

Internet of Things (IoT) for Smart Precision Agriculture and Farming in Rural Areas

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Abstract—Internet of Things (IoT) gives a new dimension in the area of smart farming and agriculture domain. With the use of fog computing and WiFi-based long distance network in IoT, it is possible to connect the agriculture and farming bases situated in rural areas efficiently. To focus on the specific requirements, we propose a scalable network architecture for monitoring and controlling agriculture and farms in rural areas. Compared to the existing IoT-based agriculture and farming solutions, the proposed solution reduces network latency up to a certain extent. In this, a cross-layer-based channel access and routing solution for sensing and actuating is proposed. We analyze the network structure based on coverage range, throughput, and latency.

Index Terms—Cloud computing, fog computing, Internet of Things (IoT), smart agriculture, WiFi-based long distance (WiLD) network.

I. INTRODUCTION

FARMING and agriculture is the basis of human life which gives food, grains, and other raw materials. Technology holds a tremendous role in increasing production and decreasing extra manpower. Internet of Things (IoT) has opened up a suitable solution for smart farming and agriculture, however, it remains a dream till the connectivity is not reached to rural areas. The WiFi-based long distance (WiLD) network is successfully been used to connect the rural regions with low cost [1]–[3]. With the extended range, for better and efficient IoT in such region, fog computing, and cloud computing solutions can be incorporated in WiFi devices [4], [5].

Wireless sensor network (WSN) is proven to be an economically viable solution for the farming domain [6], [7]. Features like the integration of sensors/actuators, digital transmission, low power consumption, scalability, and security of WSN enable us to use in different IoT applications. Irrigation, farm monitoring, control use of fertilizer, soil monitoring, intruder detection, water quality monitoring, etc., operations

can be supported using WSN [8]. To support efficient routing and auto-configuration in such network, 6LoWPAN is widely used [9]. The 6LoWPAN can be integrated into WSN-based IoT to uniquely identify a large number of devices [10]. It allows us to achieve interoperable communication among different technologies. 6LoWPAN border router (6LBR) is responsible for collecting the sensor information and forwarding to an IoT cloud server. At the same time, 6LBR also carry the available commands from a remote user or from an automation server. The agriculture and farm-related solutions and decisions are handled by a cloud-server.

The WiLD network has revealed to be an affordable alternative to the other low cost and long distance solutions [1], [11]. The WiFi (IEEE 802.11) commodity hardware is available at low cost and it supports license-exempt operation in the ISM radio bands [12]. Replacing existing cloud, a local solution station in these devices is required for such long-range wireless network which saves bandwidth and reduces the delay. Fog computing has emerged as a solution to this problem. It can reduce the delay to milliseconds to subseconds of time by creating a local and collaborative solution system.

In this paper, we propose a network solution in the domain of IoT connecting the rural region with various agricultural and farming applications. In summary, the primary contributions of this paper are as follows.

- 1) We introduce WiLD network and fog computing in the existing WSN-based solutions for covering longer range with lesser delay.
- 2) A cross-layer-based MAC and routing solution that adapts traffic nature and sets the duty cycle accordingly to improve delay and throughput performances over multihop IoT is proposed.
- 3) We discuss the testbed evaluation processes and analyze the performance of the proposed architecture.

Remaining of this paper is organized into four sections. The IoT and its potential for smart farming and agriculture are discussed in Section II. Section III presents the proposed IoT network solution for farms and agriculture in rural areas. Section IV gives the performance evaluation process of the proposed network. Finally, Section V concludes this paper.

II. IoT AND ITS POTENTIAL FOR SMART FARMING AND AGRICULTURE

IoT monitoring and automation from anywhere in the world is replacing human being and hence yielding more benefits in agriculture. It is predicted that by the year 2050, the agriculture

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using IoT will increase the food production by 70% and provide foods up to 9.6 billion people, and 2 billion sensors will be used in 525 million farms. Due to this prediction, IoT-based agriculture and farming is becoming popular with the promise to deliver all-time visibility of soil and crop health, used machinery, storage conditions, fertilizer used, energy consumption, and animal behavior.

IoT can help farmers in numerous ways. With the deployed sensors/actuators across farms and machinery, farmers can gain as an abundance of insightful data such as temperature, fertilizer used, water used, etc. Once an IoT-enabled smart system is in place, farmers can easily monitor a variety of environmental parameters and do analytics. Table I shows a list of IoT-based agricultural applications. From the table, it is clear that longer latency is intolerable for most of the applications.

Gutiérrez *et al.* [14] proposed an IoT-based irrigation system comprising of a WSN connected by a gateway and a remote server. Other than the efficient use of water, this project also deployed soil moisture and temperature sensors. Smart sensor Web [16] was proposed to measure soil moisture with the deployed sensors and controlled them from a Web-based system. To monitor pH, temperature, humidity, etc., Cambra *et al.* [15] proposed a video sensing-based fertilizer controlling in agriculture production. An IoT-based smart security and monitoring system is developed in [17]. Security devices are kept in agricultural fields like rainstorms and cold stores to control and monitor from a remote location. A soil moisture monitoring system is developed in [13], which worked on an energy efficient algorithm. Dan *et al.* [18] monitored climate conditions using a greenhouse monitoring system with short-range ZigBee technology. Ojha *et al.* [8] discussed the deployment processes of WSN for agriculture and farming and analyzed the network with respect to technologies, standards, and hardware. However, these solutions mainly consider short-range technologies deployed in an area where Internet connectivity is available nearby. As farms and agriculture primarily available in rural areas, connecting the short-range WSN from long distance and solving the farm-related issues still challenging. Further, provisioning QoS for such application to fulfill different network requirements is very important.

III. PROPOSED NETWORK ARCHITECTURE FOR SMART FARMING AND AGRICULTURE

The proposed architecture is a practical and promising solution for connecting rural farms using IoT with low cost and better QoS. The proposed network (\mathcal{N}) is a combination of one WiLD network (\mathcal{W}) and a set of 6LoWPAN enabled WSN networks (\mathcal{w}). Network \mathcal{N} , can be represented as a graph $\mathcal{N}(\mathcal{A}/\mathcal{R}_i/g_i/s_i, E)$, where \mathcal{A} is the gateway, \mathcal{R}_i is any WiFi relay node, g_i is any sensor gateway, s_i is any sensor node, and E is the set of links between two nodes in the network. Fig. 1 shows the proposed IoT architecture. The architecture combines multiple networks for scalability and larger coverage range. Components of the proposed architecture are described below.

