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Internet of things-based indoor smart hydroponics farm monitoring system

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ABSTRACT

Internet of things (IoT)-enabled systems are being used to monitor, control, and optimize agricultural systems like hydroponics. Optimization of these systems requires monitoring of various growth factors for plants which will also require multiple sensors. With the number of wireless sensors needed to track the conditions of the hydroponics system, the wireless sensor network will also grow in size and complexity. In this paper, a hybrid IoT-based monitoring system, with both wired and wireless components, with a target indoor farm application is proposed. The system was implemented using controller area network for the wired component, IPv6 over low power wireless personal area network (6LoWPAN) for the wireless component, and Amazon Web Services for the cloud services. Network simulations were performed to compare the network performance of the proposed hybrid system and the purely wireless system. The simulations show that incorporating a wired system results in improvements such as the reduction of packet loss from 12.23% in the purely wireless system to 5.62% in the hybrid system with burst traffic and even down to 0.0% in the hybrid system with continuous traffic.

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1. INTRODUCTION

Internet of things (IoT) is becoming a widely popular solution for making different aspects of the world more intelligent. IoT-based systems aid in detecting, solving, and possibly preventing problems in the daily lives of people. Large amounts of data, or big data, are being utilized to process diverse information to aid in understanding and improving various fields [1], [2] such as in transportation [3]–[5], health [6]–[8], industrial [9]–[11], and smart environments [12]–[14].

In particular, advancements in wireless sensor networks (WSNs) enable a widely interconnected computing environment by combining sensing and wireless communication technologies. WSN’s ability to collect and relay data between nodes in a real-time environment has unlocked the potential for WSNs to be used for a wide array of applications. One of these fields is agriculture. Smart agriculture focuses on predicting and/or optimizing yield by monitoring various growth factors for plants [15]–[17]. Having a smart monitoring system for agriculture application will help agronomists optimize farm production by understanding optimal conditions that promote plant growth. This will result in a more efficient and productive farm.

In the field of farming, there has been an increasing interest in hydroponics due to rising urbanization and consequently, decreasing land available for cultivation [18]–[20]. Hydroponics replaces the dependence on soil with water to easily control the different materials that the crops interact with. This reduces the risk of exposing plants to harmful chemicals and materials found in soil. This method also helps agriculturists easily adjust the macronutrient and micronutrient content in the growing medium.

It is critical to be able to measure the different factors that can affect plant growth to help optimize the crop yields for soilless culture facilities. Some of the growth factors include data on the water medium used such as water temperature, pH level, as well as electrical conductivity, air temperature, light intensity, and humidity. However, with the number of wireless sensors needed to track the conditions of the hydroponics system, the WSN will also grow in size and complexity.

As a solution, a hybrid sensor system, comprised of both wireless and wired networks, is proposed in this paper. This paper aims to implement an IoT-based system to monitor the conditions in a hydroponics setup. Additionally, the system is intended as a vertical hydroponics system in an urban farming setup. This article builds upon an existing proposed hybrid system [21] and explores the improvements that the introduction of the wired system can bring to the wireless system by comparing the network performance of the purely wireless system and the hybrid system.

2. METHOD

The monitoring system is designed for an indoor hydroponics farm. One of the target farm environments is a 40-ft container van. A 3D model of the envisioned setup is shown in Figure 1. The setup is equipped with four vertical farming grow racks, shown in Figure 2. Each rack consists of 4 layers with each layer having grown lights, water channels, and tubing.

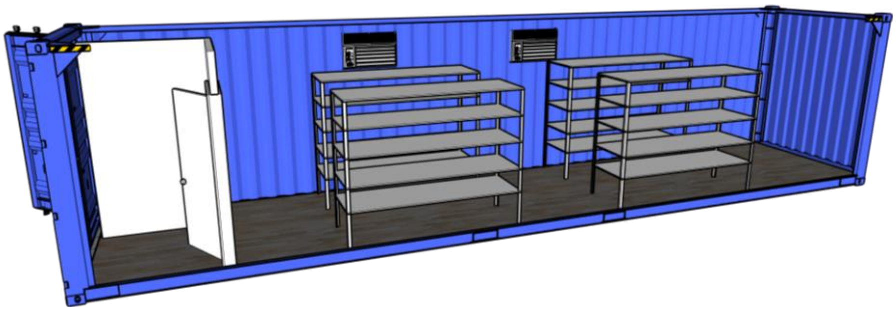


Figure 1. 3D model of a container van with 4 grow racks as the target application of the system

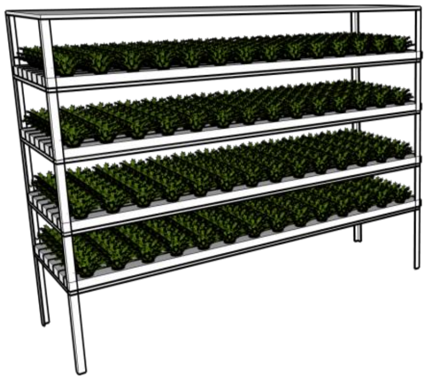


Figure 2. 3D model of a grow rack

2.1. System design

Because the setup revolves around hydroponics, different parameters in the water that are relevant to plant growth such as nutrient concentration and water temperature must be monitored. Furthermore, the setup also requires the monitoring of growth factors both inside the rack environment such as light intensity, relative humidity, and outside the rack environment such as room temperature and room relative humidity. Thus, three sensor sets were identified in the system: macroenvironment sensors, microenvironment sensors, and water sensors.

