Wireless channel path-loss modelling for agricultural and vegetation environments: a survey

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Abstract: This work undertakes an extensive survey of the channel modelling methods and path-loss characterization carried out in agricultural fields and vegetation environments to study the state-of-the-art in this field, which, though vastly explored, still presents extremely diverse opportunities and challenges. The interface for communication between nodes in a typical agricultural field is the wireless channel or air interface, making it imperative to address the impairments that are exclusive to such a communication scenario by studying the characteristics of the medium. The performance of the channel is a direct indicator of the quality of communication. It is required to have a lucid understanding of the channel to ensure quality in transmission of the required information, while simultaneously ensuring maximum capacity by employing limited resources. The impairments that are the very nature of a typical wireless channel are treated in an explicit manner covering the theoretical and mathematical models, analytical aspects and empirical models. Although there are several propagation models characterized for generic indoor and outdoor environments, these cannot be applied to agricultural, vegetation, forest and foliage scenarios due to the various additional factors that are specific to these environments. Owing to the wide variety, size, properties and span of the foliage, it also becomes extremely challenging to develop a generic predictive model for all kinds of crops or vegetation. The survey is categorized into fields containing specific crops, greenhouse environment and forest/foliage scenarios and the key findings are presented.

Keywords: Channel Modelling, agriculture, wireless sensor networks, path loss, propagation models.

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1 Introduction

Agriculture has always played an integral role in the daily fabric of our society and in the sustenance of lives and livelihood of human beings. In the earlier years, agriculture had been the singular source of livelihood support in the society. However, with the advent of the industrial era, primary engagement in agriculture has slowly witnessed a decline. Today, limited availability of large portions of cultivable land, unpredictable and erratic climatic conditions and the increasing pressure on the available natural resources (Jones et al., 2017) are some of the complexities that stakeholders engaging in agriculture find extremely difficult to address. On the other hand, it has also sparked the interest of several researchers around the globe since these complexities have formulated several challenging research problems(Jones et al., 2017). Due to this reason, modelling of agricultural systems is no longer limited to just addressing the productivity or economic rewards, rather, it is being treated with a much larger and world-wide perspective in line with the new UN Sustainable Development Goals (FAO, 2016).

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The field of agriculture can also be seen as a prospective application for the highly upcoming thrust areas of Internet of Things (IoT), Cyber Physical Systems and Wireless Sensor Networks (WSN) (Dumitrache et al., 2017). Cyber Physical Systems in agriculture can gather timely information of the status of the network to accurately indicate the soil moisture content for smart irrigation, to monitor the temperature of the area and the nutrient contents in the soil for the purpose of application of manure and fertilizers, monitoring the growth of the plants to decide on the harvest and so on (Dumitrache et al., 2017). These new areas have proliferated in a big way due to the need for automation in the field of agriculture because of adoption of modern methods to meet the growing demands, counter the alarming problems of water scarcity and climate change (Moreno-Moreno et al. 2018). The primary advantages of using wireless sensor networks for agriculture is the flexibility in deployment, lesser human intervention and therefore lower cost and requirement of labour, longer life of battery since data needs to be sampled at fewer intervals only. Although the notion of using wireless sensor networks to support precision agriculture can be traced back by at least a decade, the field is still in the nascent stage in terms of smart disposition. A lot of research needs to be done prior to deployment in real time scenarios (Sivertsen et al., 2013) to achieve practical targets of yield. Some of the most recent advances in agriculture is the use of unmanned aerial vehicles (UAV) to communicate with nodes deployed in fields for smart farming and precision agriculture (Bacco et al., 2018), implementation of AI and machine learning in agriculture (Treboux et al., 2019), computer vision and robotics in agriculture (Barhate et al., 2019) and to characterise organic communication channels (Roopnarine et al., 2019), just to name a few technological contributions out of the vast literature available.

1.1 Channel Modelling – Concept, classification and application

Channel Modelling is an important functionality at the physical layer of the network model (M.1225, 1997). It deals with the calculation of all the physical processes affecting the signal as it gets transmitted from the sender to the receiver. The primary aim of the task of channel modelling is to understand the way by which the propagation environment degrades and impairs the wireless signals in a manner useful for the design, test and simulation of wireless systems. Designers and researchers employ such channel models to predict and analyse the performance of the systems under realistic and practical conditions and to formulate and evaluate methods for mitigating such impairments.

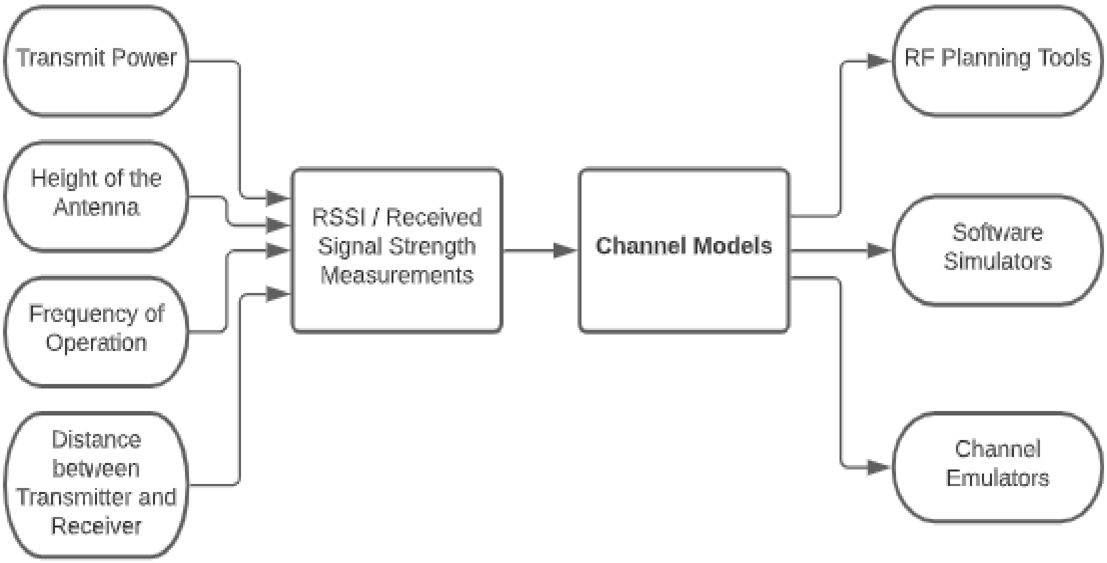

Figure 1 Channel Modelling – A system perspective

Channel models lay the foundation for designing software simulators, channel emulators and Radio Frequency (RF) planning tools. The inputs required for generating a practical channel model is shown in Figure 1. From Figure 1, it can be inferred that the primary parameters that play a decisive role in the channel measurements are the transmit power, height of the antenna, frequency of operation and the distance between the transmitter and receiver. The received signal strength will depend on the channel impairments, from which the channel model can be devised. This can be achieved with the help of RF planning tools, software simulators and channel emulators.

In general, channel modelling is done to address the following three applications. Firstly, performing computer simulations is extremely useful to obtain the optimized location of the base station and other network design parameters which are very tedious to obtain by experimental means. Using these models, the designers can utilise the data so obtained which contains the information of the channel forms that are very often specific to the geographic location. The only caution to be exercised is that the model must be sufficiently stable to avoid or overcome the small errors that may arise due to the variations in the geographic conditions. Secondly, a simple yet efficient channel model, represented in terms of its impulse response parameters, will provide information about the properties that affect the system performance. Thirdly, a summary and analysis of the existing channel model and its characteristics, including the limitations, can also help to refine the channel parameters and thereby helps to develop future channel models (Mao et al., 2010).

There are two broad classifications of channel modelling techniques, namely Empirical Modelling and Deterministic Modelling (Mao et al., 2010). Empirical modelling can be broadly divided into methods based upon stored channel impulse response and stochastic channel modelling. The stored channel impulse response method uses channel sounding to obtain the channel coefficients. Although this method yields measured values that are quite close to the actual values, it only characterizes a small region. As a result, generalization of the obtained model is not possible, and it also requires a lot of memory for processing and storage. The stochastic modelling method aims to overcome the drawbacks of the former by predicting the channel impulse response of a larger environment by predicting a large range of the probability density function. Although this may not help in precise field-based network deployment, it helps to obtain a generic model. Further, the empirical modelling methods are also classified into outdoor and indoor modelling methods. The outdoor model is generated with the help of many experimental measurements and can be considered very alike to the traditional linear model. The main deviation from this similarity is when the measurements are made at increasing antenna heights where the accuracy of the empirical models are seen to be much higher than the measured models. Indoor channel modelling is done using mathematical approach, modelling it as a complex, stochastic and time-varying linear filter (Mao et al., 2010). The indoor environments are usually more restricted in the spread of its terrain and are therefore subjected to predictable multipath interference.

Several approaches for mathematical modelling of multipath propagation environment are available in (Goldsmith, 2005; Rappaport, 2001). Another approach is the statistical modelling where the arrival of the multipath waves (line-of-sight and reflected signals) are modelled as a probabilistic process with a defined distribution. In this method, the performed measurements record the received signals corresponding to the number of distinguishable paths, which in turn, depends on the dimensions of the indoor environment. The deterministic channel model, also called the fixed-point propagation model, uses two methods of modelling – ray tracing techniques (Yang et al., 1998)and finite difference time domain (FDTD) method. Ray-launching or ray tracing is a very common optical model which can give very accurate results. In addition, this method can be employed in a fixed location and can predict the broadband parameters. However, the knowledge of the exact path is seldom available and relatively slow which compels the implementation of pre-processing and simplification prior to the actual implementation. In contrast, the FDTD method (Schuster et al., 1997)involves solving Maxwell's equations, which will provide the accurate spread parameter values of a spatial point and fully contain the effects of radiation, reflection and diffraction. It is extremely accurate, provides the coverage area information and can simultaneously supply the complete data of all locations in the area (Yang et al., 1998; Michelson et al., 2009) Although FDTD is a computationally intensive mathematical method, due to the advantages stated above, it can also be used to validate the results obtained from the other modelling techniques. Much of the literature suggest the use of the log-distance model to characterise the channel since this model considers the effect of vegetation, foliage and other obstacles characteristic of agricultural scenarios through varying values of path loss exponent when modelling the loss (Li et al., 2013; Guo et al. 2015; Guo et al. 2014; Correia et al. 2017; Gao et al. 2018; Zhang et al. 2012; Srisooksai et al. 2019).

