A Heterogeneous PLC with BLE Mesh network for Reliable and Real-time Smart Cargo Monitoring

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***Abstract*—Electronic Freight Systems are increasingly being deployed to reliably monitor the cargo in real-time and prevent theft in air cargo. As the existing technologies fall short in achieving these goals due to cost of deployment and/or higher latencies, we propose to exploit the existing infrastructure of power lines when the aircraft is on the tarmac. We propose an architecture that extends power line communications with Bluetooth Low Energy (BLE) devices that are embedded on the cargo. We show that BLE mesh can extend the range by interfacing with PLC modems to achieve a smart Internet of Things (IoT) solution for continuous monitoring and tracking.**

In order to evaluate this, we also propose a novel software-defined radio based testbed that can be used to evaluate various scenarios. We characterize the testbed by performing extensive latency measurements. The novelty of our testbed includes BLE mesh network that supports high reliability and low latency communication and support for emulation of electrical loads to inject impulse noise into the powerline network. We then measure end-to-end latencies and packet delivery ratios in realistic settings for the smart cargo monitoring solution. Our results indicate that our hybrid network offers a worst case latency of 24.85 ms for a 570 m distance between warehouse and cargo monitoring station.

I. INTRODUCTION

An increased trend of cargo thefts over the years has led to the adoption of Electronic Freight Security (EFS) systems by a few cargo insurance companies [1]. The goal of EFS is to ensure real-time end-to-end monitoring of cargo shipments. To achieve this goal, the EFS systems are adopting embedded tracking technology.

For airport cargo monitoring, the EFS is majorly employed when the aircraft is on the tarmac. Thus, traditional technologies such as RFID and camera-based solutions are potential technologies for EFS. However, they fall short of providing a holistic solution. RFID is cost-effective for tracking with cargo localization possible only in the presence of RFID readers [2]. Camera sensors suffer from high infrastructure requirements such as good lighting and high communication bandwidth. Furthermore, occlusion (human or otherwise) of cargo objects makes the detection of camera-based cargo tracking systems non-trivial. Also, during cargo movement there might be several out of coverage areas with camera systems [3].

In this paper, we propose a heterogeneous communication infrastructure that facilitates real time, continuous monitoring and tracking of air cargo. Typically, when the aircraft is near a terminal for the cargo loading/offloading, there is a powerline cable that runs from the terminal building to the aircraft. We propose to use this existing infrastructure to carry data. To monitor the cargo, the idea is to embed each piece of cargo with an ultra-low power Bluetooth Low Energy (BLE) communication device. The BLE devices send their sensor information wirelessly over a BLE mesh network to a gateway device that incorporates both BLE and Powerline Communication (PLC) adapters. Such a heterogeneous network seamlessly extends the range of connected objects with minimum latency overheads to accomplish smart cargo monitoring.

In order to evaluate the proposed architecture, we develop a novel testbed consisting of PLC modems and BLE mesh network. A unique characteristic of this testbed is that the PLC modem is developed using software-defined radio (SDR) platforms. These are not only cost-effective but also allow us to emulate different electrical loads, inject various noises including impulse noise, and other scenarios easily. We also interface these PLC modems with the BLE mesh that can be configured easily. We evaluate the proposal in this testbed and found that it offers a worst case latency of 24.85ms for a 570 m distance between warehouse and cargo monitoring station. Furthermore, we observed a 2× reduction in the worst case latencies for BLE networks compared to previous work [16]. Specifically, our contributions through this work are as follows.

- We propose a novel heterogeneous network consisting of PLC and BLE mesh for the smart cargo monitoring application.
- We propose a novel testbed that assists in the design and development of a smart IoT network using BLE and PLC systems. The PLC modem is implemented using software-defined radios. The testbed deployment parameters for BLE and PLC are configurable. The SDR PLC modem allows us to emulate several impulse noise scenarios. Thus, our testbed does not require electrical loads and other high-power equipment to inject noise and channel impairments for the powerline. This will assist network planners to arrive at appropriate transmit power

level, node density, retransmission count, and connection interval (for BLE). The testbed itself can easily be extended to other wireless standards instead of BLE if required.