Additionally, due to the number of nodes and sensors required, the sensor system was also categorized into a wired component and a wireless component. To aid with the management and compartmentalization of a single grow rack as a repeatable unit, this system proposed all sensor sets inside the grow rack to be aggregated into a single wired network using a controller area network (CAN). Therefore, there are three main components of the entire monitoring system: the CAN system, the IPv6 over low power wireless personal area network (6LoWPAN) system, and the cloud services.

2.2. Sensor sets

The indoor smart hydroponics system is comprised of three categories of sensor sets. The three categories include macroenvironment sensor sets, microenvironment sensor sets, and water sensor sets. These are categorized based on the growth factors that are measured by the device and the location of the device in the room.

2.2.1. Macroenvironment sensor set

Macroenvironment sensor set refers to devices that measure the condition of the environment outside the growing cabinets. Data from macroenvironment sensors provide inputs used for maintaining the optimal and/or desired conditions in the grow room. This sensor set measures air temperature, relative humidity, air pressure, and illuminance. Additionally, the sensor set’s supply voltage and battery temperature are also being observed to monitor system health. Each macroenvironment device is 6LoWPAN-enabled and is treated as a wireless node. The sensor set may also be used to measure conditions outside of the grow area/container van to provide external data.

2.2.2. Microenvironment sensor set

The microenvironment sensor set measures the different conditions inside the grow rack which are significant to plant growth. This sensor set supports gas sensors, illuminance sensors, analog acidity sensors, and analog electrical conductivity sensors. Unlike the macroenvironment sensor set, the setup for the microenvironment sensor set communicates through a wired system CAN and is all powered by a single power supply. Since multiple microenvironment sensors are placed in a single grow rack and these are connected through a wired network, only the master device of the wired system connects to the 6LoWPAN wireless network.

2.2.3. Water sensor set

The water sensor set also measures conditions inside the grow racks that are significant to plant growth but focus on water-related measurements. Since the desired application for the monitoring system is a hydroponics farm, water-based factors such as water temperature, acidity (pH), and electric conductivity (to evaluate nutrient content) are crucial data to be measured. Like the microenvironment sensor set, the water sensor set is also connected to the wired network in each grow rack.

2.3. Communication systems

The proposed system in [21] and in this paper is a hybrid system, a mix of a wired CAN system and a wireless 6LowPAN system. CAN is a wired protocol widely used in industries such as the automotive industries because of the protocol’s robustness [22]. The CAN system is a set of sensing nodes communicating via a common CAN bus, as shown in Figure 3. The wired network allows the measurements to be aggregated to a common point and for the configuration to be centralized. This network is designed to include all sensor sets inside a grow rack such that each grow rack has a single CAN master and a separate CAN bus from other racks.

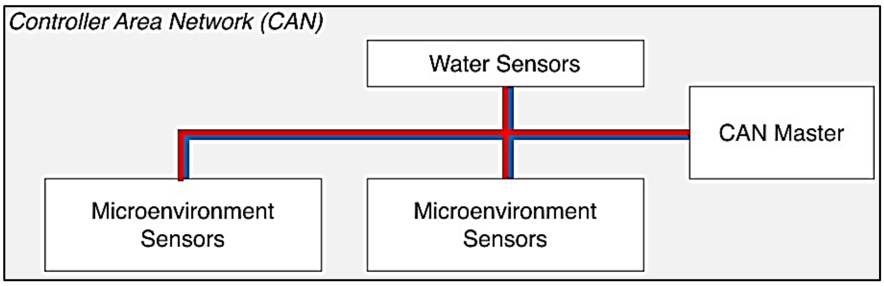


Figure 3. An example of a CAN bus [21]

The sensing nodes are designed to be modular such that sensors can be added or removed from each node. The centralized configuration allows such modularity to be interfaced easily. Aside from providing modularity and ease of configuration/management inside the grow racks, the CAN system also decreases the number of wireless nodes in the 6LoWPAN system.

2.4. The 6LoWPAN system

6LoWPAN is a wireless network protocol designed for constrained devices making it is very suitable for IoT applications [23]. In the 6LoWPAN system, there is a single border router device that acts as the network gateway and the sink node. All wireless sensor nodes send their data to the border router for storage, post-processing, and uploading to the cloud. The CAN master devices act as wireless sensor nodes, aggregating the data of all CAN slaves in their local wired networks per grow rack. A side from this, multiple standalone wireless sensor nodes are placed around the room to measure different room conditions. The deployed hybrid system is illustrated in Figure 4.

