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Investigating signal propagation and strength distribution characteristics of wireless sensor networks in date palm orchards

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ABSTRACT

To efficiently plan and deploy wireless sensor networks in palm orchards, it is crucial to obtain preliminary knowledge of radio signal propagation and strength distribution characteristics. Various received signal strength indicator (RSSI) measurements were taken with antennas, operating with a 2.4-GHz band and located 0.05 m away from trunks. The RSSI measurements, at seven different antenna heights along one certain horizontal line, revealed that there were three distinct signal propagation characteristics resulting from the morphological features of the date palm trees. Compared with other heights, the attenuation rate was lower when the antennas were placed below the crown base due to the relative lack of obstacles in the propagation paths, which also provided good options for installing the antennas. In addition, off-shoots had a slightly negative impact on signal propagation. Comparison analyses showed that the logarithm model was the most accurate and convenient of all the empirical signal attenuation models for predicting low power wireless signal propagation characteristics in date palm orchards. Further measurements were conducted to investigate the received signal strength distribution around individual trunks and between the orchards of different ages. Results indicated that the reliable communication range showed an increasing trend with increasing orchard age. Moreover, the trunks negatively impacted the signal propagation, and the interference strength depended on the position relationship among the trunks, the Tx and Rx antennas. Finally, the specific and detailed references were provided for the planning and deployment of wireless sensor networks in date palm orchards. Concluding remarks address potential future research.

1. Introduction

Advances in wireless sensor networks (WSNs) technology continue to provide new and significant benefits to precision agriculture (Aqeel-ur-Rehman et al., 2014; Ojha et al., 2015). In the past decades, WSNs have been developed and deployed in various crop production applications such as: soil water content sensing (Sun et al., 2014); soil temperature, soil electrical conductivity and video surveillance (Garcia-Sanchez et al., 2011); crop temperature sensing (O'Shaughnessy et al., 2013); automated irrigation management based on the water content and temperature of soil, humidity, temperature, wind speed, and irradiance (Nikolidakis et al., 2015); autonomous closed-loop zone-specific irrigation (Goumopoulos et al., 2014) and valve control (Coates et al., 2013; Dobbs et al., 2014); and frost protection and dew condensation prevention (Park and Park, 2011; Pierce and Elliott, 2008). WSNs have been deployed to improve the quality of some economically valuable crops, e.g., orchards and vineyards (Lloret et al., 2011; Matese et al., 2009). In orchards, WSNs have been used, for example, to monitor sap flow (Losilla et al., 2007), as well as the maximum daily trunk shrinkage signal intensity (Puerto et al., 2013) in almond tree trunks for regulated deficit irrigation.

Since date palms are an important commercial crop cultivated widely in semi-arid and arid regions (Sperling, 2013), in the past few years, great efforts have been made to investigate the relationships between irrigation water, tree growth, frond elongation, and fruit size and quality (Cohen and Glasner, 2015; Sperling et al., 2012; Tripler et al., 2012). In order to effectively monitor the conditions and take actions at appropriate times, more and more sensors are being installed in fields, such as tensiometers, sensors of soil water content/electrical conductivity/temperature, frond

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elongation, sap flow and fruit size, and irrigation control valves (Sperling et al., 2015). To efficiently collect and deliver data in palm orchards, WSNs are a good option (Ojha et al., 2015). However, the key issues in the planning and deployment of WSNs include the ideal location in which to place the sensors so that the target data in the field can be obtained, and the number of sensors required so that the data accuracy meets the application requirements (Dabach et al., 2016, 2015). In addition to adequate spatial sampling of target parameters, reliable communication between sensors should be guaranteed to provide timely and accurate data delivery. Consequently, the reliable inter-node communication is crucial to successfully plan and deploy WSNs. The multiple random media present in real agricultural scenarios can block, scatter, diffract and absorb the WSNs' electromagnetic waves. Therefore, it is essential to identify the effect of vegetation and environment on radio signal propagation, and to ascertain the received signal strength distribution for the planning and deployment of WSNs for any target agricultural environment.

Over the past years, many researchers have been working on these issues and the use of a two-ray ground reflection model (also called a logarithm model because of its expression) to predict signal attenuation (path loss) at WSNs-scale wavelengths in many different agricultural environments. The logarithm model was shown to be suitable for the prediction of 2.4-GHz wireless signal attenuation with multiple antenna heights during the main growth period of wheat fields (Li et al., 2010; Liu et al., 2010; Zhang and Zhang, 2014). Li et al. (2013) investigated the received signal strength distribution of a 433-MHz carrier frequency under different transmitting powers and transmitting signal locations within an orchid greenhouse. Their work demonstrated that there were logarithmic relationships between the received signal attenuation and communication distance even though the orchid greenhouse greatly impacted the signal propagation. Moreover, the logarithm model was found to be capable of predicting the signal attenuation of a 2.4-GHz wireless channel at multiple directions and heights in a greenhouse of green peppers (Li et al., 2014). The signal attenuations of a 900–928-MHz and a 2.4-GHz radio at various distances, heights and vegetative growth stages could be fitted by the logarithm model in apple orchards (Andrade-Sanchez et al., 2007; Guo et al., 2012). The logarithm model offered the highest accuracy of the signal attenuation fitness in a mixed crop environment compared with the other two models (Ndzi et al., 2014). Most importantly, the abovementioned research demonstrated that the wireless signal attenuation of WSNs-scale wavelengths in some agricultural environments can be predicted by the logarithm attenuation model.