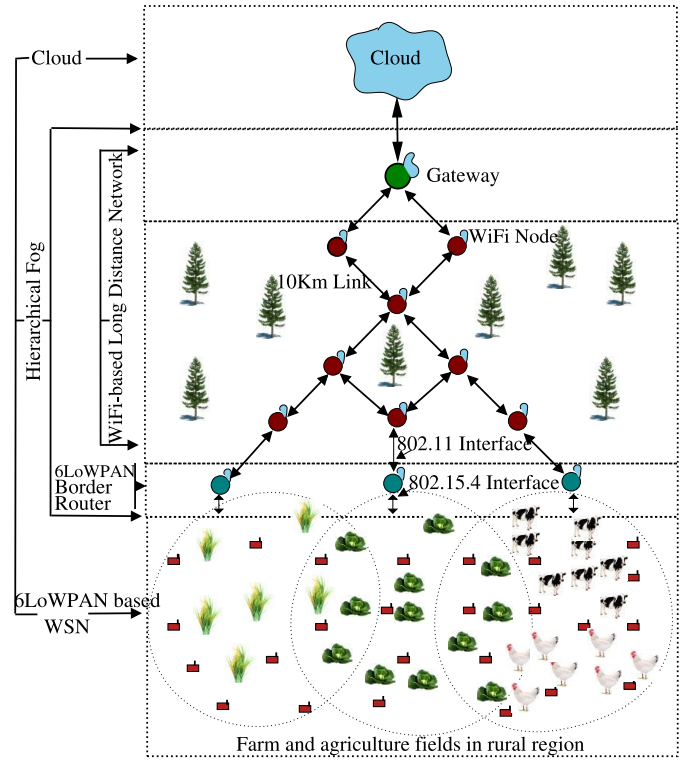


Fig. 1. Proposed IoT network architecture connecting rural areas.

A. 6LoWPAN-Based Wireless Sensor/Actuator Network

The 6LoWPAN-based wireless sensor and actuator network is used in the farm domain for sensing and actuating many operations. 6LoWPAN is a low power wireless personal area network with devices of IEEE 802.15.4 standard using IPv6.

Definition 1 (6LoWPAN-Based Sensor Node): A sensor node is a tiny device accessible using IPv6 address having low storage capacity, capable of low computation and processing capability, and low power consuming.

According to their functionalities, a sensor node s_i can perform sensing, actuating, or both operations. Multiple on-field sensor nodes deployed across the farm areas which are accessible through a set of gateway nodes g_i s available to their respective coverage range. 6LoWPAN-based network is widely used in IoT implementations. The considered network in this phase can be defined as follows.

Definition 2 (6LoWPAN-Based WSN): A 6LoWPAN enabled WSN is a collection of sensor nodes ($s = s_1, s_2, s_3, \dots, s_n$) which are identifiable by a compressed version IPv6 addresses and accessible through a gateway node g .

A large number of IoT devices need larger address space and auto-configuration which is provided by IPv6. Characteristics of a 6LoWPAN network are small packet size, low bandwidth, lossy link, and mesh management. It uses the 6LoWPAN protocol stack (IPv6 and adaptation layer). The challenge of such combination is to adapt the packet sizes between the two layers, i.e., 1280 bytes in IPv6 and 127 bytes in LoWPANs. 6LBR fragments the packet in IPv6 layer and reassemble them in 802.15.4 layer. As shown in Fig. 1, the nodes are enabled with IPv6 addresses for better scalability. The deployed sensor

TABLE I
NETWORK REQUIREMENTS OF DIFFERENT IOT APPLICATIONS IN FARM AND AGRICULTURE

Application	Benefit	Network Requirement
Soil and water quality monitoring [8]	(i) Choosing perfect breed of plant, (ii) Applying fertilizer if required, and (iii) Detecting water related disease in pond and agriculture domain	(i) Low latency for immediate action, and (ii) Generate huge amount of periodic traffic to the network
Farm monitoring [13]	Automation and remote monitoring of machines used help to manage a large scale farms	Longer delay may damage the production system
Irrigation management [14]	Optimization of water or other material usages in the farm or agriculture domain	Low latency should be taken for lesser losses
Scientific disease and pest monitoring [15]	(i) Efficient usage of fertilizers and pesticides, and (ii) Increases the crop quality and minimizes the farming cost	(i) Longer delay is not tolerable for massive lost, and (ii) The periodic traffic may take a large bandwidth of the network
Controlled use of fertilizers ([8] and [16])	(i) Maintaining plants growth and crop quality, and (ii) Balancing soil nutrition	Large amount of data may be generated due to the large number of sensors used
Cattle movement monitoring [17]	Saving damages from cattle's movements	Longer delay is intolerable
Intelligent greenhouses [18]	Controlling greenhouse gases	Delay is the most considerable parameter
Remote control and diagnosis [8]	Remotely controlling and diagnosing different farm related equipments	Longer latency may harm the equipment
Asset tracking [8]	A farmer can continuously track the position of vehicles and irrigation systems from any place	Mobility support and less delay are the primarily required parameters

TABLE II
COMPARISON OF DIFFERENT WSN MAC PROTOCOLS

Protocol	Traffic adaptive	Heterogeneous Duty Cycle	Multi-hop Decision	Downlink Scheduling
[19], [20], [22]	✗	✗	✗	✗
[23], [24], [25], [26]	✓	✓	✗	✗
CLAD	✓	✓	✓	✓

nodes communicate using 6LoWPAN-based network, monitors the environment to provide precision farming and agriculture management. To provide security, identifying, managing, and to collect and deliver data to the devices, a gateway is used. The gateway devices run 6LBR for interfacing between two different networks. It is coped with two different interfaces supporting IEEE 802.15.4 network (6LoWPAN) and 802.11 networks (WiLD networks). The gateway device has more processing capability than deployed sensor devices.

1) *MAC and Routing Solution for Internet of Things:* Monitoring and taking actions over a large scale farm or agricultural area, a huge number of sensor and actuator nodes may need to be deployed. The traffic generated by the nodes are mostly periodic in nature which is transmitted over multiple hops till the gateway. On the other hand, bursty traffic may be generated toward downlink direction for controlling actuators. WSN-based MAC protocols [also called low power listening (LPL) protocol] such as X-MAC [19], B-MAC [20], ContikiMAC [21], and SpeckMAC [22] do not meet our goal to achieve lesser delay and energy consumption, and also the nodes of the network need to operate homogeneously.