- We demonstrate a smart cargo monitoring application using the testbed where we create a network to assist in monitoring and tracking. We evaluate the system for various scenarios (i) dense and sparse BLE mesh network with PLC and arrive at worst case latencies for our smart cargo application deployments; (ii) BLE-PLC network under WiFi, Bluetooth and impulse noise interference on the PLC line; and (iii) various noise and channel impairments on the PLC line.
- We present the scope of BLE-PLC network design from different zones of an airport terminal and tabulate latency analysis results.

The rest of the paper is organized as follows. In Section II, we describe the current practices in PLC and BLE and present the need for heterogeneous network. In Section III, we present the proposed heterogeneous architecture for Smart cargo monitoring used at the airport terminal. In Section IV, we present the testbed setup with transceivers, emulators for PLC and BLE interferences and parameter settings in both PLC and BLE networks. In Section V, we evaluate the performance of individual PLC, BLE and integrated PLC-BLE networks. In Section VI, we discuss the results and finally in Section VI, we conclude with significance of this testbed and its applications in various areas.

II. RELATED WORK

The PLC narrowband and broadband communication with existing powerline infrastructure is extensively studied in literature. The works are indicated in [4]–[7], [9], [10]. Kumar et al., propose combination of PLC network with other wired/wireless networks for data transfer from an aircraft to airport networks. Several patents [11], [12], [13] are filed by the authors. However, most works focus on large data downloads with high bandwidth requirements from the aircraft. On the other hand, our testbed focus is on applications that demand low latency with low to medium bandwidth requirements. Thus cargo tracking and monitoring is our application of interest. A recent work on PLC for monitoring application is explored for cable fault detection [14]. The work of David et al., [15] discusses a monitoring application at an airport network, but the authors do not provide latency analysis between two events. While reviewing recent literature related to BLE, Rondon et al., evaluate the suitability of BLE technology for time critical industrial applications with BLE star network in their work [16] and report worst case latency of the system. Yuri et al., state the observable and controllable variables in BLE mesh network and deduce the impact of each controllable variable on the observable variables [17]. Our testbed evaluates for a denser network with inter-node distances of 0.6 meters which might be suitable for cargo stacks in a warehouse. While the number of sensors or nodes are increasing at a rapid pace, the scalability [18] and reliability of service is a major challenge for any individual technology. This paper attempts to overcome this challenge by our heterogeneous network where we combine BLE with PLC network to meet PDR and latency requirements.

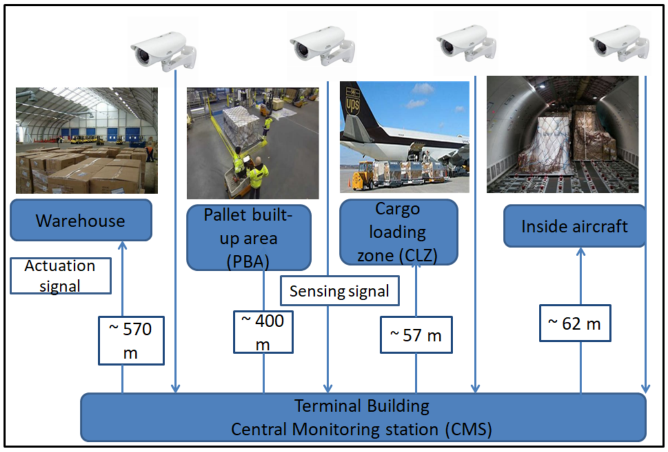


Fig. 1: Typical cargo movement at airport terminal [3]

III. PROPOSED ARCHITECTURE FOR SMART CARGO MONITORING

Typical cargo movement within an airport terminal is depicted in Fig. 1. Fig.1 shows four different locations of cargo movement. Initially, cargo enters the warehouse of the airport terminal. Soon after the cargo may be moved to a palette built-up area (PBA), and then to the Cargo Loading Zone (CLZ), before it gets loaded into the aircraft. The architecture is to monitor and track the complete flow of cargo in a Central Monitoring Station (CMS).

Fig.2 shows the proposed architecture. The idea is to embed each cargo with a BLE node that can communicate over a mesh with other BLE nodes (see Fig.4). The mesh network has the ability to communicate with a gateway node which incorporates a BLE node and a PLC adapter. The entire cargo loading and unloading can thus be reliably monitored and tracked. In general, the purpose of pop up power lines or ground based power cart is used to power up the aircraft when parked at the gate. In this architecture, a reliable ring mains topology supplies power to different locations in the airport area. These power lines in addition to supplying power have been used for data upload and download from the aircraft to terminal and vice versa. This existing support infrastructure is cost effective and also this is a high available communication network system.