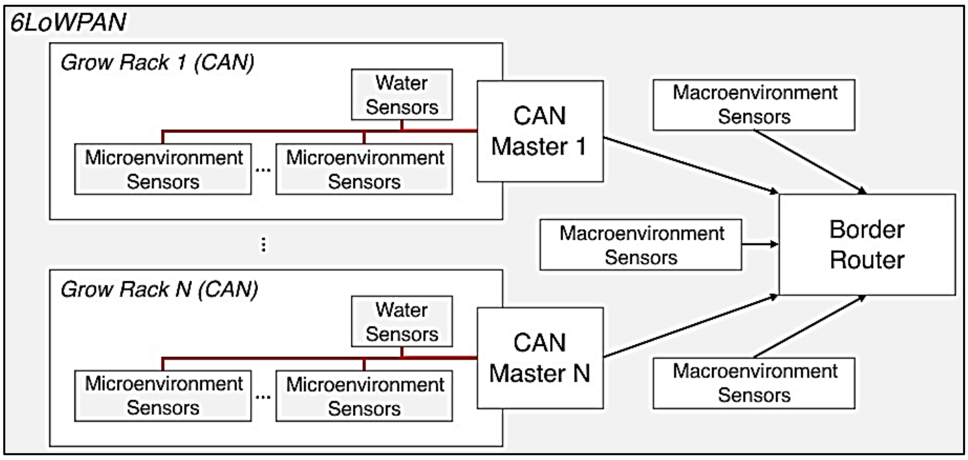


Figure 4. An overview of the 6LoWPAN system interfaced with the CAN system

2.5. Cloud services

To make farm data available to the user, cloud services are deployed to handle data storage, visualization, and analytics. In the design process, the different cloud services are divided into three categories based on functionality. These categories include the device-centric pipeline for IoT devices and data management, the user-centric pipeline for end-user access, and the analytics pipeline for data insights.

2.5.1. Device-centric pipeline

The device-centric pipeline is composed of cloud services geared towards management of the IoT devices and data. These include services for device registry, certificate management, and policy management, data ingestion, and data storage. Cloud services in the device-centric pipeline provide connection endpoints for the edge devices such as the border router. This pipeline also handles the routing to different cloud services handling other functionalities such as fault detection and visualization.

2.5.2. User-centric pipeline

The user-centric pipeline focuses on providing end-users with access to the data and includes insights that will help the user optimize yield. This pipeline consists of cloud services that host the user applications and services that handle fetching data as requested by the user. The implemented user applications include a web application and a mobile application. These applications are used for sensor data monitoring. The applications can also act as a remote controller to the hydroponics system by providing users with a settings module to change the desired configuration of the system.

2.5.3. Analytics pipeline

The analytics pipeline provides insights into the hydroponics system. This pipeline includes cloud services geared towards the detection of WSN and hydroponics system faults, as well as handlers when faults are detected. The system will notify the user via SMS and e-mail, as well as push notifications from the user applications.

3. RESULTS AND DISCUSSION

There two main motivations in using a hybrid system instead of implementing a purely wireless system are first, for the easier and independent management of sensors inside the grow racks, and second, to reduce the number of wireless sensor nodes in the 6LoWPAN system. The following subsections aim to characterize network performance with the changes brought by the introduction of the wired CAN system into the purely wireless system, more specifically, the decrease in the number of nodes and the increase in the traffic of rack nodes. Lastly, the end systems (the purely wireless system and hybrid system) will be compared to show the overall effects of the introduction of the wired system.

3.1. Simulation setup

The simulation tool used in this paper is Cooja, the network simulation tool for the Contiki and Contiki-NG operating systems. Cooja offers node output logging and packet capture logging during simulation to be able to assess network connectivity and performance [24]. The operating system used in the tests is Contiki-NG, which is designed for WSN for Texas Instruments devices [25].

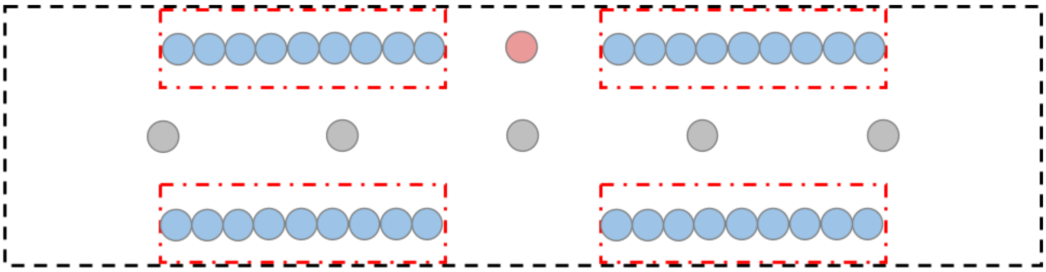
The simulations were set up to be similar to the intended application of the system is an indoor hydroponics setup, specifically a 40-foot container van. There are a total of four grow racks inside the room, with each rack having four layers each. The node breakdown inside a grow rack is described in Table 1. This results in the number of nodes in the room as described in Table 2. Figure 5 shows the different node layouts simulated in Cooja. Figure 5(a) shows the layout for the purely wireless setup, while Figure 5(b) shows the layout for the proposed hybrid setup. The node layout follows the expected node placement in the intended farm application.