To adapt with heterogeneous traffic scenarios, MaxMAC [23] adjusted their duty cycle dynamically. However, switching its mode of operation causes more energy consumption. With the use of routing, AADCC [24] gathers neighborhood information and modifies the MAC duty cycle. However, there may high latency due to the wake-up interval, which can be extended to save energy. A traffic adaptive MAC protocol, T-AAD [25] uses senders queue length which reduces transmission delay but cannot eliminate/reduce channel contention and does not support

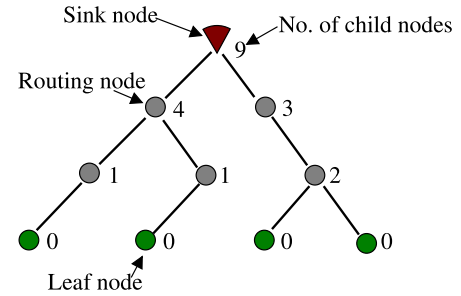


Fig. 2. DODAG topology constructed by RPL routing protocol.

burst transmission. Enabling burst transmission, a queue length-based dynamic duty cycle MAC protocol Q-BT [26] is proposed. Due to the fixed length of it, queue length-based approaches are not efficient. Further, these protocols cannot adjust duty cycle accurately among nodes that have periodic traffic and different child-parent links and nodes in a multihop IoT. Table II compares the proposed MAC solution with the related works.

Enhancing ContikiMAC, a cross-layer and adaptive duty cycle (CLAD) protocol based on routing over low power and lossy networks (RPLs) is proposed to solve the above problem. The protocol uses a cross-layer approach and utilizes the destination oriented directed acyclic graph (DODAG) topology to know the number of children nodes. As shown in Fig. 2, sink and routing nodes keep the counts of their children nodes. For uplink traffic, a node keeps track of its number of child nodes and adjusts its duty cycle dynamically. If (Q) be the number of children nodes of any sensor node s_i , then the duty cycle (\mathcal{D}_{dc}) varies as

$$\mathcal{D}_{dc} \propto \frac{1}{Q}. \quad (1)$$

Although the uplink traffic is mostly periodic in nature, downlink traffics are bursty (as an action happens is informal). In the next step, to handle bursty traffic, the proposed protocol calculates the traffic load index as

$$\mathcal{L}_i = \frac{r_r + f_r + c_r}{C} \quad (2)$$

where \mathcal{L}_i is the load index at a particular routing node i and \mathcal{C} is the link capacity. Also, r_r represents the successful packet arrival rate, f_r shows the successful packet forwarding rate, and c_r represents the packet collision rate at the particular relay node. The higher value of \mathcal{L}_i means the higher is the congestion in the node. All nodes periodically send their load index to the sink node along with the number of child nodes (\mathcal{Q}). As the downlink traffics are mostly burst in nature, based on the received \mathcal{L}_i values, sink node uses less congested path for routing decision. The traditional RPL routing can create one or more DODAG, the sink node in the proposed protocol keeps records of them. The \mathcal{L}_i received from different intermediate nodes are compared with a threshold value $\mathcal{L}_{Th} = ([\mathcal{C}/2] + o_r + a_r)/\mathcal{C}$, where a_r is the required data rate for alert/command and o_r is the extra data rate due to packet and control overhead. The best downlink path is created comparing \mathcal{L}_{Th} and \mathcal{L}_i for all nodes.

2) *Performance Analysis of the CLAD Protocol*: In the proposed protocol, the sensor nodes periodically check in the adjusted \mathcal{D}_{dc} for any incoming packet. It uses two consecutive CCAs of duration, \mathcal{D}_{cca} with a short sleep gap, \mathcal{D}_s . Once the CCA can detects a packet from sender, the expected delay for one-hop can be calculated as

$$\mathcal{D}_{td} = j \cdot \mathcal{D}_{dc} + (2 + i) \mathcal{D}_{cca} + \mathcal{D}_s + \mathcal{D}_{data} + \mathcal{D}_{ack} + 2\mathcal{D}_{pt} + \mathcal{D}_b \quad (3)$$

where \mathcal{D}_{data} , \mathcal{D}_{ack} , \mathcal{D}_b , and \mathcal{D}_{pt} are data transmission (Tx) time, ACK Tx time, backoff time, and propagation time, respectively, and $i \in \{0, 1, 2, \dots, n\}$ and $j \in \{0, 1\}$. Delay may change with the changing value of i, j, \mathcal{D}_{dc} , and \mathcal{D}_b . The proposed protocol sets dynamic duty cycle according to the number of children nodes ($\mathcal{D}_{dc} \propto \mathcal{Q}^{-1}$). \mathcal{D}_b can be calculated from the probability of successful Tx (p). According to Bernoulli's theorem [27], probability of random variable (\mathcal{X}) can be given by

$$\mathcal{P}(\mathcal{X} = y) = (1 - p)^{y-1} p \quad \forall y \in \mathbb{R}. \quad (4)$$

Average backoff window (W_b) can be calculated from expected value of y as $W_b = [(2 - p)/p]$, which gives an average backoff time as $\mathcal{D}_b = W_b \cdot t_s$, where t_s is the slot time. Considering default value of Contiki-3, sending a packet of 100 bytes, \mathcal{D}_{td} is found to be (\approx) 8.56 ms, assuming $i = j = 0$, $W_b = 64$, and $t_s = 50 \mu s$. Therefore, expected delay for h hops will be $h \times \mathcal{D}_{td}$. Wasteful and unnecessary activities in the considered network may cost a huge energy consumption. A proper and application load aware duty cycling scheme can solve the issue. The proposed scheme uses traffic load and number of nodes to optimally utilizes the \mathcal{D}_{dc} for better delay performance. Energy consumption in the proposed protocol is primarily because of Tx, reception (Rx), backoff, and idle listening. Assuming packet interarrival time λ , energy consumption due to idle time (\mathcal{E}_{id}), transmission (\mathcal{E}_{tx}), reception (\mathcal{E}_{rx}), backoff time (\mathcal{E}_b), and (\mathcal{E}_{sl}) are calculated as