Each power socket is potentially a source of entry to a communication network. A power line modem acting as a master will be placed near CMS and multiple slave power line modems in each zone can be connected to the power sockets. Each power line modem connected to a socket has a unique identified (ID), MAC address, and an associated network name. These are stored in a database. Hence its placement location may be trivially mapped. A similar mapping can

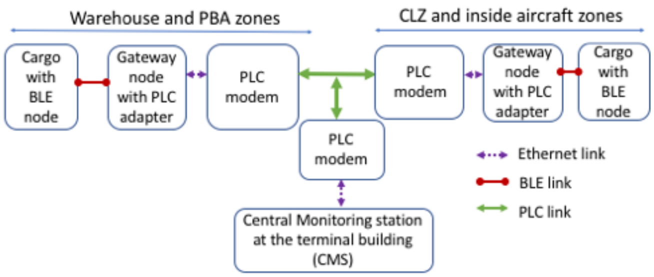


Fig. 2: Proposed architecture for smart cargo monitoring

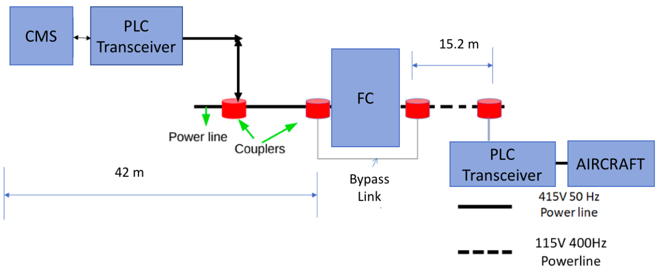


Fig. 3: Bypass architecture to extend power line communication across Frequency Converter (FC)

be carried out at pop-up power sockets on the tarmac. BLE nodes communicate to a nearby PLC gateway with a packet containing the source address which uniquely identifies a cargo. When a BLE client sends a packet, the slaves respond with their source address which passes through the PLC slave modem can be retreived at PLC master modem located at CMS. Thus power lines in the aircraft parking ramp areas are used to extend the BLE mesh communication to a CMS. Fig.3 shows the powerline infrastructure between CMS and the aircraft.

As our goal is to track and monitor cargo within the aircraft, one challenge is to use the PLC network seamlessly over a 50Hz to 400Hz powerline. Fig.3 describes the method used to bypass the frequency converter [19] and extend the power line communication across medium voltage to low voltage power supply. In this method, we use a pair of inductive couplers on either side of the frequency converter to link CMS data to aircraft and vice-versa. In order to design the testbed, we collected information related to typical distances between each zone to the CMS. We also require knowledge of the number of PLC modems required to cover such distances. Additionally, we require evaluation of PLC channel noise effects and wireless interference to BLE communication channels. Table I depicts typical distances from each zone to cargo monitoring station.

TABLE I: Minimum distances of each zone from cargo monitoring station (CMS) [20], [21]

Aircraft to CMS	15.2 to 62.7 m
Warehouse to CMS	140 to 570 m
PBA to CMS	75 to 400 m

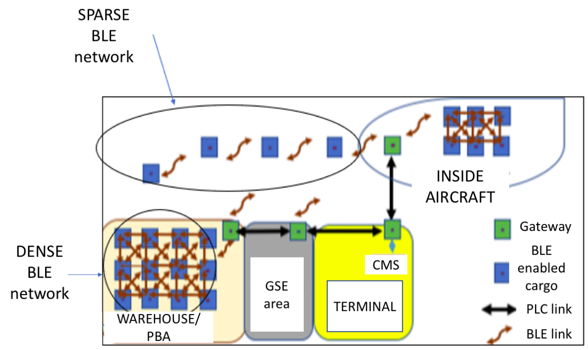


Fig. 4: Dense and Sparsely connected cargo

IV. The Proposed Testbed

We describe the creation of BLE and PLC networks, and their seamless support to carry the application traffic comprising of cargo monitoring and tracking data payload. We have developed a testbed for this purpose as represented in Fig.5. The testbed consists of three hop PLC communication with two relays between a transmitter and receiver. This testbed supports real and emulated interferences. We inject the impulse noise generated by several emulated electrical loads in a PLC network using an open source platform such as the Universal Software Radio Platform (USRP). Thus our testbed provides support for several virtual loads during every measurement. The USRP used in this testbed serves as a relay as well as an impulse noise emulator.