1.2 Channel Modelling – Relevance and challenges in agricultural applications

Since the interface for communication between nodes in an agricultural field is the air interface, it is important to have a clear understanding of the nature of the channel to ensure quality in transmission of the data, while simultaneously ensuring maximum capacity by employing limited resources (Mao et al., 2010). The impairments in a typical wireless channel are dealt in an explicit manner covering the mathematical concepts (theoretical models), analytical aspects and experimental models, with separate models characterizing indoor and outdoor environments (Goldsmith, 2005; Rappaport 2001). However, the models previously developed can only be used in a general perspective under very specific conditions and cannot be applied to agricultural scenarios due to the various additional factors that are specific to vegetation, foliage of forest environments.

While modelling channels for agricultural fields, the attenuation due to the presence of vegetation is indispensable. Owing to the wide variety, size, properties and span of the foliage, it also becomes an extremely difficult task to develop a generic predictive model for all kinds of crops or vegetation. For instance, the reference document released by the International Telecommunication Union – Recommendation (ITU-R) dealing with the specific issue of attenuation in vegetation (ITU-R 2016) states that the specific attenuation due to trees containing leaves is about 20% greater than for trees devoid of leaves. The document also states that there can result in a variation in attenuation due to the movement of leaves and branches of the trees due to wind (ITU-R 2016). As much as wireless sensor networks is indispensable in the field of agricultural technology, researchers need to strike a balance and arrive at a trade-off in the experimental and simulation studies in this area. The possibility of executing experimental studies is not always feasible since traditional agricultural fields span several acres. Any number of experimental studies can only provide results that are limited to an area which is a small subset of the vast field. In most cases, it is safe to assume that the modelling of this small area will be representative of the larger field, since the macro-climates rarely vary erratically in a region. However, more minute details like the presence of water content in the soil, nutrient content etc. can change locally. On the other hand, resorting to simulation studies alone can never account for the real time parameters that will affect the agricultural fields (Roccia et al., 2012). Therefore, much of the literature in this domain presents a combination of both experimental and simulation studies.

One main feature of the characterisation of channel models in agricultural environments are with respect to the placement of antenna at the measurement site. By virtue of the proximity of the transmitter and receiver antenna to the surface of the earth, research problems in this domain can be classified under near-ground communications. In the presence of vegetation, the following are the main factors that influence radio-wave propagation when the antenna heights are close to the ground – vegetation, foliage density, moisture, frequency of operation and antenna radiation pattern (Joshi et al., 2005). A typical sensor deployment for vegetation environment is shown in Figure 2. Near ground deployment of sensors is especially significant for agricultural scenarios since it helps avoid using tall unwieldy antenna masts for data measurements. However, the consequence of such a deployment is that the level of attenuation experienced is high due to the proximity of grass and soil. The path-loss due to the near-ground positioning of the antenna can mainly be justified by the concept of Fresnel zones (Klaina et al. 2017; Klaina et al. 2018).

Considering the extent of intricacies involved in the modelling of a channel, it can be stated that channel modelling is indeed a crucial aspect of any wireless system design. The knowledge of the channel characteristics is essential for radio planning, optimum deployment of wireless sensor networks, in terms of the location and the number of nodes (Azpilicueta et al., 2015). Improperly positioned nodes can drastically degrade the channel as the signal may be subjected to severe scattering due to the presence of tree trunks, thick branches and foliage (Kamarudin et al., 2010). In the light of the extensive literature available in this field, the authors opine the necessity for a comprehensive survey of the state-of-the-art in the field of channel modelling in agriculture and vegetation environments. This work, therefore, aims at exploring the state-of-the-art till date in near-earth or near-ground wireless sensor networks especially for the closely related fields of agricultural scenarios and vegetation environment. The authors of this work have, therefore, selected relevant literature in this field pertaining to agricultural/vegetation/forest environment applications and presented the key findings. The study has been categorised under three broad subdivisions – specific crops, greenhouse environment and forested environment - with minor overlaps owing to the nature of the study. However, the authors have been careful to avoid redundancy in the presentation of the data and findings.

2 Survey of channel models in agriculture and vegetation environments

In the context of agricultural fields, several works have individually addressed the analytical and empirical channel measurements for different crops, vegetation and foliage scenarios. When implementing the wireless sensor networks in agricultural field for path loss characterisation, the distance between the transmitting and receiving nodes and the antenna height are two very important and decisive parameters (Kong et al., 2011). The authors have classified the literature under the categories – specific crops, greenhouse environment and forest/foliage scenario - so that a comparative study can be done along some common basis. A summary of the most important parameters is listed in Tables 1, 2 and 3. The parameters specified in the tables are the maximum values that are used by the various authors in the experimental work depending on the conditions of deployment. Some of the parameters chosen are the models used, frequency of operation, transmit power (Pt), antenna height (Ht), distance of separation between the transmitter and receiver (X).

2.1 For specific crops

This section details the main features, experimentation details and findings of the radio channel modelling that is done for specific crops. A wide variety of crops are addressed in this section. Due to the variations in the physical structure of the crops/trees, suitable classifications are made to define the crops. For instance, corn and sugarcane are treated as tall food grass category of crops. Also, the cover of the trees in an orchard has a very different effect on the path loss characteristics.

In (Thelen et al. 2005), the authors perform a measurement campaign to study the radio propagation characteristics in a potato field. The experimental set-up employs 13 nodes devoid of sensors, in a potato field of dimension 154 × 104 m, where the crops are planted along vertical lanes. The nodes are mounted with sensors that measure the temperature, relative humidity and rainwater level. The sensors are placed on the ridges between the lanes and the nodes are placed at a spacing of 3 m with a tolerance of 5 cm. The channel measurements are made during two stages of crop growth – one during the flowering stage and the other during the return stage of the crop, with the measurements being made over a duration of two weeks. The experimentation results show that the maximum distance to achieve reliable communication is smaller than that laid down by the plane earth propagation model when compared for the two crop stages. This reduction in the range can be attributed to the change in the foliage spread over the different growth stage of the potato crop (Yang et al., 1998). The key findings of this paper are that the radio range is restricted to 10 m when the potato crop is flowering and that the radio waves propagate better under high humidity conditions. The authors explain this deviation from the expected behaviour to the change in the reflection coefficient off the top part of the canopy of the potato crop. Also, the value of the obtained path loss exponent was 4, irrespective of the growth stage of the crop.

In (Li et al., 2013), the authors perform an experimental characterization of the radio channel using log normal distribution model in a corn field, at three different stages of plant growth – seedling, heading and grain filling stage, at different heights of the crop growth culminating in the complete growth of the plant. The values of Received Signal Strength Indicator (RSSI) and path loss exponent are measured with experimental set up. The obtained data is studied using data fitting. From their results, the authors obtained the value of path loss exponent as 3.19 in the first stage, 3.25 in the second stage and 3.92 in the third stage, showing an increasing trend in the value of the path loss exponent over the different growth stages of the corn plant. The authors also show that the value of the path loss exponent is inversely proportional to the antenna height variation.

The authors in (Raheemah et al. 2016) perform empirical measurements inside a greenhouse environment for mango plantation to study the effect of each section of the tree on channel characteristics using different values of transceiver heights. They propose a new linear path loss regression curve-fitting model (LRCFM) founded on the regression method of computing the total path loss inside the greenhouse environment. Effects of the vegetation are observed within 1.5 m tree height. The authors also show that the path loss prediction based on the two fundamental path loss models namely the free space path loss and two-ray propagation models is far from accurate in predicting the loss in real time scenarios, especially in greenhouse environment. This is because these approaches overlook the boundary constraints and obstacles that are characteristic of greenhouses.

In (Guo et al., 2015), the authors study the radio propagation characteristics of an apple orchard stating that the vast literature in this domain address only forest and tall tree scenarios. The trees in the orchard, at an approximate height of 3 m, are vertically planted and spaced 3.2 m apart. The authors have carried out the measurements at ten different growth stages of the tree, and therefore, considers the effect of density of the leaves on the tree and the varying size of the fruit as it grows in the duration that the measurement campaign is carried out. The measurement set up consists of a transmitter, 18 nodes acting as receivers, one sink node and a laptop to collect and process the data. The authors introduce a new empirical model using a parameter called LAI (leaf area index), measured using image processing techniques, to study and quantify the effect of the presence of leaves at various stages of the tree growth. They validate the authenticity of the model by showing that the measured data and fitted data are in consensus.

The experimental work (Guo et al. 2014) likes (Guo et al., 2015), in which, the authors have performed the experimentation on apple orchards itself, except that the focus in this work is on young apple orchards of four years of age. Hence, the materials, methodology and the specifications of the experimental set-up in terms of the spacing between the trees, the heights at which the antenna are mounted for measurements, the distance of the receiver nodes from the transmitter are similar as in (Guo et al., 2015). The experiments are carried out in two scenarios – in the orchards and in the open space - to identify the extent of path loss in the presence of trees. The authors conclude that young orchards have lesser influence on the radio propagation as compared to older trees and the presence of trees increase the attenuation in the orchards irrespective of the antenna height. As expected, the coverage range is smaller in the orchards than in open spaces. The propagation distance increases when the antenna height is increased; whereas, in older orchards, the propagation distance first decreased and then increased with increase in the height of the antenna. As a point to note, the authors of this survey would like to point out that the experimental work in (Guo et al., 2015), (Guo et al., 2014) were carried out in 2012, however, the publications are dated as shown in the table.