$$\begin{aligned} \mathcal{E}_{id} &= \mathcal{P}_{id}(\lambda - k \cdot (\mathcal{D}_{dc} + 2\mathcal{D}_{cca}) + 2\mathcal{D}_{cca} \\ &\quad + \mathcal{D}_{data} + \mathcal{D}_{ack} + \mathcal{D}_b + \mathcal{D}_{tr}) \\ \mathcal{E}_{tx} &= \mathcal{P}_{tx}(\mathcal{D}_{data} + \mathcal{D}_{ack}) \end{aligned}$$

$$\begin{aligned} \mathcal{E}_{rx} &= \mathcal{P}_{rx}(2\mathcal{D}_{pt} + \mathcal{D}_{tr}) \\ \mathcal{E}_{bo} &= \mathcal{P}_{rx} \cdot \mathcal{D}_b \\ \mathcal{E}_{sl} &= \mathcal{P}_{sl} \cdot (\mathcal{D}_{dc} + \mathcal{D}_s) \end{aligned}$$

where \mathcal{P}_{id} , \mathcal{P}_{tx} , \mathcal{P}_{rx} , \mathcal{P}_{sl} , and \mathcal{P}_{bo} are power required per unit time in idle, Tx, Rx, sleep, and backoff modes, respectively. \mathcal{D}_{pt} is the propagation delay, \mathcal{D}_{tr} is the transition delay for switching over from sleep to receive mode, and $k = \lfloor (\lambda/\mathcal{D}_{dc}) \rfloor$. For any collision, a subsequent re-transmission will consume extra \mathcal{E}_{tx} and \mathcal{E}_{id} energy. The operating voltage of CC2420 is 2.1–3.6 V and it requires 17.4 mA, 18.8 mA, and 1 μA (max) in transmit, listen, and sleep mode, respectively. The value of \mathcal{D}_{dc} is not fixed in our case, so considering an average value of 200 ms $\in \{150, 250\}$, for 2.3 V, $\lambda = 500$ ms, idle time (\mathcal{D}_{id}) is found to be 91.168 ms and hence $\mathcal{E}_{id} = 3.94$ mW. Similarly, $\mathcal{E}_{rx} \approx 0.02$ mW, $\mathcal{E}_{bo} = 0.138$ mW, and $\mathcal{E}_{sl} = 0.00046$ mW. Total energy consumption in one-hop transmission will be $\mathcal{E}_{total} = 4.1$ mW. Further, other parameters like distance, weather and cross-layer complexity may consume additional energy. The simulation and testbed performance of the proposed protocol are extensively discussed in Section IV.

3) *Architectural Complexity and Communication Overhead in CLAD Protocol*: The proposed cross-layer MAC protocol shares \mathcal{Q} and \mathcal{L}_i value of routing which helps to decide appropriate sleep duration. The cross-layer decision enables the network for a distributed construction and reduces control overhead at the MAC layer. In network protocol stack of 6LoWPAN-based architecture like Contiki, there is an adaptation layer in between MAC and routing layer. The message propagation latency for multilayer (layer 1 to n) can be calculated as

$$\mathcal{D}_{1 \rightarrow n}^t = \sum_{i=1}^n (\mathcal{D}_{Ti} + \mathcal{D}_{Pi}) \quad (5)$$

where \mathcal{D}_{Ti} is the message travel time between layer i interface and layer $i + 1$ interface and \mathcal{D}_{Pi} is the processing time. However, direct signaling is used to exchange information between MAC and routing layer. For two nonadjacent layers l_x and l_y , direct propagation latency is calculated as [28]

$$\mathcal{D}_{l_x \rightarrow l_y}^d = \frac{\mathcal{D}_{1 \rightarrow n}^t}{n - 1}. \quad (6)$$

This scheme of cross-layer signaling gives $n - 1$ speedup factor.

4) *Effects of Weather in the Proposed 6LoWPAN-Based Network*: Weather-related parameters such as humidity, temperature, fog, cloud, and rain affect the signal strength in proposed IEEE 802.15.4-based 6LoWPAN. The received signal strength indicator (RSSI) is most widely used to estimate signal quality [29]. For a link of distance d , received signal power, $\mathcal{P}(d)$ is computed according to the following equation:

$$\mathcal{P}_{rsi}(d) = \mathcal{P}_0 - 10\eta \log\left(\frac{d}{d_0}\right) + \mathcal{G}_\sigma \quad (7)$$

where \mathcal{P}_0 is the RSSI value at a mention distance d_0 , η is the attenuation factor, value of which depends upon the environmental factors around the receiver node, and \mathcal{G}_σ refers to

Gaussian random variable at zero means and σ^2 variance. The ITU recommended a model for fog or cloud attenuation which is valid up to 200 GHz [29]. According to which specific attenuation due to fog/cloud is

$$\eta_c = \varphi \mathcal{M} \quad (8)$$

where φ and \mathcal{M} are specific attenuation coefficient and liquid water density, respectively. Value of \mathcal{M} varies with changing air temperature as [30]

$$\mathcal{M} = \frac{\frac{\rho}{\gamma_a \mathcal{T}} (1 + \mathcal{H}_c)}{1 + \frac{\mathcal{H}_c \gamma_w}{\gamma_a}} \quad (9)$$

where \mathcal{T} is the absolute temperature of air, ρ is the pressure in humid air, γ_a and γ_w are the individual gas constants of air and water vapor, respectively, and \mathcal{H}_c is the specific humidity. Luomala and Hakala *et al.* [31] discussed the effect of temperature on different states of humidity. Other than attenuation due to rain, the increased size of water droplets may cause reflection, refraction, or scattering. A performance comparison of RSSI for cloudy and normal weather in hilly terrain areas is discussed in Section IV-B.

B. WiLD Network

Different LPWAN technologies such as LoRaWAN, SigFox, and NB-IoT are designed for long-range connection, but due to very low data-rates and processing capabilities, these are not suitable for carrying a huge amount of data and running fog computation. However, both of them can be supported by the use of the WiLD network with ease. The WiLD network is used to connect the rural regions from a remote location situated far away from the point of Internet connectivity. A WiLD network in our proposed system can be defined as follows.

Definition 3 (WiLD Network): A WiLD network can be presented as a graph $G(R, E)$, where R is a set of WiLD nodes including a gateway, set of the relay nodes and a set of leaf nodes, and E is the set of long-distance point-to-point links.