A. *BLE mesh network*

We used NRF52832 based SoC boards [24] as BLE nodes. Parameters such as transmit power, Connection Interval (CI), Re-transmission count (RC) are some of the controllable parameters of a BLE node. To obtain the target PDR, the CI and RC parameters are set to 100 ms and 0 respectively. These values were obtained after an extensive measurement study. Thus one is expected to tune these parameters to obtain the required Quality of Service (QoS).

B. *PLC network*

PLC modems are based on IEEE 1901 standard. The transmit frequencies used in the testbed are DC to 30 MHz and 50 to 60 MHz. An inductive coupler [23] is used to couple data to the powerline. The coupler's operating frequency is in the range of the frequency band of 2-40 MHz. Our testbed incorporates standard broadband powerline modems. The PLC network is created on one side over a three phase 415V 50Hz powerline. To support communication from inside the aircraft, we installed a solid state frequency converter that provides an

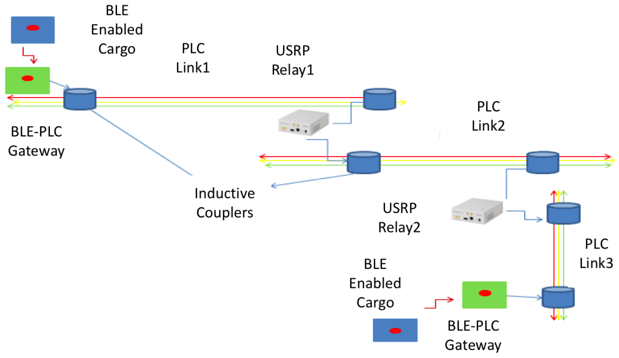


Fig. 5: Testbed for connected cargo with three PLC hops

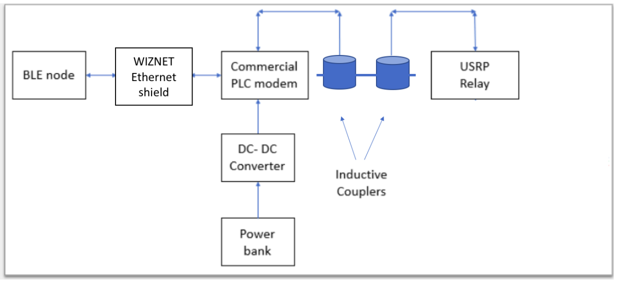


Fig. 6: Gateway node

output of 115V 400 Hz. A stinger cable used for supplying power from output of the converter is about 15.2 m length with a 2 inch diameter. This stinger cable is insulated, flexible and suits all weather conditions for powering an aircraft parked at the gate [11].

C. Gateway for payload support

A gateway node is constructed as shown in Fig.6. A BLE node is connected to a commercially available hardware: a Wiznet 5550 board [26]. This Wiznet 5550 provides BLE to support a standard TCP/IP communication protocol stack. An ethernet link connects wiznet board to a PLC modem. The PLC modem is powered externally using a battery and a boost converter provides 3.3 V at the input of PLC modem. This setup adapts the commercial PLC modem that usually powers using the powerline AC to also operate using the DC power.

D. BLE channel interference

BLE's Radio Frequency (RF) channels lie in a crowded space with other devices also operating in the ISM 2.4GHz. There are nearby WiFi devices embedded in the mobile phones carried by cargo handlers. Thus the interference can be a significant component to undermine the performance of the chosen solution. The developed testbed has taken this interference for most measurements. The BLE mesh performance under dense BLE network with and without these WiFi hotspots are measured and presented in Table II. While the sparse network latency with WiFi interference is performed between two BLE nodes and presented in Fig.7. The results indicate that the worst case latency for a 150 m inter node distance is 13.54ms for a power level of -4dBm.