In the next paper (Correia et al., 2017), the authors have chosen to study the nature of the communication channel to perform the path loss predictions and assess the effects of the signal propagation in a grape vineyard. To study the different propagation mechanisms, the farm area was divided into four areas based on the density of vegetation and the presence of obstacles and scatterers. The experiments were performed in the same farm over many weeks, and it was observed that the main aisle of the plantation favoured the guided signal propagation. At the same time, the presence of vegetation along the secondary aisles compromised the propagation. Measurements were also taken along a diagonal path, with respect to the main aisle, and from the obtained results it was evident that diffraction by the grape vines was the main mechanism of propagation.

In a very recent paper (Cama-Pinto et al., 2019) that has attempted to model the radio propagation characteristics in a greenhouse environment, the authors have proposed a linear and cubic regression model to develop a better estimate of the channel model. They have also done an extensive comparison with existing models like the free-space path loss model, two-ray propagation model, ITU-R,Fitted International Telecommunication Union – Recommendation (FITU-R), Weissberger model and COST 235 model (ITU-R 2016). The authors performed a thorough and extensive comparison of the empirical results they obtained, with the existing models mentioned. They conclude that there is a path loss attenuation due to the presence of vegetation and due to the height of the antennas. The salient feature of this characterisation is that it helps to plan how to deploy the nodes in the tomato greenhouse, in terms of the coverage, connectivity and exact distance between the nodes.

The work in (Srisooksai et al. 2018) considers fundamental concepts of wireless communications (Rappaport, 2001) and addresses small scale characteristics while performing the propagation measurement and modelling in a sugarcane field. The measurements were conducted such that the location of the transmitter was fixed, and the receiver was moved every 5m into the vegetation and over 10-degree angular shifts and measurements were recorded. The salient observation is that the excess loss could be fitted with the Maximum Attenuation (MA) model, in which the model's parameter was observed to be strongly dependent on the angle at which measurements are taken. Then, to represent the excess loss better, the Vegetation Obstruction (VO) model was proposed and accordingly, a prediction procedure was proposed based on the above.

The authors (Gao et al., 2018) have conducted field tests to study the channel characteristics at the three main stages of development of the rice crops, the different transmission distance and varying antenna heights. The experiment was carried out at four antenna heights as per the canopy coverage of the crop. The authors also compared their results with four popularly known wireless channel models and identified the primary factors responsible for path loss characteristics at 2.4 GHz for rice fields.

The authors (Wu et al., 2017), investigate the effects of the different growth stages of the wheat crop on the RF channel, for varying plant heights and heights of the antenna, very similar to the parameters considered in (Gao et al. 2018). The wheat crop has 12 main stages of which the authors choose three significant stages to conduct the path loss study. The parameters studied are RSSI and packet loss rate for the above-mentioned parameters. The coverage range at different antenna heights is also obtained and a regression analysis of the path loss is also carried out. The results are compared with the early ITU model, Weissberger model, COST 235 model and linear logarithmic model using Matlab simulations, and the results are optimally fitted using the parametric exponential decay (OFPED) model.

The authors of (Rizman et al., 2011) have done the measurement and characterisation of oil palm trees and studied the propagation characteristics at 0.9 GHz, 1.8 GHz and 2.3 GHz. The main inferences from the results are that the leaves of the oil palm trees block the propagating signal the most, followed by the fruits and finally the tree trunk. The results showed an exponential attenuation of the propagating signal while transmitting, since the attenuation is proportional to the frequency.

The authors (Vougioukas et al., 2012) studied the radio propagation characteristics in a plum orchard (for the conditions where the trees were with and without leaves) and find that the parametric exponential model is the best fit for the measured data and second best is the Weissberger's exponential decay model. Since the plane earth model does not account for the losses due to the presence of foliage, they combined the plane earth model with other vegetation attenuation models to obtain the best fit. From their results, they also conclude that the path loss values obtained from the ITU-R model clearly overestimates the actual values and therefore can only be considered as an upper bound. The authors in (Zhang et al., 2012) perform the characterisation of the wireless channel for peach tree orchards. From their studies, they infer that the path loss index is inversely proportional to the antenna height at both the frequencies. The authors proposed a modified version of the log-distance path-loss model, where the new model behaviour was governed by two model parameters. The model parameters are instrumental in determining the relation between the received signal and the transmission distance. The model parameter exhibited varying behaviour, becoming inversely proportional to the antenna height at 2.4 GHz and directly proportional to the antenna height at 433 MHz.

In the study on the path loss modelling in a durian orchard (Phaebua et al., 2012), the researchers apply mathematical methods such as the (modified unified geometric theory of diffraction) UTD model and complex source point (CSP) technique to represent the tree trunk and durian fruit while modelling the path loss. In this rigorous analysis, the authors find that the measured results from 4m to 50m match the numerical results quite well. Beyond that, due to the dramatic decrease of the incident and reflected fields, there is a deviation in the results obtained from the numerical and measured results. However, the perfectly electric conductor (PEC) model which the authors use in their model fail to give accurate path loss results in the far field case, due to insufficient field components. This work also does not consider the effect of leaves and trunks because the antennas were placed at much lower heights when compared to the height of the durian trees in the orchard. Even then, the field distribution can be studied even if the arrangement of the trees or the spacing between them is varied. In a slightly older paper (Suwalak et al., 2008), which also perform experimental measurements in a durian orchard, the authors use the simple two-ray propagation model to validate their measurement results. Key findings of this work are presented in Table 1.

The authors (Anastassiu et al., 2014) adopt an analytical approach for the path loss computation in a cherry orchard and compare their results with available models like ITU-R, FITU-R, Free Space Path Loss (FSPL), Fitted Plane Earth (PE), Best Fit Parametric Exponential Decay (BFPED) and Modified Exponential Decay (MED). An analytical model of a cherry orchard was developed using COMSOL Multiphysics (Zimmerman, 2006) software package and the concept of Finite Element Method. The model was developed based on the actual dimensions of the orchard by applying the material properties, geometry of the orchard, modelling the ground as a lossy dielectric slab and considering the estimates of the conductivity, permittivity and permeability of the air, foliage and soil in the model. The model was also developed to consider the scenario of trees with and without leaves. The obtained values from the model were validated using available path loss models. Experimental measurement campaign was carried out at the actual site for the scenario where trees were with and without leaves and the obtained results were compared with the analytical model. The advantage of this analytical model is that it offers a method to deploy WSN in an orchard, without having to carry out extensive field measurements.

The papers (Srisooksai et al., 2019) are path loss measurement related studies carried out by the same group of authors in a jackfruit orchard under exactly similar experimental conditions and the same channel sounding parameters. The authors (Srisooksai et al., 2019) perform the experimental path loss characterisation in the jackfruit orchard and study the influence of the angular direction in which the measurements are made and the number of trees in the line-of-sight path between the transmitter and the receiver. From the results, the authors observe that there is a relation between the above two parameters and infer that the number of trees existing along the line-of-sight path is a significant factor affecting the variation in angular path loss. A modification to the Equivalent Vegetation Obstruction (EVO) model is proposed and the excess loss (loss is addition to the free-space loss) is calculated using the proposed excess loss model.

In addition to the work done in (Srisooksai et al., 2019) the authors study the Rician K-factor and Root Mean Square (RMS) delay spread for vegetation depths lesser than 40 m in the same jackfruit orchard. The choice of vegetation depth to be less than 40m is taken to represent practical wireless networks as applied to smart farming. The Rician K-factor is used to study the small-scale fading behaviour and the RMS delay spread is used to analyse the wideband characteristics. As stated by the authors, however, the results from (Srisooksai et al. 2019) are valid only under the conditions that all the trees in the orchard are of the same age and therefore the same physical stature, the planting of the trees have to be in grid pattern (therefore not applicable in natural forested environments) and that the antenna height has to be lesser than the canopy height of the trees in the orchard and therefore cannot be applied to the initial growth stage of the orchard.

In (Xu et al. 2018), the authors study the propagation characteristics of an orchard environment situated in a hilly terrain by considering various measurement scenarios like line-of-sight and non-line-of-sight propagation paths in a sloping terrain, under sunny and rainy conditions, at 433 MHz and 2.4 GHz. With their measurement results, they propose a new model including path loss factor and rain attenuation factor, analyse the blocking coefficient due to the presence of fruits on the trees and study the effect of rain on the propagation path loss. For experimentation, the height of the antenna is set at 1.5m, with a transmitting power of 0 dBm. The obtained results are fitted with Line of Sight (LOS) and Non Line of Sight (NLOS) empirical fitting curve and the results are found to be in high correlation with each other. This work has not been added in Table 1 since the authors of (Xu et al. 2018) have not specified which fruit orchard has been taken for their study. The knowledge of the fruit/vegetable in the orchard plays a significant role in modelling the path loss since much of the loss characteristics vary according to the properties of the plant type.

In (Dhanavanthan et al., 2013), the authors perform channel measurements for 2 scenarios – crop fields and gardens. Three crops were considered for the measurement (crop details and other specifications are given in Table 1) and the measurements were conducted during the growth stage and maturity stage of the crop. The MSE between the measured data and the existing models was calculated. In corn, it was found that the main contributor of attenuation is the FSPL and reflection from the canopy. For paddy and groundnut, it is primarily due to ground reflection. For coconut gardens, the attenuation is mainly due to diffraction from the thick and irregular surfaced trunks and for open grass/lawn environment, the attenuation is due to surface attenuation by the grass. The authors found different factors prominently contributing to channel attenuation for the different chosen scenarios.

