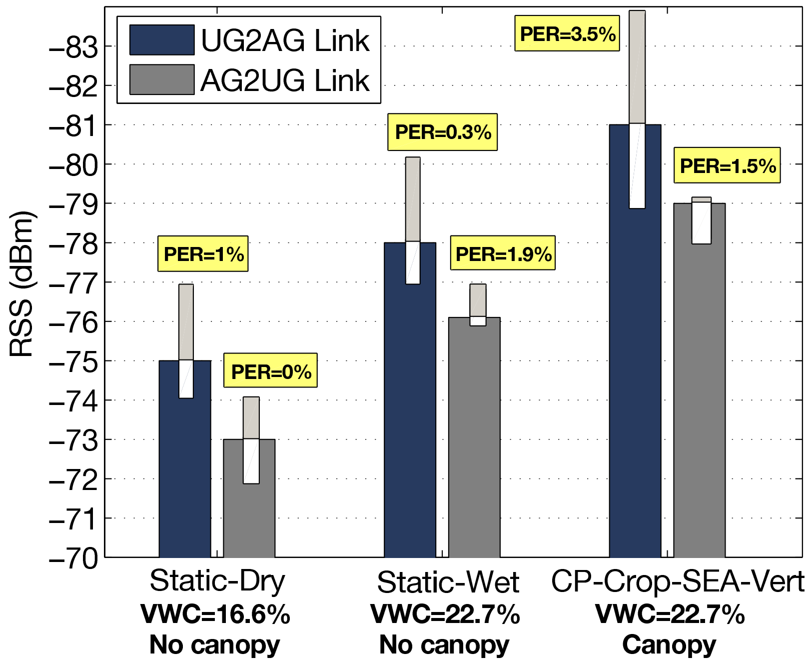


Fig. 13.15: The received signal strength for di erent vegetation canopy and VWC combination

Soil moisture is an important parameter to consider while designing UG communication as it can have negative impact on the signal depending on the soil path that signal may have to traverse. These results play an important role in designing WUSA-CP.

13.6.6 The Impact of Crop Growth on Received Signal Strength

To understand the impacts of the crop growth on communication quality, the received signal strength between an UG and an AG node is recorded for a growing season. The RSS is measured when the center pivot is stopped at the south side of the field, $20\,\mathrm{m}$ away from the UG node buried at the south side .

In Fig. 13.16, the RSS values for both the UG2AG and AG2UG links for the period of June 23rd to Oct. 5th are shown. It can be observed that the growth of the crops, in addition to the soil moisture level, has a strong impact on the communication quality, especially on the AG2UG link. When at the peak of the crop growth ($2.7\,\mathrm{m}$), the RSS value for the AG2UG link is deteriorated by $25\,\mathrm{dB}$ ($-75\,\mathrm{dB}$ to $-100\,\mathrm{dB}$. The RSS values vary during July 21st and July 30th due to the change of soil moisture caused

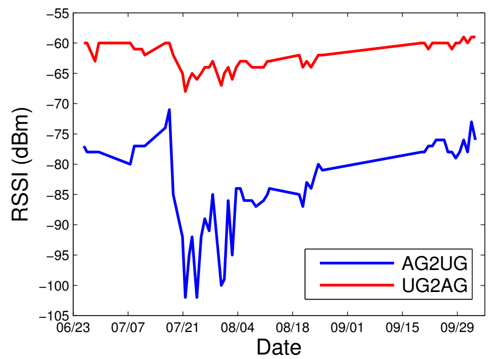


Fig. 13.16: The received signal strength during the growth of the crops.

by precipitation and irrigation. From August 4^{th} to Oct. 5^{th}, the RSS values increase gradually due to the drying of the crops at the end of the growing season.

The result of the RSS over time shows that for the application of WUSNs in agriculture, the impact of the crops growth should be incorporated into communication decisions. As each crop may have di erent growth rates in each growing season, tailored decisions are needed to maintain communication quality high with low energy cost. This impact on RSS call for adaptive transmit power control, which adjusts the transmit power based on the environment factors, such as soil moisture level and the growth of the crops.

13.7 Recent Advances and Future Trends

VRA systems are widely adopted by many farmers. A survey conducted from retail crop input dealers of USA shows that 70% of the customers has acquired some sort of VRA fertilizers application and 27% acquired VRA pesticide application [10]. Many producers implemented the VRA without taking help from their dealers. Producers were more interested in area specific application of fertilizers in a controlled manner because 74% of the dealers reported average of 33% customers interested in GPS-based section control sprayer.

The same survey reported incompatibility (mechanical or electrical/electronics) of PA technology and equipment as a hindrance to adoption on much wider scale. The reason of this could be that many companies o ering the PA services uses their own equipment and data formats for the data. A standard PA data format is needed so that interoperability can be achieved in PA system.

VRA has provided many environmental and economical benefits by minimizing the overall application of fertilizers and pesticides. Environmental benefits of VRA are reviewed by [6]. Several studies reports the economical benefits of VRA application [6, 14, 56]. It is also shown that VRA system with real-time sensing were more popular than the ones based on soil variability. However, [64] reported that if all cost is accounted, VRA systems rarely gives profit but he also reported that advancement in technologies (real-time sensing and DSS) can reduce the cost significantly making VRA a viable option.

Currently, economic and sustainability features of VRA system is challenging aspect for researcher and producer. Development of robust and accurate application algorithm can help in widespread deployment of VRA systems [24].

Future systems will see a significant improvement in terms of accuracy in spatial application of fertilizers and pesticides. Enhanced spatial accuracy can transform VRA systems from section control to independent nozzle control. Advanced equipment design and control systems can be used for accuracy in application rate by reducing error rate.An improved sensing and Decision support system will optimize the future VRAs.

Future VRA systems will use the combination of real-time sensed data, weather forecast and mapped soil information to predict the need of crop. However, issues like interoperability, security, connectivity, and privacy should be resolved to accomplish this.

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