A WiLD network can be modeled as a tree with levels L_c . For any level l_i , position of i th node is $R_{i,l}$. Similarly, any link between three levels $l-1$, l , and $l+1$ for nodes i th, j th, and k th communicating in a multihop manner can be written as $(R_{i,l} \rightarrow R_{k,l+1}) \in E$. The gateway node, A is responsible for handling the initialization, synchronization, and scheduling of channel access. As shown in Fig. 1, WiLD network consists of multiple P2P links forming a mesh scenario. The network connectivity from a gateway node situated at district head-quarter extended till rural areas for last mile coverage. The TDMA-based MAC protocol is proven to be suitable. The proposed architecture uses a two-color scheduling 2C-MAC protocol [3], which reduces the overall data frame into two slots by slot reuse concept.

C. Fog Computing

A prediction by International Data Corporation found that the amount of data analyzed on devices that are physically close to the IoT is approaching 40% [32]. That is, analyzing the data close to the sensor areas minimizes latency up to a large value.

Definition 4 (Fog): A virtualized platform which enables storage, computation, and networking services in between the sensor nodes and the existing cloud computing centers.

It analyzes agricultural data close to the deployed field to reduce latency. It also increases greater business agility as developers can quickly develop fog application with less cost and deploy wherever needed [12]. All these computations can be carried out locally due to the support of a specific node or set of nodes called as fog node.

Definition 5 (Fog Node): A fog node is a part of connected network situated closer to “things” of IoT and extends services toward the cloud.

The hierarchical fog nodes structure helps to provide distributed computing in the network and ensures QoS for the delay sensitive applications. In the proposed model, reception of sensory information is done using application layer protocol like MQTT or COAP. Further, real-time control, analytic with milliseconds response time, and sending only aggregated data calculated from periodic traffic generated by sensors are done by a fog node.

D. Cloud Computing

Definition 6 (Cloud): A cloud in IoT provides autonomous and on-demand access to a shared list of computing resources kept in the storage server. The services that an IoT application demands from a cloud are as follows:

- 1) Supporting a huge number of devices to communicate.
- 2) Available anytime for computation.
- 3) Provisioning security and privacy to data.
- 4) Available storage.
- 5) Helps in analytic report generation.
- 6) Low cost.

E. Performance Model of the Proposed Framework

The proposed framework is a union of multiple networks having multihop communication in each of the modules. Hence, a key concern of the proposed dense network topology is the end-to-end delay. The primary alternatives of delays are as follows:

- 1) Transmission and processing delay, Δ , and if there are multiple hops, this delay will be multiplied,
- 2) Propagation delay, which is dependent on the Euclidian distance [33] between two ends and speed of wireless signals.

Let us consider the sensor network component for delay calculation. If d be the distance covered by a wireless signal travel per unit time and $E_{i,j}$ be the Euclidian distance between any pair of nodes i and j , then the discrete propagation delay in a one-hop link (i, j) will be $[E_{i,j}/d]$. So, delay over multihop is the sum of one-hop delay. If first hop delay is \mathcal{D}_1 and total delay is $\mathcal{D}_{\text{total}}$ then for WSN

$$\mathcal{D}_1 = \left\lceil \frac{E_{i,j}}{d} + \Delta \right\rceil \quad (10)$$

$$\mathcal{D}_w = \sum_{\text{hop}=i}^{j-1} \left\lceil \frac{E_{i,j}}{d} + \Delta \right\rceil. \quad (11)$$

Similarly, for the WiLD network, from node j to gateway k , multihop delay (\mathcal{D}_W) can be given by

$$\mathcal{D}_W = \sum_{\text{hop}=j}^{k-1} \left[\frac{E_{j,k}}{d} + \Delta \right]. \quad (12)$$

Then the total delay would be

$$\mathcal{D}_{\text{total}} = \mathcal{D}_w + \mathcal{D}_W. \quad (13)$$

As the WSN gateway and WiFi nodes are fog nodes, the decision can be processed and action can be taken from these nodes. Any decision taken in j node (i.e., first fog node), total delay (T_1) for complete sensing and actuation operation would be

$$T_1 = 2\mathcal{D}_w + \mathcal{D}_p \quad (14)$$

where \mathcal{D}_p is the decision processing delay in a fog node, which depends on the availability of sensor data and processing capabilities of the system. Again, for the first WiLD node, i.e., second fog node, $j + 1$

$$T_2 = 2(\mathcal{D}_w + \mathcal{D}_2) + \mathcal{D}_p. \quad (15)$$

Similarly, for remaining fog nodes $j + 2, j + 3, \dots$, and k , the total action time can be calculated and finally the time required, if the gateway node is used as fog is calculated as

$$T_{k-1} = 2(\mathcal{D}_w + \mathcal{D}_{k-1} + \mathcal{D}_{k-2} + \dots + \mathcal{D}_j) + \mathcal{D}_p \quad (16)$$

where $\mathcal{D}_{k-1} + \mathcal{D}_{k-2} + \dots + \mathcal{D}_j = \mathcal{D}_W$. From (15) and (16), it is clear that $T_1 < T_2 < \dots < T_{k-1}$. Based on the critical nature of different agricultural applications and to share the processing of data, priority of choosing a fog node ranges from j to k . Similarly, fog computing in the system can save bandwidth of the network up to a huge amount. For sending a packet P in the WiLD network having capacity \mathcal{C} , required bandwidth is $\mathcal{B}_{\text{req}} = (P/\delta)$, where δ is the transmission time and $\mathcal{B}_{\text{req}} \leq \mathcal{C}$. However, a fog node holding the responsibility to process the packet does not further forward the data to next hop saving bandwidth \mathcal{B}_{req} for the remaining of the network.

IV. PERFORMANCE ANALYSIS

We have analyzed the performance of the proposed system in simulation as well as testbed environment.

A. Simulation Analysis

The performance of proposed framework is analyzed in two phases.

- 1) Individual performance of the proposed WSN and WiLD network.
- 2) Performance of the overall framework using results achieved in the first phase.

In Cooja simulator of Contiki, we used CC2420-based Skymote device for the simulation of 6LoWPAN. A network topology with 50 nodes are created, where the position of nodes from the sink is kept static to ensure multiple hops. A detailed tabular description of the test setup is given in Table III.