Table 1 Summary of key parameters for specific crops

Ref No.	Year	Crop	Experiment Area	Model used	Parameters (Pt, Ht, X)	Frequency	Key findings
Thelen et al., 2005	2004	Potato	Field (154 m × 105 m potato field)	Not mentioned	Max Pt: 10 dBm, Ht: 11 cm, X: 0.5 m	433 MHz	* Radio range is restricted to 10 m when the potato crop is flowering * Radio waves propagate better under high humidity conditions
Li et al., 2013	2013	Corn	Flat open farmland (100 m × 50 m)	Log normal distribution model	Max Ht: 200 cm, Max X: 100 m	2.4 GHz	* Path loss exponent over the different growth stages of the corn plant. * Path loss exponent is inversely proportional to the antenna height variation.
Peng et al., 2013	2013	Tea	Plantation (50 m × 30 m)	Not applicable	Pt: 0 dB, Ht: 10 cm (near ground), 85 cm (at canopy), max X: 20 m (ground), 50 m (canopy)	2.4 GHz	* Received signal strength decreases with distance. * RSSI decay at ground level is faster due to more reflection, absorption etc than at the canopy. * Channel characteristics mainly depend on height of nodes and not propagation direction.
Dhanavanthan et al., 2013	2013	Corn, Paddy, Groundnut and Coconut	Field & Garden scenario (Separate for each crop)		Pt: 10 dBm, Ht: 1 m (corn), 15 cm (paddy & groundnut), 1 m (coconut) and 2 cm (lawn beneath the coconut)	2.4 GHz	* For crops, the path loss values were lower in the growth stage than in the maturity stage due to the structure of the plants. * As the vegetation depth increases, the path loss increases.
Raheemah et al., 2016	2016	Mango	Greenhouse (50 m × 10 m × 5 m)	Linear path loss Regression Curve-Fitting Model	Pt: 1 mW, Max Ht: 3.5 m, Max X: 21.5 m	2.425 GHz	* Existing large-scale propagation models are inaccurate when implemented to compute the total path loss in greenhouse environments.
Guo et al., 2015	2015	Apple	Orchards (80 m × 30 m)	Log normal model (for fitting)	Pt: 3dBm, Max Ht: 3m, Max X: 57.6 m	2.4 GHz	* Attenuation index increases linearly with LAI for increasing antenna height. * The average value of path loss at various growth stages was seen to increase with the antenna height. * For antenna heights between 1.5 and 2.5 m, the apples had very little effect on the radio propagation.
Guo et al., 2014	2014	Apple (4-year young trees)	Orchard (dimension not specified)	Log normal model (for fitting)	Max Ht: 2.75 m, Max X: 54 m	2.4 GHz	* Young orchards have lesser influence on the radio propagation as compared to older trees and the presence of trees increase the attenuation in the orchards irrespective of the antenna height. * The coverage range is smaller in the orchards than in open spaces. * The propagation distance increases when the antenna height is increased; whereas, in older orchards, the propagation distance first decreased and then increased with increase in the height of the antenna.
Correia et al., 2017	2017	Grapes	Vineyard plantation (10 hectares)	Weissberger Model & Log-distance model	Max Ht: 3 m, Max X: 400 m	2.4 GHz	* The main aisle of the plantation favoured the guided signal propagation. * The presence of vegetation along the secondary aisles compromised the propagation.
Le Vine et al., 1996	1996	Corn and Soybeans	Farmland (Dimensions not	Discrete Scatter Model	Not specified	Maximum value: 10 GHz	* Establishes the relationship between the optical depth of the vegetation and amount of water content

Ref No.	Year	Crop	Experiment Area	Model used	Parameters (Pt, Ht, X)	Frequency	Key findings
			specified)				in the canopy; the relation does not hold if the structure is small compared to the signal wavelength. * The attenuation due to the leaves increases linearly; attenuation due to stalks increase and then level out.
Suwalak et al., 2008	2008	Durian	Garden (Dimensions not specified)	Two-Ray propagation model	Ht: 0.5 m, 1 m, 1.5 m max X: 130 m	5.8 GHz	* Path loss is less than -50 dB for distances greater than 128 m. * Received power increases with distance and at antenna heights of 1m and 1.5m, the received power varies since it is a function of a sinusoidal distribution as per the model.
Cama-Pinto et al., 2019	2019	Tomato	Greenhouse (100 m ×100 m)	Linear and Cubic Regression	Max Ht: 2 m	2.4 GHz	* Attenuation is due to vegetation and the antenna height. * Helps to plan how to deploy the nodes in the tomato greenhouse, in terms of the coverage and exact distance between the nodes.
Srisooksai et al., 2018	2018	Sugarcane	Field (50 m x 40 m)	Ikegami Model, Weibull distribution (for fitting)	Ht: 1.7 m, Max X: 40 m	2.45 GHz	• The relation between the Rician K-factor and its corresponding path loss value for each point was fitted with the log-linear line. • The results of the RMS delay spread are independent of d and number of ridges. So, the Weibull distribution was identified to best fit the data.
Gao et al., 2018	2018	Rice	Field (600 m × 100 m)	FSPL, Two Ray, One Slope log-distance, Modified two-slope log-distance model	Pt: 18 dBm, Max Ht: 2 m, Max X: 490 m	2.4 GHz	* RSSI attenuation decreased with increase in antenna height whereas the transmission range increased with increase in antenna height. * FSPL is not suitable for path loss estimation in rice fields. * Two-ray model is applicable, only if antenna height > 1.2m, because of the dependency of the model on height parameter. * One slope log-distance model was good enough, but did not match the relative error performance of modified two-slope log-distance model.
Wu et al., 2017	2017	Wheat	Field (Dimensions not specified)	Parametric Exponential Decay model (OFPED model), linear logarithmic model	Pt: 0 dBm, Max Ht: 0.6 m, 1 m, 1.2 m (for the 3 chosen stages), Max X: 100 m	433 MHz & 2.4 GHz	* RSSI decreases as the distance between transmitter and receiver nodes increases. * Packet loss rate increases as the distance between transmitter and receiver nodes increases. * Path loss decreases with increasing antenna height. * Under the same test conditions, the path loss at 2.4 GHz was found to be more severe than 433 MHz.
Riz man et al., 2011	2011	Oil Palm Trees	Estate (Dimensions not specified)	Not specified	Pt: 0 dBm, Ht: 1.5 m, Max X: 30 m	0.9 GHz, 1.8 GHz, 2.3 GHz	* Received signal corresponding to 0.9 GHz is much stronger than at 1.8 Hz and 2.3 GHz. * Received signal degraded faster when the number of obstructing trees in the path were lesser. * For increasing frequency, the number of fruits and leaves have a significant effect on the received signal since the size of the obstacle becomes comparable to the wavelength.
Vougioukas et al., 2012	2012	Plum	Orchard (25 m × 120 m hillside)	Parametric exponential model, Weissberg exponential decay model	Pt: 25 mW, Max Ht: 2 m	2.4 GHz	* Plane Earth model was combined with other vegetation attenuation models and the best fit was obtained. * Path loss values obtained from the ITU-R model clearly overestimates the actual values and therefore can be considered to provide an upper bound.

Ref No.	Year	Crop	Experiment Area	Model used	Parameters (Pt, Ht, X)	Frequency	Key findings
Zhang et al., 2012	2012	Peach	Orchard (dimensions not specified)	Log-distance path loss model	Pt: 0.6 dBm, Max Ht: 4.5 m, X: 200 m (for 2.4 GHZ), 370m (for 433 MHZ)	2.4 GHz & 433 MHz	* Initial path loss incurred in 2.4 GHz channel is greater than in 433 MHz. * Influence of antenna height is more in the 433 MHz frequency than in 2.4 GHz and from the results, the optimum height is 3.5m.
Phaebua et al., 2012	2012	Durian	Orchard (dimensions not specified)	UTD model (Weissberger, Chen & Kua models are used for comparison)	Max Ht: 2.2 m, Max X: 80 m	2.45 GHz	* The UTD model effectively represents scattered signals from the trees and ground. It also models the field distribution due to incident, reflected and scattered waves. The advantage of using this mathematical model is that the field distribution can be studied even if the arrangement of the trees or the spacing between them is varied.
Anastassiu et al., 2014	2014	Cherry	Orchard (25 m x 110 m hillside)	FEM based model. (ITU-R, FITU-R, FSPL, Fitted PE, BFPED and MED – for comparison)	Pt: 40 mW (+16 dBm), max Ht: 3 m	2.4 GHz	* FEM solver underestimates the measured attenuation at the middle of the canopy. The discrepancy was more when leaves are present and at longer distances.
Srisooksai et al,. 2019	2019	Jackfruit	Orchard (48 m × 24 m)	EVO model + Excess loss model	Ht: 1.7 m	2.45 GHz	* Uses the Monte-Carlo simulation consisting of the numerical electromagnetic scattering computation called hybrid T -matrix method, reducing the measurements required for the path loss prediction procedure. * Modified Equivalent Vegetation Obstruction (EVO) model is proposed and the excess loss is calculated using the proposed excess loss model.
Srisooksai et al., 2019	2019	Jackfruit	Orchard (48 m × 24 m)	EVO model, Excess loss model, Log linear model and Weibull distribution	Ht: 1.7 m, max X: 40 m	2.45 GHz	* Estimates the Rician K factor and the RMS delay spread using the same approach as in (Cama-Pinto et al. 2019), thereby studying the small scale fading and wideband characteristics for a jackfruit orchard. * RMS delay spread range: 28 to 58 ns.