Meanwhile, some studies have tried to consider the path loss from ground reflection and the vegetation-induced effect separately. That is to say, the total propagation attenuation is the sum of the path loss in the target environment in which the plants are grown and in the bare field that has the same soil as the target environment. In the past decade, much work has focused on developing complex theoretical analytical models (Anastassiu et al., 2014; Phaebua et al., 2012; Phillips et al., 2013; Ziade et al., 2005). To do this, accurate data of the environmental information regarding electromagnetic wave propagation is required. However, the vector data describing the location, shape, and type of vegetation is difficult to obtain in most applications. As a result, oversimplification of the vegetation medium often occurs. The computational cost of the numerical analysis is rather high (Meng et al., 2009; Vougioukas et al., 2013). Hence, to mitigate these complications, considerable attention has been given to the empirical modeling on the basis of repeated measurements, which predicts signal attenuation as a function of wave frequency and path length through the vegetation, in terms of simple mathematical expressions.

The proposed empirical vegetation–attenuation models include the parametric exponential decay (PED) model, the modified exponential decay (MED) model, the ITU-R (International Telecommunication Union Radiocommunication Sector) model, the fitted ITU-R (FITU-R) model and the COST-235 model (Meng et al., 2010; Phillips et al., 2013; Vougioukas et al., 2013). These models are summarized in Table 2 in Section 2.4. However, subsequent research has revealed that some of the aforementioned vegetation-attenuation models focused on higher power communication networks and were rather specific. Given a certain environment, parameter fitting must be performed (Meng et al., 2009; Ndzi et al., 2014; Vougioukas et al., 2013). Moreover, it is not feasible to measure directly the path loss induced by vegetation. Generally, two options are available for the parameterization of the PED model. One option is that the empirical vegetation–attenuation model, together with the free space model, is applied to fit the measured data within the target vegetation environment. The other is that one additional set of measurements needs to be taken in the bare field that has the same soil as the target vegetation environment to fit the ground reflection model. The empirical vegetation–attenuation model, together with the fitted ground reflection model, is then applied to fit the measured data within the target vegetation environment (Meng et al., 2009; Vougioukas et al., 2013). The second option is most frequently employed when one needs more practical results. As a result, the vegetation–attenuation models often require twice as much measuring and fitting work as the logarithm model to obtain more practical results.

All in all, over many years, these impressive studies have offered many available signal attenuation models, and demonstrated that there are significant differences in attenuation among different operational contexts and physical situations. However, none of them investigated the signal attenuation characteristics in date palm orchards except Meng et al. (2009). However, the goal of Meng et al. (2009) was to examine the effect of lateral waves on the 200–300 MHz radio signal propagation up to several kilometers. The transmit power output was much higher than the power employed in WSNs. The authors did not consider the scenario in which antennas are attached to the trunks. In real scenarios, e.g., date palm farming, it is necessary to attach antennas to the trunks to avoid interference with machinery use because farmers heavily depend on machinery when cultivating date palm trees and harvesting fruits. As a result, trunks could constitute predominant attenuation factors, resulting in distinct signal propagation and coverage over the orchards. Moreover, when antennas are placed closer to the trunks, existent attenuation models may also become inadequate since trunks might have a greater impact on radio signal propagation. Furthermore, date palm trees have some unique characteristics, such as evergreen leaves, large fruit bunches, densely overlapping leaflets and off-shoots, which may contribute to new signal attenuation phenomena. Additionally, it is beneficial for long-term WSNs deployment to understand the signal attenuation differences between the orchards of different ages since date palm trees grow quickly, at the rate of 0.4–0.5 m per year (Cohen and Glasner, 2015). These observations and concerns motivate us to further investigate and evaluate the signal propagation and received signal strength distribution characteristics with antennas attached to the trunks at primary WSN bands in date palm orchards.

The main objective of this study was to evaluate the 2.4 GHz signal propagation and received signal strength distribution characteristics when the antennas were attached to the tree trunks in typical date palm orchards, and more specifically: (1) to investigate the key factors influencing signal propagation at multiple antenna heights; (2) to evaluate the fitness of existing signal attenuation models in the date palm orchards; (3) to analyze the received