TABLE III
DIFFERENT PARAMETERS FOR WSN SIMULATION

Parameters	Value
No. of Nodes	50
MAC Protocol	XMAC, ContikiMAC, CLAD
Radio Driver	TI CC2420
Framer	802.15.4
Check Rate	8
Low Power Listening (LPL)	150-250ms
Environment	UDGM of Contiki
Node Position	Multi-hop and static
Simulator	Cooja
Simulation time	5 min

As shown in Fig. 3(a), with increasing number of nodes throughput, reduces. This is due to the high contention in the channel coped with the high frequency of channel check which results in a significant number of packet drops. While X-MAC relies on ACK for strobes before actual transmission of data packets, ContikiMAC directly sends the data packets. The strobes further generate unnecessary traffic in the network and thus the overall throughput of X-MAC goes down well below Contiki-MAC. The proposed MAC protocol achieved higher packet received ratio (PRR) than ContikiMAC and XMAC with increasing number of nodes. In CLAD, a node increases its duty cycle based on the child nodes, hence in multihop scenarios, chances of successful Tx/Rx in higher than the other relevant protocols. Our scheme maintains a traffic load-based solution which provides priority to the downlink traffic and hence PRR is higher. The proposed scheme chooses a less congested path for the downlink flows. To validate the congestion control mechanism in the proposed scheme, we have measured downlink PRR and end-to-end delay for the proposed and traditional routing decision. As shown in Fig. 4(a), PRR after saturation point shows worst as traditional RPL routing does not consider current load for event-driven downlink traffic.

Similarly, we have calculated multihop end-to-end delay applying different RDC protocols. The average delay is calculated for traffic sending from end nodes to the sink node for XMAC, ContikiMAC, and CLAD. From Fig. 3(b), it is clear that the proposed protocol achieves superior performance than the others. As the intermediate nodes try to become available according to the hierarchy, waiting delay in the queue is reduced. Furthermore, downlink traffics are prioritized in the proposed protocol to reduce delay and hence shows the best performance among the compared schemes. Contiki's energy module [34] is used to calculate the energy consumption of a node per second. We can observe from Fig. 3(c) that the LPL duration strongly affects power consumption in comparison with the fixed duty cycle-based MAC protocol. Changing the LPL value from 150 to 250 ms, energy consumption reduces by 40% in XMAC and ContikiMAC protocol. However, allowing dynamic LPL configurations based on traffic load and the number of nodes, the proposed scheme achieves better performance over the relevant protocols. In CLAD, with increasing hops, energy consumption increases due to the decreasing \mathcal{D}_{dc} . For one-hop with 200 ms, the simulation result shows 4.11 mW of energy consumption, which is almost the same with the theoretical result.

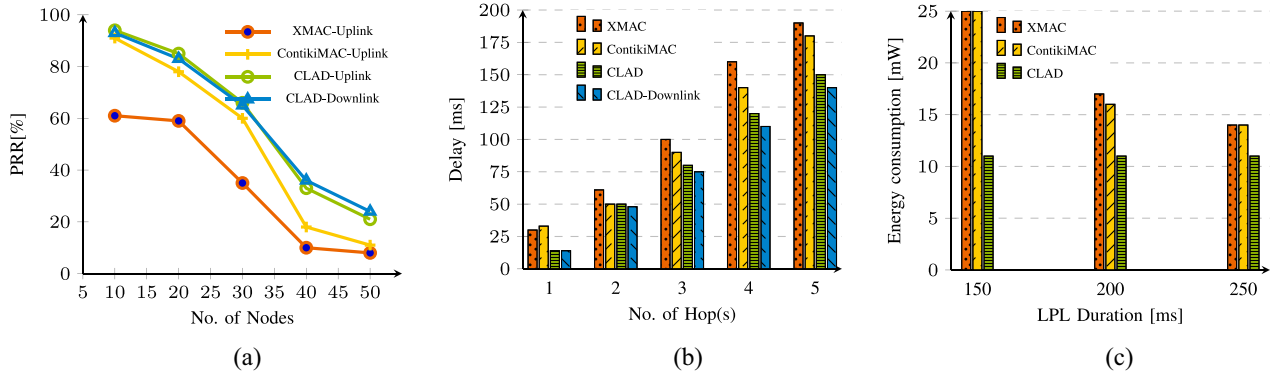


Fig. 3. Average (a) PRR over increasing number of hops, (b) end-to-end delay over increasing number of hops, and (c) energy consumption of multi-hop network.

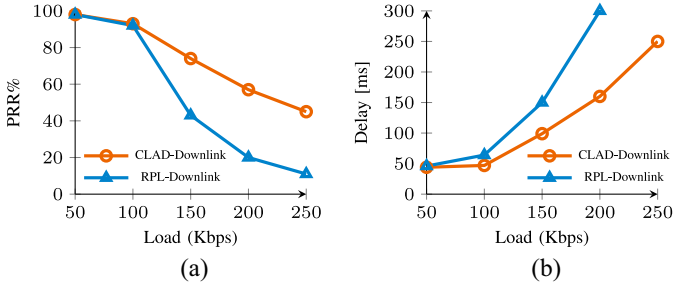


Fig. 4. Average (a) PRR (%) with varying loads and (b) end-to-end delay with varying loads.

TABLE IV
SIMULATION PARAMETERS OF THE FOG FRAMEWORK

Parameters	Value
Devices	Cloud, LDGF, LDRF, LSGF, Sensor/Actuator
LDGF → LDGF network latency	11.5 ms [From TABLE VIII]
Sensor/Actuator → LSGF network latency	17 ms [From TABLE VI]
Cloud RAM	4GB
LSGF RAM	1GB [From Subsection IV-B1]
LDGF RAM	128MB [From Subsection IV-B2]
Uplink Bandwidth	10Mbps
Downlink Bandwidth	10Mbps
Node Position	Hierarchical
Simulator	iFogSim [35]
Simulation time	1000 seconds

Once the packet from WSN is received by the local gateway, the gateway forwards it to the WiLD network. To ensure QoS requirements over such long distance networks, fog computing is used. To simulate the proposed computation mechanism, we have used iFogSim simulator [35]. Detail simulation parameters are mentioned in Table IV. The simulation is carried out over tree-based WiLD network topology as shown in Fig. 5. To cover a larger area and to test the fog performance over a various size of the network, WiLD nodes (fog nodes) are increased from 1 to 19 in between the cloud and the sensor device. WiLD nodes are positioned in a hierarchical manner and the end nodes are responsible for connecting the sensor/actuator nodes. Based on the number of fog nodes across physical topology configurations scenarios 1–5 of nodes 1, 5, 10, 15, and 19, respectively, are considered. Two placement strategies, viz., cloud and fog are created.