[Parameters: Transmit power (Pt), Antenna height (Ht), Distance of separation between the transmitter and receiver (X)]

2.2 Greenhouse environment

In addition to conventional farming methodologies, the agricultural sector is also adopting newer and smarter approaches to farming. One such method is the greenhouse farming. The greenhouse is an enclosure made of glass, plastic or a translucent material such that it provides a highly controlled environment which aids optimal plant growth. Such a structure enables equitable distribution of light, optimal heating conditions and control micro-climate parameters under otherwise adverse natural weather conditions to provide an environment suitable for plant growth resulting in increased production (Shamshiri et al., 2018). In (Yang et al., 2017), the authors perform experimental studies at 2.4 GHz to characterise the channel in an agricultural greenhouse structure containing pear, orange and kumquat bonsai trees. The originally measured data cannot be directly considered for characterisation of the path loss model due to high error. The authors introduce a novelty using the concept of Kalman filter to reduce the effect of noise in the measured data and then apply linearity regression to obtain the model parameters. The results show that path loss can be modelled using the log-distance model and the path loss index is 1.55.

In the next paper (Raheemah et al., 2015), which attempts to study the path loss in a mango greenhouse, the authors specifically study the effects of various parts of the tree on the path loss characteristics, where as in (Raheemah et al. 2016) explained in the previous section, the authors attempt to characterise the mango greenhouse environment as a whole and show that existing path loss models are inadequate for the accurate representation of the channel behaviour. In this work, the inference is that the path loss degradation occurs as the height of the transceivers are increased. On the other hand, from a height of 2 m to 3 m, the loss is less since there exists a line-of-sight path between the transmitter and receiver. Therefore, the path loss is maximum where the leaf density is the most, followed by the effects of the tree canopy and the least will be due to tree trunks. In (Wang et al. 2015), the authors study the propagation characteristics in a collection of greenhouses in a manner that the transmitter and receiver nodes are placed in and between the greenhouses. The authors take the channel measurements in two cases: between the greenhouse and within the greenhouse. From their results, they conclude that the path loss model of the radio waves between the plastic greenhouses follow the log-distance model and that the decay index was more than that of free-space. The path loss model for radio waves inside the plastic greenhouse was also obtained, which also satisfied the log-distance path loss model. The attenuation of radio waves observed was small when sensor nodes are in the canopy than when they are located on the ground. The authors therefore conclude that for the deployment of sensor nodes in a tomato greenhouse, the nodes should be deployed in the canopy or above it.

Table 2 Summary of key parameters for greenhouse environment

Ref No.	Year	Greenhouse Specifications	Model used	Parameters (Pt, Ht, X)	Frequency	Key findings
Naseer et al., 2012	2012	3 m x 6 m (A very small set up)	Not mentioned	Ht: 3.5 m	900 MHz	Effects due to motion of the nodes in a small greenhouse environment is studied, by studying the fading and outage effects.
Wang et al., 2015	2015	A collection of greenhouses each of dimension 70 m x 7.6 m (Tomato)	Log-distance model	Ht: 1 m	2.4 GHz	* The path loss model of the radio waves between the plastic greenhouses follows log- distance model and the decay index was more than that of free-space. * The decay of radio waves was slower when sensor nodes are in the canopy than when they are located on the ground.
Raheemah et al. 2015	2015	Dimensions not specified (mango greenhouse)	Free space path loss model (for comparison)	Pt: 0 dBm, Max Ht: 3.5 m	2.425 GHz	Path loss is maximum where density of leaves is the most, followed by the effects of the tree canopy and the least will be due to tree trunks.
Raheemah et al., 2016	2016	50 m x 10 m x 5 m (Mango)	Linear path loss Regression Curve-Fitting Model	Pt: 1 mW, Max Ht: 3.5 m, Max X: 21.5 m	2.425 GHz	Existing large-scale propagation models are inaccurate when implemented to compute the total path loss in greenhouse environments.
Yang et al., 2017	2017	40 m x 24 m (bonsai trees of pear, orange, kumquat)	Log-distance model with Kalman filter for noise reduction	Pt: -17.4 dBm, Ht: 0.5 m	2.4 GHz	* Noise reduction in the measured RSSI values is achieved using Kalman filtering. * The measured data from the greenhouse was best fit as per log-distance model.
Sabri et al., 2018	2018	100 m x 100 m	FSPL, Plane Earth, COST 235, ITU-R, Weissberger (all for comparison)	Pt: 0 dBm, max Ht: 3.5 m, max X: 100 m	2.245 GHz	* Perform a review of some commonly available empirical models.* Total path-loss calculated by vegetation models at same antenna heights at LOS is found to be less than the path-loss calculated at different antenna heights as per the requirements in a real field.
Cama-Pinto et al., 2019	2019	100 m x 100 m (Tomato)	Linear and Cubic Regression	Max Ht: 2 m	2.4 GHz	* Attenuation is due to vegetation and the antenna height. * Helps to plan how to deploy the nodes in the tomato greenhouse, in terms of the coverage and exact distance between the nodes.

[Parameters: Transmit power (Pt), Antenna height (Ht), Distance of separation between the transmitter and receiver (X)]

2.3 Foliage/forest environment

In this subsection, we focus on the survey of literature available in channel modelling carried out in vegetation environment. Vegetation environment, as observed in forests, grasslands and uninhabited areas, does not contain planned or predictable arrangement of the multitude of plants in the considered terrain. However, it will be useful to understand the effect of foliage on the channel measurements in such an environment as it can be considered like near ground channel modelling as in agricultural environments. Hence the available literature in this section is also surveyed. There are numerous works in literature which deal with radio channel path loss modelling under various environments like artificial turf (AlSayyari et al., 2014), sandy terrain (AlSayyari et al., 2014), snowy environment (Cheffena et al., 2017), sports court and roads (Ndzi et al., 2012), urban environment (Murdock et al., 2012), (Rappaport et al., 2013), to name a few out of the vast amount of literature available. However, this work limits the discussion to only agricultural applications and vegetation environments and hence, the surveyed papers are chosen accordingly. For modelling a forest environment, a four-layered geometry is considered (Li et al., 1998), consisting of air, canopy, trunk and ground. The prominent feature of a forest environment is the presence of the branches at a substantial height from the ground so that the presence of the tree trunks is a main factor in the propagation path. Hence, it is considered worth to survey the literature in this area separately. Generally, the excess loss due to foliage or vegetation is usually a function of the operating frequency and depth of vegetation (Adegoke et al., 2016). The vegetation environment may be considered as a single tree, a row of trees, sparse unevenly distributed vegetation or dense forested land. For measurement purposes, the forest environment can be implemented in two configurations based on the placement of the nodes – master-slave (M-S) configuration and peer-to-peer (P2P) collaborative configuration. In the M-S configuration, the base station or transmitter is situated at a prominent height above all the receiver nodes. In contrast, in the P2P mode, there is no predominant position for the deployment of the nodes. In this subsection, which surveys the advances in radio propagation in forest/foliage/vegetation environment, an attempt is made to classify each work as either M-S or P2P configuration.

The work in (Meng et al., 2010) is a survey paper which investigates the effect of foliage on the radio propagation in wireless channels. Published in 2010, the authors of (Meng et al., 2010)have surveyed literature over the duration 1981 to 2009 and has presented the key contributions of all the work, both analytical and empirical, in effects of vegetation or foliage in radio propagation, effect of shadowing and wideband channel effects. Hence, this subsection intends to supplement the studies done in (Meng et al., 2010) in the context of the framework of this paper and, therefore, considers the literature from 2010 till 2019 in addition to some of the papers prior to this duration which have not been surveyed by the authors in (Meng et al,. 2010). In (Tamir et al., 1967), one out of the early papers in this field of research published in 1967, the author studies the propagation of waves in the in the frequencies of range 1 MHz to 100 MHz when both the transmitting and the receiving antenna are present within vegetation. The forest is suitably modelled as a dissipative dielectric slab layer, including three interfaces – between ground and forest, forest and air, and air and ionosphere. The main conclusion derived is that the lateral waves, which are linked to the top portion of the tree, play a major role in determining the nature of the channel in forests. Hence, the lateral field is examined at length using mathematical methods, concluding that the transmission losses increase with increase in separation between the antennas and the refractive index (an increase in the refractive index is indicative of the fact forest is denser). Using rigorous mathematical analysis, (Li et al., 2002) studies the radio-wave propagation in an anisotropic forest medium, by deriving closed form solutions for the electric field in the three layers as described in (Tamir et al., 1967). The authors find that the results obtained corresponding to the lateral wave are in good consensus with (Tamir et al., 1967) although the formulation is quite complicated. Here, the authors also conclude that the transmission losses increase with increase in operating frequencies and that the receiver located in the trunk experiences more loss than receivers at the tree-top level. The frequency ranges used here is 200 MHz to 2000 MHz.

In another relatively early paper (Tharek et al,. 1992), the authors perform measurement campaign in the frequency range of 30 – 65 MHz with horizontal and vertical antenna polarization on tropical rainforest in Malaysia. The transmitter and receiver were placed at a height of 1 m and 1.5 m respectively with maximum separation of 1000m between the nodes. The effect of path loss was studied as a function of frequency, distance and polarization and the results were compared with existing propagation models. The principal mode of propagation is along the tree top boundary with air (lateral wave) and the direct and reflected wave mode as it moves through vegetation. The Burrow model has been suggested as the most suitable model for very high frequency (VHF) communications in tropical forested areas. In yet another early paper (Tewari et al., 1990), the authors have performed detailed channel measurements on rain a tropical deciduous and tropical evergreen rainforest in India for vertical and horizontal polarization of antenna. Measurements are carried out at 50, 200, 500 and 800 MHz and at antenna heights ranging from 1.5 m to 16.5 m above the ground, at distance of separation between the nodes ranging between 40 m to 4000 m. The seasonal effects of the foliage loss, specific attenuation, antenna height etc on the channel characteristics was also studied.