Table 1. Wireless sensor node breakdown inside one grow rack

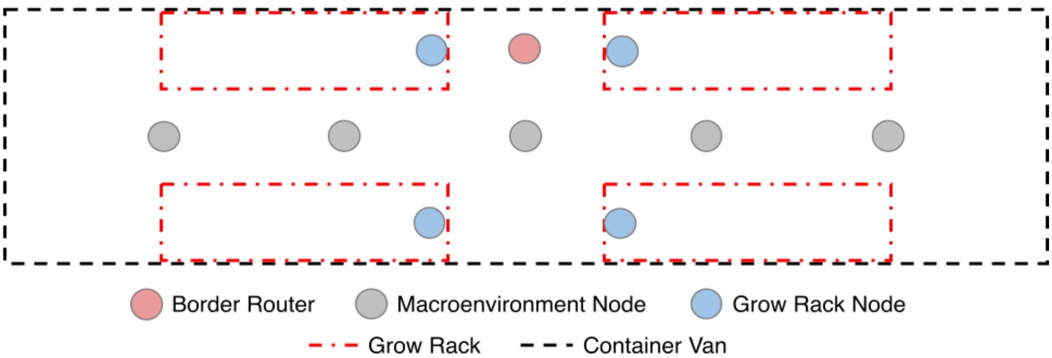
Number of water nodes per rack	Number of microenvironment nodes per layer	Total number of rack nodes per rack
1	2	9

Table 2. Wireless sensor node breakdown for the entire 40-ft container van with 4 racks

	Number of macroenvironment nodes	Number of rack nodes per rack	Total number of rack nodes	Total number of nodes
Purely wireless system	5	9	36	41
Hybrid system	5	1	4	9



(a)



(b)

Figure 5. The node layouts for (a) the purely wireless setup and (b) the proposed hybrid setup

Additionally, the radio medium used is unit disk graph medium (UDGM), specifically the UDGM: distance loss medium. UDGM: distance loss allows the user to set transmission ranges and Tx/Rx success ratio [26]. The simulations assume that the default power from Contiki-NG for CC2650 devices, +5 dBm, is used [27]. This results in a transmission range that is enough to cover the whole container van. Thus, the transmission range setting in the UDGM: distance loss medium used in Cooja was set such that the range of the border router encompasses all wireless nodes. After the initial comparison of the end-systems using the default power settings, another set of tests were done to explore the network performance when the range is reduced such that the transmission range of one device will only reach the nearest neighbor. This case forces the transmissions of nodes to hop before it reaches the border router. For each simulation, nodes send a message to the border router every 5 minutes, for a total of 100 application-layer messages per node. This is similar to the sending interval of the real-world sensor nodes implementation.

3.2. Performance metrics

For the tests involving a variable number of nodes and a variable amount of traffic in the rack nodes, the packet loss (in %) will be plotted for the different test points. The packet loss is taken as the ratio of the total number of application-layer messages received in the border router to the number of expected messages. The sequence numbers of the first five hundred packets from the border router are also plotted. This is to get a glimpse of how efficient the network is. An example plot for 1,000 packets is shown in Figure 6 where the ideal network has a constant increase in sequence numbers per packet while the less efficient network has a lower slope. This shows that the less efficient network has more packet retransmission than the ideal network. Then, the number of packet retransmissions is extracted from the packet capture logs by counting consecutive transmissions with the same sequence number. Lastly, in comparing the end-systems, the ratio of routing protocol for low-power and lossy networks (RPL) packets to user datagram protocol (UDP) packets is also shown to compare the overhead of the routing protocol during runtime.

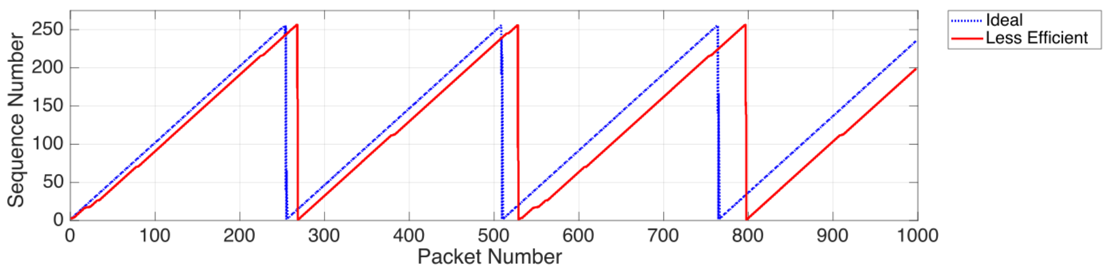


Figure 6. An example sequence number plot for two systems for 1,000 packets

3.3. Reduced number of nodes

The most evident impact of using the hybrid system is the reduced number of nodes. This is expected to improve the network performance in terms of packet loss and congestion [28]. Plotting the sequence numbers from the packet capture of transmissions from the border router, we can see that if the number of nodes is 17 and above, the network is less efficient than the ideal, which means there are more retransmissions as shown in Figure 7.

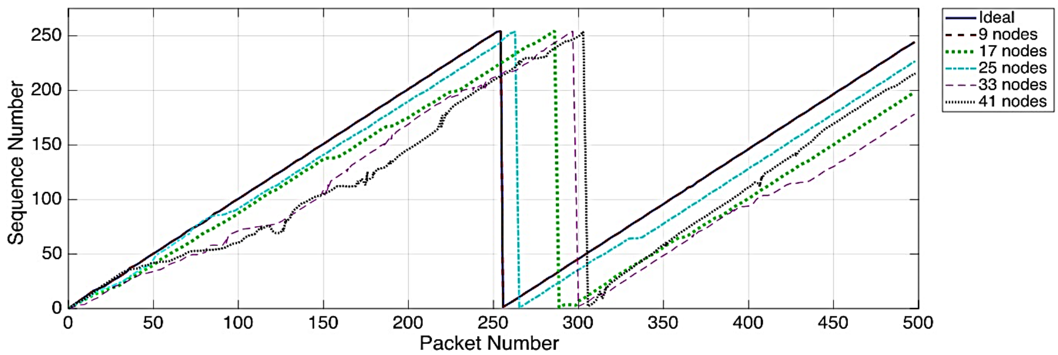


Figure 7. Plot of sequence numbers of the first 500 packets with variable number of nodes; the ideal case plot almost coincides with the for the 9-nodes system plot