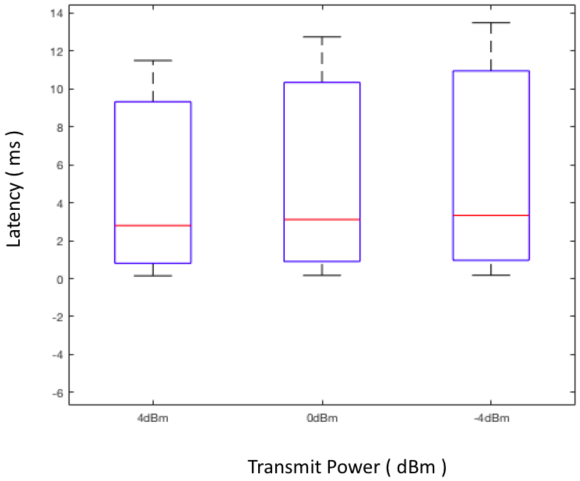


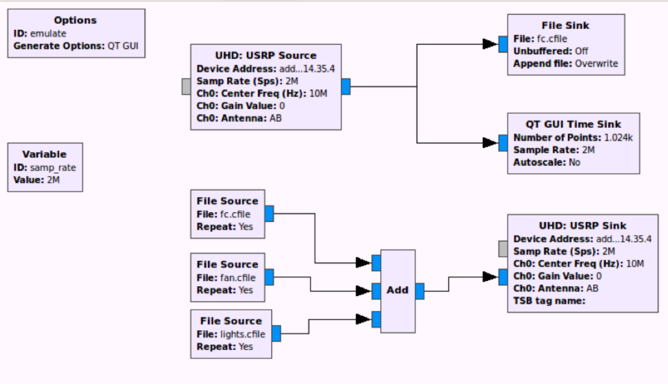
Fig. 7: Transmit power vs Latency in a sparsely connected BLE network. Worst case latency with lowest power -4 dBm is about 13.5ms and suits a real-time monitoring application

E. PLC channel Impulse Noise

Since a PLC channel is characterized by several noise profiles such as periodic impulse noise, aperiodic impulse noise and inherent background noise, we devised a method to inject these noise types into the testbed. Initially, we characterized these profiles using actual electrical devices. The waveforms generated during ON/OFF operations were recorded using USRP systems and replayed at instances of packet communication. The captured noise can be amplified or attenuated and added with other impulse sources as well to form realistic noise scenarios by building a programmable impulse noise waveform generator. Fig. 8 shows a snapshot of the software flowgraph used to capture the impulse noise using USRP hardware and GNURadio blocks. The figure shows that a USRP receiver is connected to a file sink to store time domain signals. The time domain signal is captured for different types of loads at different time instants. Fig.9 and Fig.10 shows the impulse noise amplitude and inter-arrival times for resistive loads and frequency converter respectively. One can see that the impulse noise amplitudes of a frequency converter is 100 times higher than the impulse noise due to resistive loads. The interarrival times of the impulses in resistive load is shorter than the frequency converter in a 0.5 ms duration window. The latency increases when impulse noise amplitudes increases and this is evident from the results shown in Table III. Since impulsive noise amplitudes of Frequency converter is higher than that of the resistive loads, the former has higher latency compared to the latter.

V. PERFORMANCE EVALUATION USING THE TESTBED

In this section, we first present the performance evaluation results to analyze the suitability of individual technologies and then evaluate the interworking of BLE-PLC network for the smart cargo monitoring application using the proposed


Options
ID: emulate
Generate Options: QT GUI

Variable
ID: samp_rate
Value: 2M

UHD: USRP Source
Device Address: add...14.35.4
Samp Rate (Sps): 2M
Ch0: Center Freq (Hz): 10M
Ch0: Gain Value: 0
Ch0: Antenna: AB

File Sink
File: fc.cfile
Unbuffered: Off
Append file: Overwrite

QT GUI Time Sink
Number of Points: 1.024k
Sample Rate: 2M
Autoscale: No

File Source
File: fc.cfile
Repeat: Yes

File Source
File: fan.cfile
Repeat: Yes

File Source
File: lights.cfile
Repeat: Yes

UHD: USRP Sink
Device Address: add...14.35.4
Samp Rate (Sps): 2M
Ch0: Center Freq (Hz): 10M
Ch0: Gain Value: 0
Ch0: Antenna: AB
TSB tag name:

Fig. 8: Emulation flowgraph in GNURadio to generate impulse noise.

testbed. A key and essential feature of the testbed is that it allows to collect data on the latency and reliability as most smart applications might use either time-sensitive (low latency metric) networks or delay tolerant (high packet delivery ratio) networks. As latency and reliability are the key performance metrics, we evaluate the system using the latency and Packet Delivery Ratio (PDR). The heterogeneous testbed BLE- PLC network setup is shown in Fig.5. The evaluation scenarios include with and without the respective channel interference in both BLE and PLC networks.