In the wireless path-loss modelling done for forested environment (Gay-Fernandez et al., 2010), the authors capture the LOS and Obstructed LOS values for a mature pine forest, with measurements being taken at radial points around 180 pine trees, for both M-S and P2P configurations. Because of the nature of the foliage environment, the measurements are categorized and taken at the front and rear of the trees. The power decay with distance is studied and is found to decay with increasing distance and the key findings are tabulated in Table 3, in terms of the path-loss exponent. In (Azevedo et al. 2011), the authors undertake a 2-year long measurement campaign in a forested environment consisting of pine, beech, cedar, oak and eucalyptus trees and the presence of grass in the ground, considering scanty as well as dense presence of trees. The path-loss exponent is presented for all the scenarios (Table 3) for both 870 MHz and 2.414 GHz and experimental data is found to best fit the log-normal model. The effects of obstruction caused by the tree trunks were analysed and an additional attenuation needed to be incorporated to account for this effect.

The authors in (Teschl et al., 2012), experimentally investigate the effect of slant foliage paths (at elevation angles of 20^0, 40^0 and 60^0) through roadside woodlands consisting of pine, spruce and deciduous trees at 5.2 GHz, using a helicopter as the platform for transmission. For two reasons, the authors claim that their results, although accurate, cannot be compared with the FITU-R model due to the season in which the experiment was conducted and since FITU-R model is presented for horizontal paths only. In general, the effect of the extent of vegetation along the canopy and tree-tops change for various elevation angles, especially since some of the wooded areas are reforested and since the transmitting antenna is mounted on a mobile platform in this work. To account for this irregularity, the authors propose a correction factor to the existing model.

In (Gay-Fernandez et al., 2013), the authors perform the radio channel modelling for a forested environment, where they consider pine trees, deciduous oak trees and eucalyptus groves as separate scenarios and for two types of meadows, in peer-to-peer configuration. The placement of nodes and consideration of test scenarios are like their work in (Gay-Fernandez et al., 2010), where they consider LOS and Obstructed Line of Sight(OLOS) measurements. The results reveal that the maximum distance between nodes is possible only for grasslands due to the existence of clear LOS paths, whereas minimum range is obtained for scrublands due to the presence of tall vegetation and a lack of clear LOS paths. The best P2P performance is observed for eucalyptus groves. The error ranges are in the order of 0.77 dB to 6 dB, which conforms to ITU-R standard, if not better.

In another experimental investigation as in (Ghoraishi et al. 2013), the authors perform the directional channel characterisation for a dense vegetation environment using two techniques – beam forming and the Space Alternative Generalized EM (SAGE) algorithm (Fleury et al. 1999). The main conclusions are that although the beam forming approach is easy to implement, its spatial resolution is limited, which results in a difficulty in separation of the various multipath waveforms. Using the SAGE algorithm, three main classes of multipath signals as a results of foliage scattering are identified and clustered. The authors then compute various parameters associated with the clusters using mathematical analysis. To model the channel in an inhomogeneous vegetative environment, the authors of (Azpilicueta et al., 2015) perform both simulation and experimental studies at 2.4 GHz. For the purposes of simulation, a schematic was developed using appropriate values of material properties like dielectric constant of the obstructions (wood, branches, leaves etc) considered and the loss tangent at the operating frequency. Dependency on the weather is also studied by changing the foliage density of the trees as per their behaviour in each season. Using ray-launching technique as the foundation of the simulation studies, the authors observed that the delay spread near the transmitter are higher because at nearby areas, the stronger rays produce more dispersion due to reflection, diffraction of obstacles and metallic elements present in the environment. Bit Error Rate (BER) analysis is performed and confirms the theory that BER increases with increase in noise power. Also, it was observed that the BER is lesser when the data rate is lesser. The mean error of measurements is 1.67 dB and it matched well with the simulation results.

In (Olasupo et al., 2016), the authors focus on the channel modelling for the very specific scenario of naturally occurring tall grass (height > 1 m), short grass (height < 3 cm) and dense tree environment for vertically polarized antenna and tall grass scenario for horizontally polarized antenna using data extracted from actual sensor nodes placed in the scrublands. The experiment is carried out at 2.4 GHz using Xbee S2B nodes, separately for tall and short grass environment, with nodes being placed at a maximum separation of 30 m, antennas placed at a height of 2.6 cm (going up to a maximum of 50 cm) and transmitting with a power of 18 dBm. Measurements were taken at points on a straight line between the transmitter and receiver and at angular distances between the two. The results show that the measured values did not conform to the results obtained from free-space model and the two-ray model. Based on the results, the authors recommend the use of the log-distance propagation model for most test scenarios and suggest that for the deployment of low power low data rate devices, the separation between the nodes should not be more than 15 m. The authors also employ statistical tests to check for conformity of results.

The authors of (Adegoke et al. 2016) perform radio channel measurements for isolated deciduous trees as mentioned in Table 3. The measurements were carried out at two different frequency bands: 3.2-3.9 GHz and 4.9 – 5.9 GHz. The experimentation was done for the 4 trees at two stages of tree growth – when the leaves are just sprouting from the branches and when the leaves are fully developed – to study the effect of foliage on the radio channel. Since the rate of leaf growth is different, the effect of that the foliage has on the channel due to each tree is also different. In (Aremu et al., 2016), the authors carried out a radio channel measurement campaign in a grove consisting of plantain, mango and mahogany trees and the received signal strength was used to characterise the path-loss at 100 and 300 MHz. It was observed that the path-loss was lesser at 100 MHz compared to 300 MHz. They compared the results with existing models like Weissberger and Ray-tracing model and found that the measured values match the former with good accuracy.

Further, the authors propose a new path-loss model as a function of distance.

In (Azevedo et al., 2017), the authors perform the channel characterisation for a forested environment consisting of various species of trees (Table 3). Through this work, the parameters corresponding to the log-normal model which indicate the influence of vegetation were found for each situation by performing curve fitting of the data. The root mean square error in estimation was also found for the two frequencies. The model proposed in this work includes several vegetation parameters and computes the estimate of the path-loss for any frequencies of operation between 400 MHz and 20 GHz. The error in results obtained was found to be much less than existing empirical models, of which FITU-R gave the best results and COST-235 provided the highest errors at all tested frequencies. In (Silva et al., 2018), the authors propose a new propagation model based on the experimental characterisation of tropical vegetation environment in a suburban park/sidewalk environment by considering the effects of frequency, transmission height and distance. From the measured results, the authors conclude that the results are more optimistic than the available models for the scenario of trees aligned as a single line. There is a better agreement of results with the Weissberger model for the suburban park case, especially for smaller antenna heights.

The authors of (Adewumi et al., 2018), perform experimental characterisation of long forested paths and propose a new model to represent the specific scenario considered in their work. The obtained measured results were fitted to the exponential decay model, and as expected, the attenuation was observed to increase as the depth into the forest increased. Of all models that the results were compared with, the COST 235 model showed the least error with respect to the proposed model. This is significant because all available empirical models are applicable for short distances only. Also, the attenuation increased with increase in thickness of the leaves in the forested channel. Since all the available models are for short distances, the authors proposed a new channel model which would be applicable for forested scenarios from 900 m to 8000 m, which will constitute a long channel. In (Lopez-Itturi et al., 2018), the authors recreate a dense forest scenario using the 3D Ray Launching method and study the radio channel propagation for IoT and 5G systems, to address the needs of the future, by combining both path-loss and multipath propagation. The authors also compare their simulation results with another published research paper (Cid et al., 2016), in which, the authors have performed an experimental evaluation for the same scenario as simulated in (Lopez-Itturi et al., 2018), consisting of isolated thin yet dense trees.

In (Zhang et al., 2019), the authors study the propagation characteristics of a coniferous forest at 28 GHz using the same parameters from one of their earlier papers (Zhang et al., 2018). They provide the excess path loss parameters to supplement the basic free-space path loss from the Attenuation Factor model, ITU-R model and Weissberger model. They also propose a site-specific model and provide the excess path loss, considering shallow as well as dense blockage of vegetation. In (Picallo et al. 2019), the authors consider device-to-device (D2D) communications between nodes of a WSN placed in a forest environment. This paper is closely related to (Lopez-Itturi et al., 2018) which is also by the same authors. They consider the same environment, parameters and use the same simulation methodologies and algorithm for their work in (Picallo et al., 2019), where they create an abstract geometrical and dielectric model of the forest using the software. In addition to simulation, this paper also presents the results of their experimental characterisation for isolated and non-isolated tree environments. In (Joshi et al., 2005), the authors have performed near-ground channel measurements at 300 MHz and 1900 MHz and studied the effect of height of the antenna, foliage environment and antenna radiation pattern up to 500 m of distance for both LOS and OLOS scenarios. The effect of rain has also been studied for 1900 MHz frequency. The transmitter and receiver antennas were mounted at heights of 0.75 m, 1.15 m and 1.55 m respectively. The wideband characterisation was analysed using the power delay profiles and it was found that the RMS delay spread increased with distance for the higher of the two frequencies. The RMS delay spread was seen to decrease with increase in antenna heights and increase in foliage. Results also suggested that the presence of leaves and wet vegetation do not affect the scattering of radio-waves.

In (Meng et al., 2009), the authors study the effect of tropical climate on propagation path-loss characteristics. For this purpose, the experimental study is carried out at 240 MHz and 700 MHz in a tropical palm plantation during the wettest month of the year. Preliminary results show that the stronger the wind and rain, the higher is the attenuation and the effect of deep fading is quite pronounced. It is common knowledge that rainfall usually causes attenuation only at very high frequencies > 5 GHz. But in this forest setting, it seems to affect lower frequencies as well. The effect on the channel due to the varying intensities of rain is also studied and it is found that the effect of rain for varying rainfall rate was higher at lower frequencies. Finally, the Rician K-factor was observed to be larger at higher frequencies than lower frequencies.