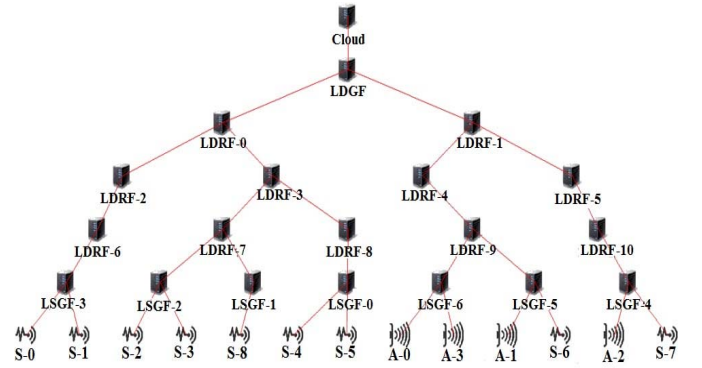


Fig. 5. Simulation topology for fog performance, where A and S are sensor and actuator, respectively. Long distance gateway fog (LDGF), long distance relay fog (LDRF), and local sensor gateway fog (LSGF) are the fog nodes.

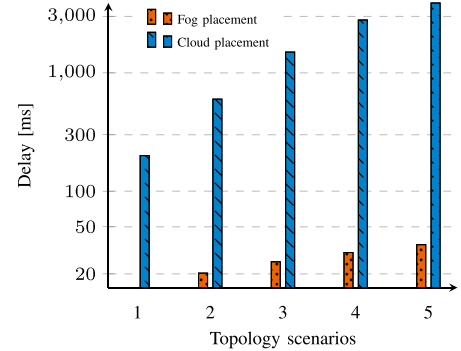


Fig. 6. Average control loop latency for different physical topologies.

In the cloud-centric scenario, all the operators (for example, diseases detection, solutions, environment issues detection, etc.) are placed in the cloud. Whereas in fog scenario, these operations are pushed toward the fog devices. In this application scenario, the delay is calculated over the control loop Sensing → reading → problem detection → taking action, i.e., the cloud or fog module will first read the sensed data, then find current problems and action will be taken to the appropriate actuator.

As shown in Fig. 6, when there is no computation in the WiFi nodes, cloud placement do the operation creating a huge delay in the control loop. With the increasing number of WiFi

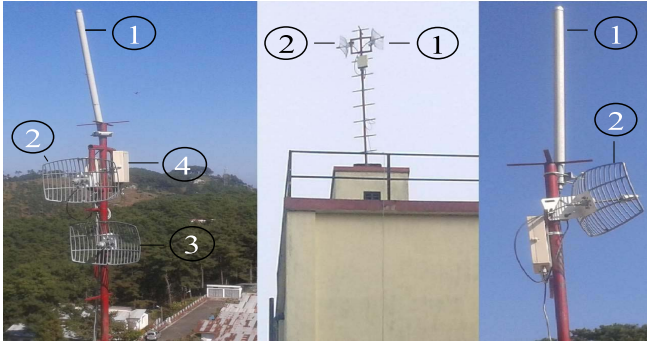


Fig. 7. Leaf/end node (right), where (1) is an omnidirectional antenna, which is closer (< 100 m) to 6LoWPAN gateway nodes, and (2) is a directional antenna connected to WiLD relay node for bridging connectivity, a relay node (middle), where (1) and (2) are two directional antennas for Tx/Rx operation and establishing multihop communication, a root node (left), where (1) is an omnidirectional antenna for local area connectivity, (2) and (3) are two directional antenna to enable communication between two sub-WiLD networks for extending connectivity, and (4) is the RouterBoard.



Fig. 8. Google map view of deployed testbed setup.

nodes, latency also increases. The primary reasons for the delay are the multihop transmission, last-mile solution, periodicity of sensor data, computation complexity, etc. However, with fog placement, the delay has been reduced up to a huge margin. Rather than shifting all the operations to the cloud, fog nodes take the responsibility locally. For analytic purposes, fog nodes only send the aggregated data using some existing data aggregation algorithms on duplication. In cloud placement strategy, due to a large number of connected devices, load also increases significantly in contrast with fog placement. We can attribute to a fact in the fog-based computation that most of the critical and sensitive communication taken using low latency links. Therefore, modules like problem detection and decision are carried on the fog nodes which further reduces the data volume earlier sent to a cloud.

B. Testbed Evaluation

Different components of the testbed setup are discussed as follows.

1) *6LoWPAN-Based WSN Setup*: The 6LoWPAN-based WSN is interfaced with the WiLD network for long distance connectivity. A RaspberryPi device configured with 1-GB RAM, 1.2-GHz ARM processor, and CC2531 for 802.15.4

TABLE V
6LoWPAN Node (CC2650) SPECIFICATIONS

CPU	4x ARM Cortex-A53
RAM	8KB Cache, 20KB SRAM
Radio	2.4-GHz RF Transceiver Compatible with BLE 4.2 and
Frequency	802.15.4 PHY and MAC
Storage	128KB Programmable Flash
Low power	1.8 - 3.8 V
Sensor controller	Ultra low power
Peripherals	10, 15, or 31 GPIOs, Temperature Sensor, UART, I2C, I2S, etc.

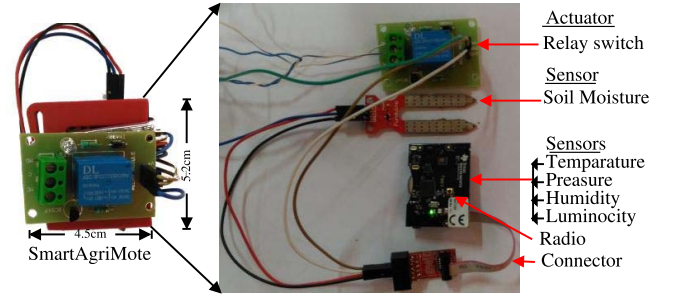


Fig. 9. Programmed smart mote for the proposed agriculture and farming application.