This can be seen in Figure 8(a), wherein the number of retransmissions increases as the number of nodes increases. The 9-node system, however, is very similar to the ideal case. Figure 8(b) shows that the packet loss of the system increases as the number of nodes increase, up to 12.23%.

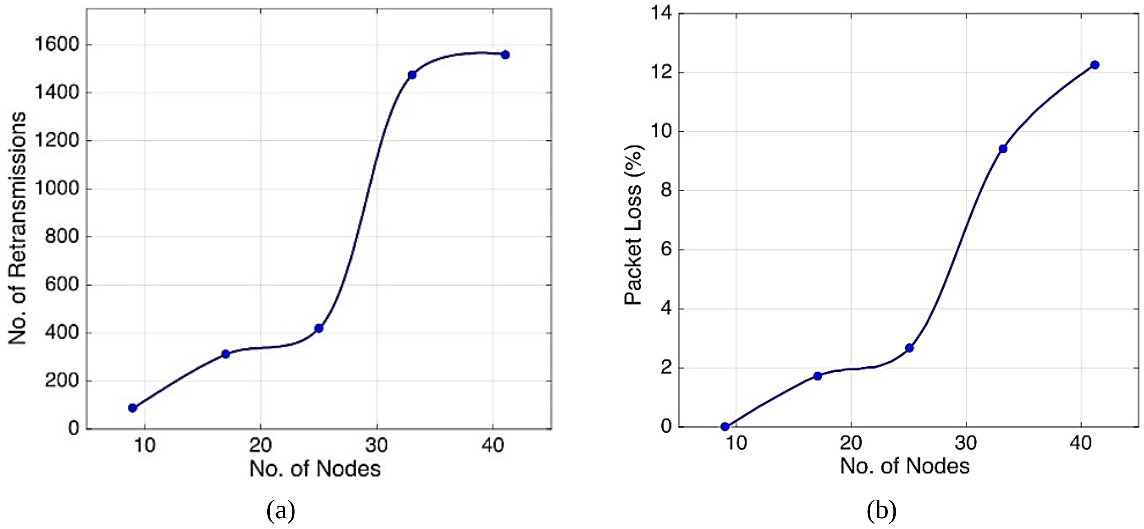


Figure 8. Plots of metrics for systems with variable number of nodes showing (a) number of retransmissions and (b) packet loss (%)

3.4. Increased traffic from grow rack nodes

In this set of tests, the layout of nodes is the same as the reduced system (1 node per grow rack) as shown in Figure 5. However, the number of messages that rack nodes send at each sending instance is increased. This multiplies the burst traffic that the nodes in the grow racks, which represent the CAN slaves that are also sending data in the racks but are hidden from the 6LoWPAN system. In the proposed hybrid system, each CAN master is interfaced to 9 CAN slaves, as seen in Table 1, so the single remaining grow rack node in the hybrid system will be sending 9 messages every 5 minutes. In these runs, macroenvironment nodes remain unchanged, sending one message only every 5 minutes.

Plotting the sequence numbers from the border router in Figure 9, we can see that each system is more similar to the ideal case than when the number of nodes is varied. The number of retransmissions, as shown in Figure 10(a), also does not increase by much while varying the traffic multiplier. The packet loss graph as shown in Figure 10(b), however, shows an increasing trend with increasing burst messages in the rack nodes.