In (Kamarudin et al., 2010), the authors adopt the simulation approach using OMNeT++ (Varga et al., 2008) to study the impact of various propagation models at 2.4 GHz as applied to near-ground communications. Well known models like ITU-R and Weissberger model are implemented. From the results, the authors infer that the antenna height and density of vegetation significantly affect the coverage and connectivity of the network and that the combination of the plain-earth and vegetation model is best suited to model near-earth channels. The authors, in (Meng et al. 2010), study the near-earth channel modelling for two types of terrains – palm plantation near sea-side and tropical rainforest. In the palm plantation, the thick tree trunk and extreme humidity gives higher path-loss than other forested environments which is best modelled by COST235. However, for the rainforest, the presence of dense undergrowth under the forest is very similar to the scenarios in the Weissberger and the ITU-R models are derived. Of the two, since the Weissberger model is derived for temperate climatic conditions, the ITU-R model gives the best prediction for rainforest environment.

The authors of (Kurnaz et al., 2014) propose a new path-loss model for a pine tree forest environment by performing the near-earth channel modelling where the nodes are configured in the master-slave mode. For comparison, they also perform measurements in a grassland to observe the effect of pine tree foliage on radio wave propagation. From the results, the authors infer that the proposed model gives an average error which is at least 2.8 times better than existing models. In (Klaina et al., 2017), the authors perform the channel measurements for tall and short grass environment with relevance to smart agriculture and on indoor ground environment for comparison purposes. From the obtained results, the authors conclude that 868 MHz is most preferred for near-ground communication in agriculture fields since it not only minimizes the path loss, but also the energy consumption, since the transmitted power is 2 dBm for 868 MHz and 25 dBm for 2.4 GHz & 5.8 GHz. The other key findings are listed in Table.3.

In (Klaina et al., 2018), a closely related work to (Klaina et al. 2017) by the same authors, the narrowband channel characteristics is studied specifically regarding 5G systems and IoT applications. The authors use the same measurement set-up, experimental scenarios (tall and short grassland), and same frequencies for their measurement campaign. The additional contribution is that a quality of service (QoS) analysis was done from the RSSI values obtained from the measurements. The bit error rate (BER) values were derived for various digital modulation schemes like BPSK, 8-PSK, 16-QAM and a performance comparison was done with the available theoretical results.

The work in (Kamarudin et al., 2010) is a review paper which surveys some realistic propagation models and simulates the ITU-R and Weissberger's Modified Exponential Decay model in OMNeT++. From the simulations, the authors conclude that the maximum communication coverage decreases exponentially with increase in vegetation depth. Also, the FSPL model gives overly realistic results which are not suitable for real-time scenario, thereby validating the applicability of ITU-R and MED model. In (Morgadinho et al., 2011), the authors choose two tree species – Schefflera and Palm – and perform the channel measurements at 40 GHz in an anechoic chamber to study the dynamic effects in vegetation media. The authors consider only the scattering phenomena for their modelling due to the experimental set-up. The parameters chosen were scattering angle, tree species, wind speed and incidence. Based on their studies, they propose a Markov model-based radio channel using log-normal distribution. The significant outcome of this work is that it has contributed to the ITU-R P.833-5 document on research findings in vegetation attenuation. The notable results from the surveyed papers are tabulated in Table.3, listed in the chronological order of publication.

Table 3 Summary of key parameters for forest/foliage environment

Ref. No	Year	Site Specifications	Configu-ration	Frequency	Parameters	Key Findings
Gay-Fernandez et al. 2010	2010	Mature Pine Forest	M-S and P2P	2.45 GHz	M-S: Pt: 18 dBm, Ht: 3.5 m P2P: Pt: 12 dBm, Ht: 1.5 m	M-S: Path-loss exponent: Front: 3.43, Rear: 2.56 P2P: LOS – Front: 2.55, Rear: 2.04; OLOS – Front: 1.42, Rear: 1.63
Meng et al. 2010	2010	Palm plantation and tropical rain forest	M-S	13 frequencies in the band of 40 - 80 MHz, 250 - 300 MHz, and 500 - 630 MHz	Ht: 2.15 m	* COST-235 gives the best fit for path-loss in palm plantation. * ITU-R model is suited for path-loss channel modelling for rainforests. * For near-ground propagation the reflection from the tree canopy cannot be ignored.
Azevedo et al. 2011	2011	Forest consisting of Pine, Beech, Cedar, Oak, Eucalyptus and Grass	P2P	870 MHz & 2.414 GHz	Pt: 10 dBm (For 870 MHz), Pt: 27 dBm (For 2.414 GHz) Ht: 3 m, X: 90 m	* Log-normal model best estimates the attenuation * PL exponent (n): n= 2.68 for 870 MHz, n= 3.23 for 2.414 GHz * For high density: PL exponent (n): n= 2.79 for 870 MHz, n= 2.92 for 2.414 GHz
Morgadinho et al. 2011	2011	Schefflera & Areca Palm (Anechoic chamber)	Not applicable	40 GHz	Not specified	*Minimum fade level decreases and signal broadening increases with bi-static scattering angle. * For Schefflera species, the signal is better enhanced for all wind incidences and when the wind speed increases. For Palm, signal is enhanced only for medium wind speed.
Teschl et al. 2012	2012	Roadside woodland (pine, spruce & deciduous trees)	M-S	5.2 GHz	Pt: 40 dB, max X: 40 m, Ht: approx. 1 km (link distance from the helicopter to the receiver node mounted on a van)	* Results are not comparable with FITU-R model since the latter is developed for horizontal paths. * Correction factor is introduced to account for varying shadowing effects due to irregular canopy.
Gay-Fernandez et al. 2013	2013	Forest (pine, oak, eucalyptus) and meadow	P2P	2.4 GHz, 3.5 GHz, 5.8 GHz	Pt: 18 dBm at 2.4 Hz, 19 dBm at 3.5 GHz and 15 dBm at 5.8 GHz, Ht: 1.6 m (for meadows)	* Mean errors in all cases are lesser than the ITU-R recommendation using this method. Gives better fitting as compared to ITU-R model. * Mean errors in scrubland environment is higher than in grassland. * Error < 6dB at 2.4 GHz, Error < 5 dB at 3.5 & 5.8 GHz
Ghoraishi et al. 2013	2013	Prominently Japanese Cedar with other Vegetation around it	M-S	2.2 GHz	Pt: 30 dBm, Max Ht: 15 m, max X: 100 m	* Although easy to implement the spatial resolution of the beam forming approach is limited.
Choudhary et al., 2014	2014	Neem tree grove	P2P	35 GHz	Pt: 20 dBm, Ht: 7 feet.	* Attenuation increases with distance and with the number of trees in the path between the transmitter and receiver. * Signal undergoes random polarization resulting in the change in attenuation.

Ref. No	Year	Site Specifications	Configu-ration	Frequency	Parameters	Key Findings
Azpilicueta et al. 2015	2014	Ray launching technique. (Experiment: a heterogeneous vegetation environment is chosen)	P2P	2.4 GHz	Simulation: Pt: 18 dBm, Ht: 1 m	* Performance parameters analysed using simulation are delay spread, channel capacity and bit error rate (BER). * Experimental values obtained tallied with the simulation results
Kurnaz et al. 2014	2014	Pine tree forest	M-S	0.9 GHz, 1.8 GHz, 2.1 GHz	Pt: 0 dBm, Ht: 2 m, max X: 400 m	* Proposed model's RMS error is in the range 4 dB to 10 dB, which is better than the 5 to 50 dB obtained from existing models. * RMS error values obtained from the COST-235 model is much higher than that obtained from Weissberger and ITU-R model.
Olasupo et al. 2016	2016	Tall and Short natural grass	M-S	2.4 GHz	Pt: 18 dBm, Ht: 0.5 m, max X: 30 m	* FSPL, Two-ray models are not suitable for this environment. * In tall grass environment, devices lose connectivity for distances > 9 m, and for short grass environment, the connectivity is available up to 12 m.
Adegoke et al. 2016	2016	Trees: Silver maple, horse chestnut, double white hawthorn & dawn redwood	Not applicable	3.5 GHz & 5.4 GHz	Pt: 20 dBm, X: 15 m	* Propagation loss is high in summer period compared to winter, due to the presence of greater amount of foliage. * The loss difference in all the cases for the two seasons range between 6 to 9 dB.
Aremu et al. 2016	2016	Vegetation area with thick mahogany, plantain tree, mango trees etc	M-S	100 MHz, 300 MHz	Ht: 1.22 m, max X: 200 m	* As frequencies increase, the path loss increases. Measured values fitted well with Weissberger model. * Ground reflection did not have much effect on the measured received signal. * MSE:13.8 dBm for 100 MHz MSE: 2.8 dBm for 300 MHz
Azevedo et al. 2017	2017	Forest environment consisting of Acacia, Pine, Oak, Beech, Spruce, Cedar, Chestnut etc	M-S	870 MHz, 2.4 GHz	Pt: 10 dBm (870 MHz) and 27 dBm (2.4 GHz) Max X: 70 to 100 m (based on environment)	* FITU-R provided best approximations of the results. * Errors computed using the proposed model is less than existing models of the order of 0.8 dB at 1.3 GHz, 0.8 dB at 2 GHz and 2 dB at 11 GHz as opposed to the FITU-R model (the best results of all in this context) results of 2.3 dB at 1.3 GHz, 4.1 dB at 2 GHz and 11.2 dB at 11 GHz.
Tokunou et al., 2017	2017	Deciduous forest, Coniferous Forest	M-S	2.4 GHz, 920 MHz	Pt: 3 mW for 2.4 GHz & 20 mW for 920 MHz, Ht: 105 cm max X: 100 m	* This paper studies the dependency of RSSI on distance. * At 2.4 GHz, ground reflection strongly affects the Two-Wave Diffuse Power fading at short distance and as the distance becomes more, Rayleigh Fading becomes prominent. * At 920 MHz, scattering was dominant even at a close distance with a clear LOS path.
Silva et al. 2018	2018	Vegetation as typical in suburban parks, small woods	M-S	700, 750, 800 MHz	Pt: 0 dBm, Max Ht: 12 m	* RMS error obtained from the proposed model is much less than existing models, of which Weissberger model is comparatively better and COST235 model is far from optimum. * Helps in determination of coverage for 5G systems.
Adewumi et al. 2018	2018	Large forested terrain with mixed (cashew, palm, odan, maize and mango trees) vegetation & with weeds on the path.	M-S	1.835 GHz	Pt: 10W (40 dBm), Ht: 100 m, max X: 8 km	* Of all models, COST 235 showed the least error with respect to the proposed model, but that itself was significant because all available empirical models are applicable for short distances only. * Attenuation increases with increase in thickness of the leaves in the forested channel.
Lopez-Itturi et al. 2018	2018	Oak and pine trees	P2P	2.4 GHz	Pt: 10 dBm	* Two scattering zones are identified and confirmed with [(Meng et al. 2010). * Delay spread is analysed for different tree heights. * Pine trees have lots of air gaps which does not affect the