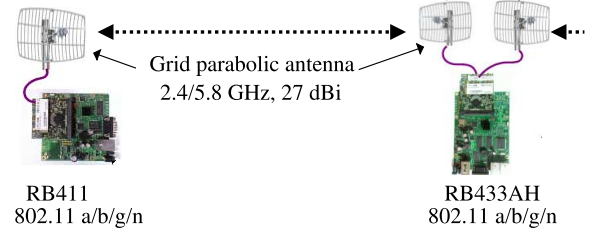


Fig. 10. Setting up WiLD links using high gain directional antennas.

interface is used for the local gateway nodes. Similarly, software like Contiki-OS, Paho for MQTT broker, COAP client, Mysql, etc., are used. Detailed specification of CC2650 is shown in Table V. CC2650 provides longer battery life using a coin cell with ultralow power microcontroller. It further saves energy with built-in low powered microelectromechanical sensors. Along with the six built-in weather-related sensors, additionally, two GPIOs are programmed out from JTAG interfaces for adding a soil moisture sensor and a relay switch to add an actuator. Fig. 9 shows the programmed low powered smart mote named as *SmartAgriMote* for the proposed agriculture and farming application.

The proposed WSN-based MAC protocol is implemented over cc26xx-Web-demo module to see the PRR and Round-trip delay using upper layer protocols MQTT and COAP. To generate uplink traffic, sensor nodes are set to send a packet at every 5 s. Similarly, with the same duration, a command button from a Web interface was used to measure downlink traffic. We have used five motes along with the gateway for the performance test. As shown in Table VI, with increasing number of hops, delay increases, and PRR decreases. From RTT, end-to-end delay for one-hop would be $(34/2 =) 17$ ms, which almost vary close to the simulation result. The same case can be applied for multihop scenarios too. In hilly terrain areas,

TABLE VI
PERFORMANCE RESULTS OF THE PROPOSED
6LOWPAN-BASED SENSOR NETWORK

	1-hop	2-hop	3-hop	4-hop	5-hop
Uplink-PRR%	98	88.5	72.4	48	20
Downlink-PRR%	97	86	73	51	23.7
RTT	34ms	84ms	190ms	276ms	410ms

TABLE VII
RSSI IN CLOUDY AND NORMAL WEATHER CONDITIONS

	2m	10m	20m	30m	40m
Normal	-53dBm	-61dBm	-75dBm	-79 dBm	-80dBm
Cloudy	-56dBm	-64dBm	-79dBm	-82 dBm	-82dBm

TABLE VIII
PERFORMANCE OF THE PROPOSED WILD NETWORK

	1-hop	2-hop	3-hop	4-hop
UDP-Throughput	18Mbps	17.3Mbps	15.4Mbps	14.3Mbps
TCP-Throughput	18.7Mbps	15.3Mbps	12.3Mbps	9.5Mbps
UDP-RTT	23ms	56ms	156ms	210ms

cloud and fog are common for most of the time. We have analyzed the weather effect on RSSI for different distances. Unavailability of an external antenna in CC2650, it can cover maximum up to 40 m in a single hop scenario. However, as shown in Table VII, RSSI measured in cloudy weather condition is lesser than normal condition. Also, we have measured the downlink PRR for the proposed congestion aware solution and shows improvement over traditional routing.

2) *WiLD Network Setup*: As shown in Fig. 7, three types of nodes are used for complete WiLD network setup. We have used two types of router boards: a) Mikrotik RB433AH and b) Mikrotik RB411 for the WiFi nodes. These boards are configured with 128-MB RAM and 680 MHz of nominal clock speed. The configuration of a P2P connection using these two boards is shown in Fig. 10. Google map view of the testbed is shown in Fig. 8. The main purposes of two relay nodes in the setup are: a) creating a multihop scenario covering longer distance and b) achieving a proper line of sight in hilly terrain. We have implemented the 2C-MAC protocol over Atheros-based Ath9k driver package of OpenWrt. Iperf and Ping are used to check the throughput and delay performance of the network. In 2C-MAC protocol, same slots are used by every two hops nodes, and hence throughput performance does not get reduced significantly over multiple hops (which can be seen in Table VIII).

After individual performance evaluations of both network components, we have analyzed the control system in two scenarios:

- 1) Doing cloud computation at the Internet.
- 2) Doing fog and cloud computation at WSN gateway and Internet.

In the first approach, computations and report generation are done at the cloud. Whereas, in the second approach, except the report generation, other computations are carried out at the local gateway. The sensor network gateway only sends deflected data to the cloud to reduce bandwidth in the network. Calculating RTT at edge node (i.e., local gateway) we found the average value as 357 ms, whereas, at hosted cloud, it is 5032 ms. Fig. 11 shows a deployed on-field sensor node.



Fig. 11. Deployed on-field sensor node (SmartAgriMote).

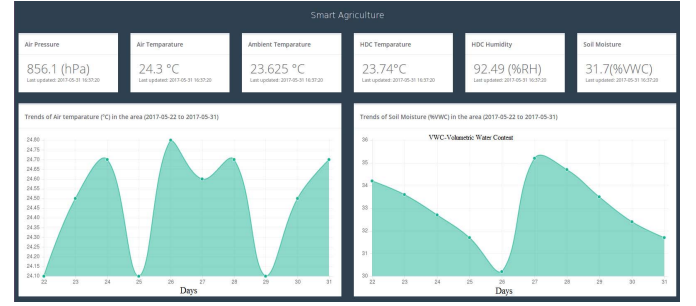


Fig. 12. Web-based interface to monitor current trends of the field.

A Web-based interface for visualizing the system is shown in Fig. 12. Based on the current requirements of agriculture fields, automation is also carried out. For example, based on the soil moisture values received, automatically water supply switches its mode to *on*.

V. CONCLUSION

This paper has presented an IoT-based control system for advancement in agriculture and farming of rural areas. Different components and enhancements of the control system are discussed and analyzed in all aspects including testbed evaluation. The MAC and routing solution for IoT have achieved better energy, delay, and throughput performance. Combining the proposed solution with the WiLD network, it is possible to reduce delay and improve throughput for end mile connectivity. The proposed fog computing solution takes action with lesser delay and saves bandwidth in the network. The economy of a developing country mainly depends on agriculture and farms in rural areas and applying traditional approaches is not sufficient. Use of modern technologies like IoT with low cost and scalable solutions are very important. The proposed solution is also suitable for other applications like smart healthcare and smart grid in rural regions.

To reduce congestion in the proposed large-scale network, along with the routing and fog computing solution, technologies like IEEE 802.11n/ac/ah having more physical data-rate capacity can be used. Moreover, dynamic bandwidth allocation-based configuration at existing relay WiLD node can further be installed. The chance of attacks like tampering and manipulation of data is high if we do not secure the long distance covering wireless network. Similarly, the privacy of individual devices is very important to autonomously communicate over different entities such as fog, cloud, and Internet.

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