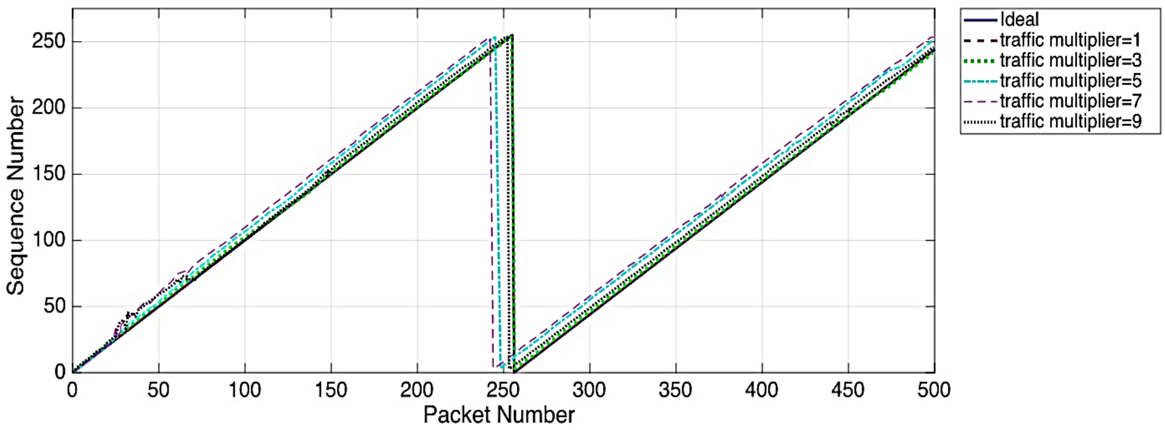
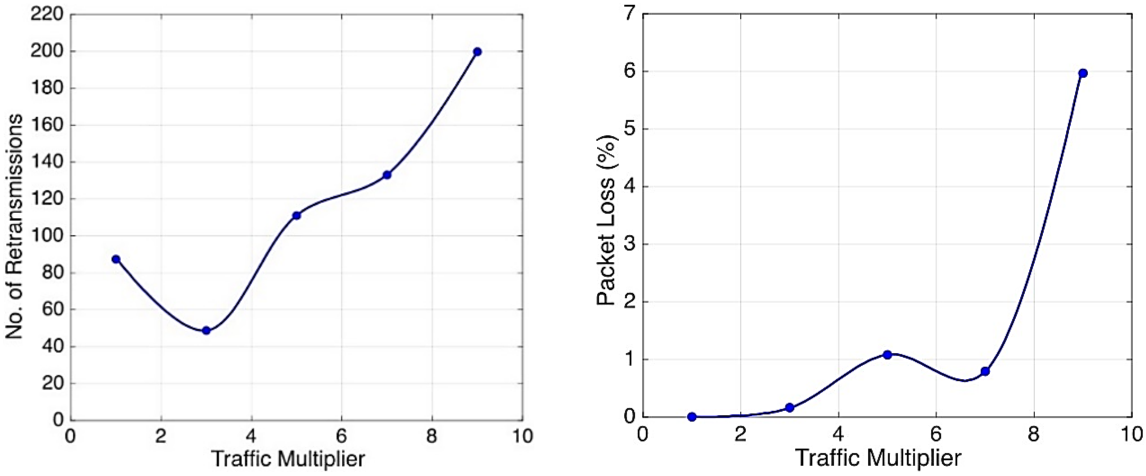


Figure 9. Plot of sequence numbers of the first 500 packets with variable rack node traffic multiplier



(a) (b)

Figure 10. Plots of metrics for systems with variable amount of burst traffic from the rack nodes showing (a) number of retransmissions with varying rack node traffic multiplier and (b) packet loss (%)

3.5. Comparison of end-systems

Having seen the effects of varying the number of nodes and the traffic volume of rack nodes on the network performance, the end-systems are compared. Since the previous tests that increased the traffic from the rack nodes did so in burst, another case is explored: increased continuous traffic in grow rack nodes. In this case, instead of the grow rack nodes sending 9 messages in a single burst every 5 minutes, the nodes send 9 messages spaced out in those 5 minutes. This essentially changes the sending interval of grow rack nodes from 5 minutes to 5/9 minutes.

Plotting the sequence numbers of border router packets, we can see that the purely wireless system is less efficient than the hybrid system, both burst and continuous, both of which are highly similar to the ideal case as shown in Figure 11. Figure 12(a) also shows that the number of retransmissions for both the hybrid system with burst sending and the hybrid system with continuous sending decreased. Retransmissions were reduced from 1,558 to 200 for the burst system and to 71 for the continuous system.

The packet loss of the different end-systems can be seen in Figure 12(b). It can be seen that there is an improvement in packet loss in the hybrid system that utilizes burst traffic. It can also be seen that the packet loss was reduced to 0.0% using continuous sending. This means that proper scheduling in the wired (CAN) system is important to further improve the system.

Furthermore, Figure 13 shows the comparison of the number of RPL and UDP packets, and the RPL:UDP ratio of end-systems. It can be seen in Figure 13(a) that the hybrid systems, both burst and continuous, have less number of RPL packets. Less number of packets will indirectly result in less chance of collision, as well as possible reductions of power consumption for the radio. Figure 13(b) shows that the ratio of RPL packets to UDP packets is also higher in the case of purely wireless systems.