Ref. No	Year	Site Specifications	Configu-ration	Frequency	Parameters	Key Findings
						channel to a large extent. The oak trees constitute a homogenous environment.
Zhang et al. 2018	2018	Coniferous forests	M-S	28 GHz	Pt: 23 dBm, Ht: 27 m, max X: 1000 m	* Traditional foliage models at low frequencies do not provide correct path loss predictions. * Weissberger model shows the best fit out of all the existing models. * Excess path-loss parameters are specified for the site-specific model.
Klaina et al. 2017	2018	Short and tall grass environment	M-S	868 MHz, 2.4 GHz, 5.8 GHz	Pt: 2 dBm (for 868 MHz) and 25 dBm (for 2.4 and 5.8 GHz), Ht: 0.2m & 0.4 m, max X: 120 m	* Path-loss increase with decreasing antenna heights. * Transmitted signal has highest attenuation in tall grass fields owing to longer grass blades and more leaves obstructing the LOS paths especially at 5.8 GHz. * Of the considered frequencies, 868 MHz is most suited for agricultural applications.
Klaina et al. 2018	2018	Short and tall grass environment	M-S	868 MHz, 2.4 GHz & 5.8 GHz.	Pt: 17 dBm, Ht: 0.2 m & 0.4 m, max X: 50 m	* Path-loss increase with decreasing antenna heights. The difference between measured path-loss and FSPL decreases with increase in frequency range. * Position of the sensors from the ground level affects signal strength and the signal quality. * BER values are higher for more complex modulation schemes. (Values of data rates chosen are 56, 115.2 and 256 kbps)
Picallo et al. 2019	2019	Oak and pine trees	P2P	2.4 GHz	Isolated trees: Pt: 10 dBm, Ht: 2m, max X: 4.6 m Non-isolated trees: Ht: 1m, max X: 15 m	* Two scattering zones are identified and confirmed as in (Adegoke et al. 2016). * The trees affect the diffuse zone's positive effect on the received power level, which in turn helps appreciate the effect of single trees on SNR. * Isolated tree: Signal fading will not depend on the foliage distribution of the tree considered as for a thin tree. Existing prediction models may not match the experimental results. * For non-isolated tree, simulation results match the measured results, which is due to the appropriate consideration of multipath effects.
Duangsuwan et al. 2021	2021	Grass farms	Not mentioned	2.4 GHz	Pt: 20 dBm, max X: 20 m, Ht: 1.5 m	* Presents a novel channel model called GS-to-UAV and a detailed path loss characterization using machine learning models. * Experimental set-up is implemented, and models are validated using statistical indicators like root mean square error, mean absolute error etc.

[Parameters: Transmit power (Pt), Antenna height (Ht), Distance of separation between the transmitter and receiver (X)]

3 Discussion

Of the various research challenges that is encountered in the field of agriculture, channel modelling presents a wide scope in terms of analysis and experimentation. In the earlier section, the authors have broadly surveyed the path-loss characterization and channel modelling in agricultural environments based on three environments. Firstly, crop-specific fields were considered, which included all kinds of crops like fruits, vegetables and grains. Then, greenhouse cultivation environment was considered which is a protected environment and quite different from natural settings. Finally, the effect of the presence of foliage/forest/grasslands environment was considered. These three environments are unique and vastly different from each other. From the data presented in Section 2, it is evident that no single channel model can uniquely characterize all agricultural scenarios due to several factors such as the varying requirements of water, soil conditions and the electrical properties of each of the crops, plants or vegetation. Moreover, the terrain, nature of the soil, crop height, various stages of growth of the crop, density of the crops and spacing between them are all additional factors that affect the signal transmission between transmitter and receiver nodes. Several models in the literature do not consider the influence of vegetation since the phenomenon of scattering at lower frequencies was assumed to be insignificant. However, as frequency increases, the effect of scattering due to vegetation cannot be neglected since the wavelength of the signal will be comparable to that of the obstacles in the channel like leaves, twigs and small branches. Therefore, its effects need to be studied in great depth.

The frequency of operation listed in the tables above is very significant. The operating frequency chosen for experimentation plays an important role in the design of wireless networks. It is found that most of the applications are in the frequency range (300 MHz - 30 GHz). The WSN implemented in vegetation environment is suited to work in this frequency range because of its short wavelength. The increase in operating frequency permits high data transmission rate and sufficient bandwidth. It is observed that much of the literature address the 2.4 GHz band because this band suffers much higher propagation loss than the sub-1GHz band and at the same time, can provide comparatively higher data transmission as stated in (IEEE Std 802.15.4, 2015). Also, the maximum distance at which we can place the transmitter and receiver depends largely on the environment, which can be ascertained from the results in (Tamir et al., 1967).The pattern of signal behaviour varies significantly due to attenuation. At frequencies less than 30MHz (HF bands), the path loss is due to diffraction, since at this frequency range, the signals can easily penetrate buildings and thick foliage. If the path is Obstructed LOS, the diffraction loss increases significantly as the frequency increases. For frequencies between 30 MHz and 1 GHz, reflection, refraction and diffraction are equally significant. Above 1 GHz, attenuation becomes more prominent and the effect of reflection and refraction becomes lesser. Extreme fading also occurs above 1 GHz due to atmospheric multipath propagation. Therefore, it can be inferred that higher frequency bands face more difficulty in signal propagation through physical obstacles as compared to lower frequencies. The most used empirical methods for model fitting or for comparison purposes are Weissberger's modified exponential decay (MED) model, FSPL, two-ray model, log-distance path-loss model and ITU-R in some cases. Most of the above models are applicable for characterizing the wireless channel in an outdoor environment. The special case of characterization of vegetation in residential environments, as seen in (Chee et al., 2012) and (Torrico et al., 2011) is also possible. However, in this work, the authors have restricted the discussion to include only open outdoor channels which consider the presence of vegetation and foliage. From the papers surveyed, the authors have also identified the network deployment configuration in the forest environments. It can be inferred that most of the communication systems for path-loss measurements is set up in a master-slave configuration where, in most instances, the transmitter antenna is located just outside the area under consideration or is located at a higher elevation than the receiving antennas although this is not a strict condition to be followed in a peer-to-peer wireless sensor network.

To shed light on the prospects of wireless channel modelling in the agricultural environment, the authors would like to conclude the discussion by mentioning some very recent achievements and the use of latest technology. The adoption of embedded systems, internet of things (IoT), microelectromechanical systems (MEMS) (Khairunnisa et al. 2018), machine learning, automation, and more recently artificial intelligence (AI), has paved the way for a technological revolution in smart farming. The authors in (Duangsuwan et al., 2021) propose and develop the path loss characterization using UAV and machine learning models. Although the works in (Bauer et al., 2019; Benos et al., 2021; Sharma et al., 2020) present the implementation of machine learning for smart farming scenarios, there is very limited research literature in the applications of machine learning and AI in the specific context of wireless channel modelling in agriculture and vegetation environments. Hence, the application of AI in agricultural channel modelling can be considered an open research topic till date.

4 Conclusion and future work

The authors have undertaken this survey on channel modelling in agricultural systems and vegetation environments as a conduit to explore the earlier works and recent advancements in the vast field of radio propagation path-loss characterisation, in the context of near-ground communications. The authors have categorized the study based on three broad types of agricultural environments – crop-specific agricultural fields, greenhouse environment and forest/foliage environment. Various relevant literature was reviewed and the basic results and findings, models that were adopted, parameters considered, and the environment/site specifications were presented for all the above environments. Most of the experimental studies deployed off-the-shelf technologies for the measurement campaign. In future works, the authors would like to investigate and explore the possibility of configuring low-cost independent network of nodes for the channel characterisation of wireless sensor networks in agriculture. The effect of vegetation on residential environments has been intentionally deferred to a later study owing to the vast scope of the present work. Due to the extremely diverse nature of the parameters that impact the study, the scope of this work has been restricted to presenting the key results and identifying the configuration of network deployment. This work is intended as a one-stop reference for a newcomer to the field of near ground channel modelling in wireless networks with an emphasis on applications in agriculture, foliage, forest and vegetation environments.

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