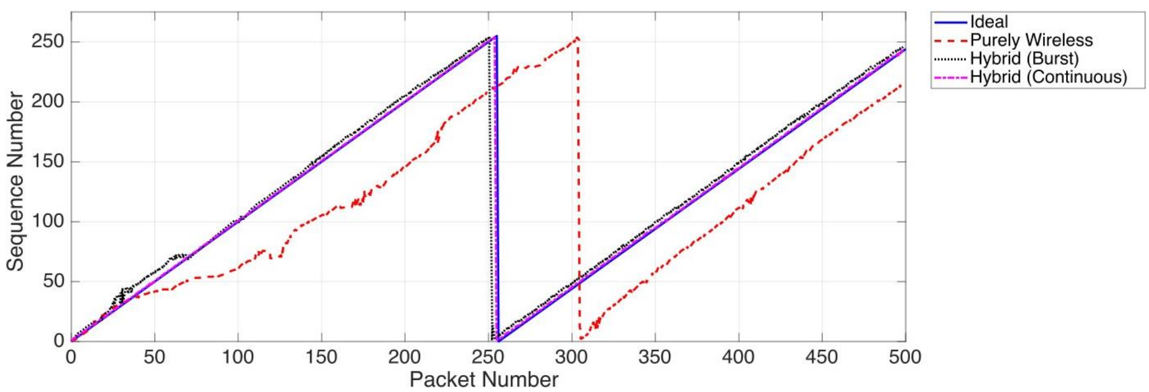


Figure 11. Plot of sequence numbers of the first 500 packets of the end-systems

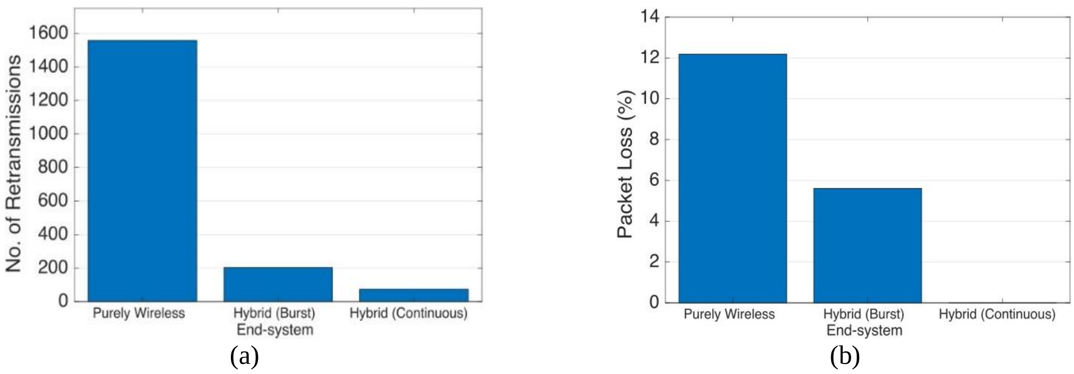


Figure 12. Comparison of end-systems showing (a) number of retransmissions and (b) packet loss (%)

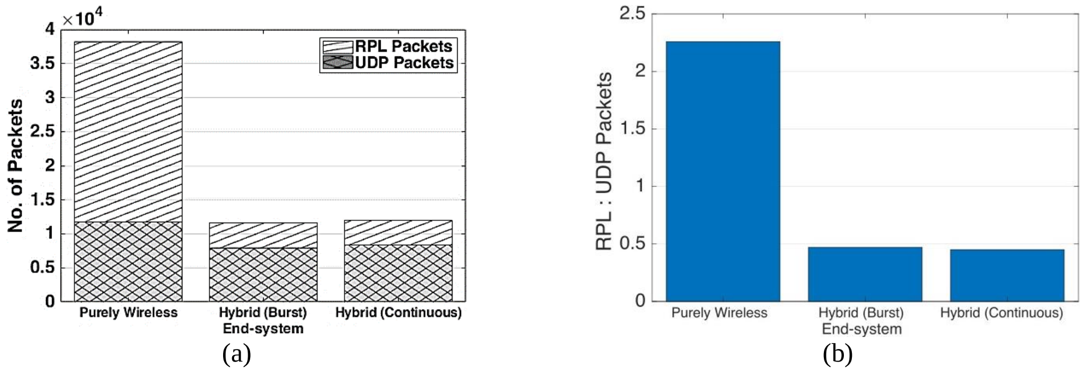


Figure 13. Comparison of end-system metrics showing (a) number of RPL and UDP packets and (b) RPL:UDP ratio

3.6. Reduced transmission range

As previously discussed in section 3.1, all simulations so far assumed the default output power for nodes, thus resulting in the transmission range enough to encompass all nodes. However, this is not always the power one would use. A higher output power setting is expected to result in higher power consumption overall and consequently shorter battery life for battery-powered nodes. The following set of tests compare the end-systems using different transmission range settings.

Comparing the packet loss of the end-systems using two ranges, it can be seen that reducing the range decreased the packet loss in the purely wireless system while increasing the packet loss in the hybrid (burst) system as sown in Figure 14. This means that the output power should be optimized to ensure improvements in packet loss. Furthermore, the hybrid system that uses staggered/continuous sending still had 0.0% packet loss. This further cements the need for proper scheduling of the grow rack node transmissions.

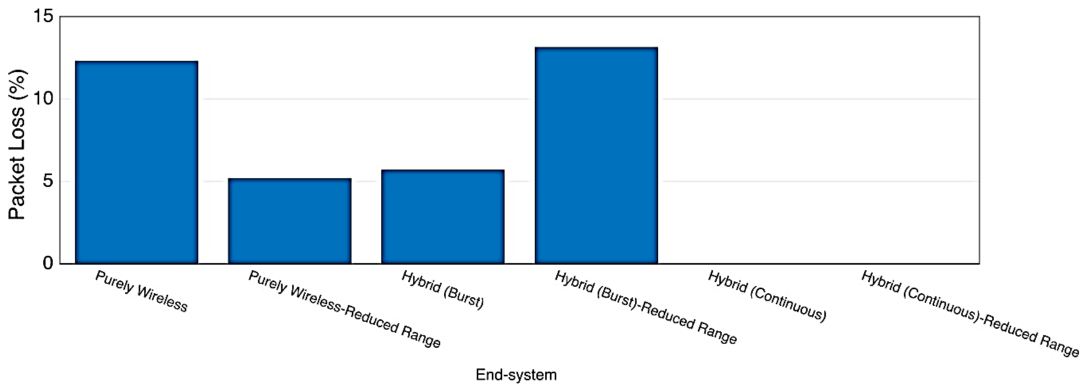


Figure 14. Packet loss (%) comparison of the end-systems with different transmission range settings

Looking at the number of RPL and UDP packets shown in Figure 15, it can be seen that there is an increase in UDP packets. This is due to the increased number of hops in the system for the reduced range. However, looking at Figure 16, it can be seen that the ratio of RPL packets to UDP packets is reduced when the range is decreased. These results show that even though the hybrid system offered some improvements over the purely wireless system when the wireless sensor node power level and consequently, the transmission range settings were the default, reducing the range may prove to be detrimental to the proposed hybrid system. Therefore, further simulations and optimizations for output power must be done.

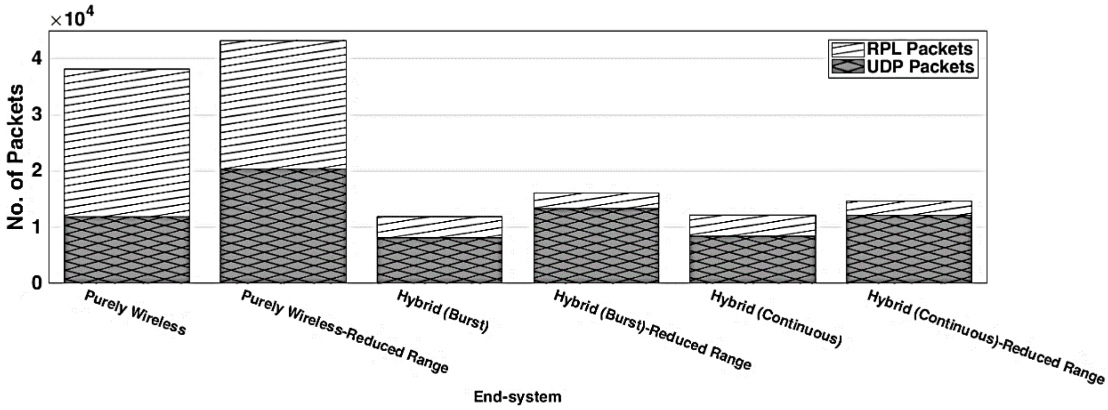


Figure 15. Number of RPL and UDP packets of the end-systems with different transmission range settings

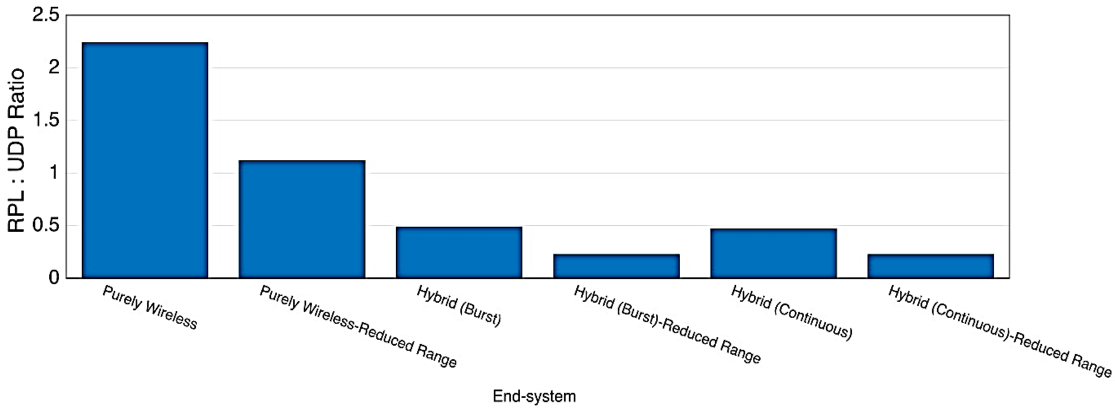


Figure 16. RPL:UDP ratio comparison of end-systems with different transmission range settings

4. CONCLUSION

In this article, a hybrid system consisting of both wired and wireless components is proposed for a smart hydroponics setup, specifically an urban, indoor farm. One target application is a 40-ft container van farm setup with 4 grow racks with 4 layers per rack. Network simulations were done in the Cooja simulator to compare the two systems. From the simulation results, it was seen that there are advantages in using a wired CAN system for the grow rack cabinets. Firstly, the network of the hybrid system had fewer retransmissions than the purely wireless system. There are also improvements in packet losses in the hybrid system. Also, the overhead due to RPL is reduced as seen in the decrease in the number of RPL packets to the number of UDP packets in the system.

Since the grow rack nodes in the hybrid system oversee multiple slave sensor sets, the type of traffic in these nodes was also explored. While the hybrid system had improvements when compared to the purely wireless system, changing the traffic type from burst to continuous further improved the hybrid network, reducing the packet loss to 0.0%. This emphasizes the need for proper scheduling in the nodes. This may be done by implementing a CAN scheduling protocol or by keeping transmissions to the 6LoWPAN network staggered.

Lastly, the network performance of both the purely wireless system and the hybrid system changed when the transmission range of the nodes was reduced. While reducing the transmission range improved the purely wireless setup, it was seen to be detrimental to the hybrid system. Thus, it is imperative that further testing and optimization for the power used by the nodes be done.

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