TABLE II: Performance measurements in dense BLE mesh.

BLE Transmit Power (dBm)	Inter BLE node distance (m)	PDR without WiFi interference %	Latency without WiFi interference (ms)	PDR with WiFi interference %	Latency with WiFi interference (ms)
4	0.6	97.5	6.302	96.5	6.492
0	0.6	97	7.142	95.5	7.276
-4	0.6	93	8.198	91	8.4

A. BLE mesh network evaluation

We consider two scenarios for the BLE mesh: a dense network and a sparse network. BLE nodes are placed close to each other form a dense network of cargo depicting a warehouse scenario. However, during cargo movement towards the CLZ and aircraft zones, they might form an expanded and perhaps even a sparsely formed BLE network. Also, when the cargo reaches CLZ and inside aircraft they might again form a dense network. Fig.4 shows the scenario of dense and sparse mesh network during cargo movement.

For emulating a dense network, we placed BLE nodes at a distance of 0.6 m from each other. The network consists of 12 nodes. For emulating a sparse network, we placed the BLE nodes towards the edge of their communicating ranges. For the measurements, we ensured that almost all nodes have a uniform PCB antenna. Further, the re-transmission count for each node is set to 0. This is for the purposes of reliability evaluation (PDR in our testbed) of a BLE network communication.

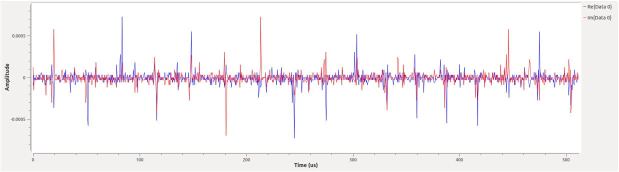


Fig. 9: Impulse noise due to resistive loads

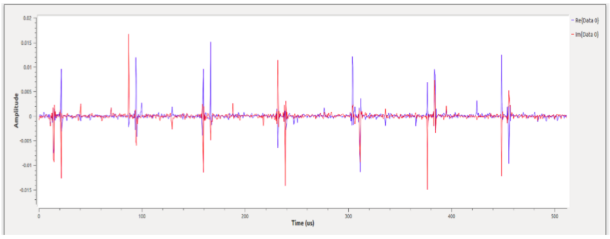


Fig. 10: Impulse noise due to frequency converter

In an airport cargo scenario, it is possible that WiFi interference occurs due to smartphones being carried by cargo handler approaching significantly close to a cargo. To emulate this interference, we measured all performance parameters with specially erected Wi-Fi hotspots. This arrangement is in addition to other external WiFi interference.

We measured the the worst case latency, average latency, best case latency and Packet Delivery Ratio (PDR) for the dense and sparse BLE mesh. Furthermore, we obtained the maximum possible range extension with 12 nodes empirically with different power levels, with and without interference.

B. PLC network evaluation

TABLE III: Latency measurements in a single hop PLC link.

Center Frequency MHz	Latency		Daughter boards used in USRP	Modulation	Packet size in Bytes
	with resistive loads (ms)	with freq converter (ms)			
10	6.9*	10.8**	LFTX/ LFRX	BPSK 1/2	136
20	6.6	10.3			
30	6.3	9.8			
52	6.2	9.5	WBX		
54	6.1	9.1			
56	5.8	8.8			

*Worst Case Latency (WCL) of single PLC hop with resistive loads.
** WCL of Single PLC hop with frequency converter as a load.

In order to emulate impulse noise, we first capture the impulse noise using a USRP system by powering on and off various types of loads. The emulation setup is as shown in Fig.5. Table III shows a single hop PLC link latency for modulation BPSK 1/2, packet size 136 B for various centre frequencies. While latencies range from 5.8 to 10.8 ms, we have to notice that these measurements utilizes the USRP+host computer setup.

TABLE IV: Worst case end to end latency for each zone with single BLE hop to gateway in zone1 and multiple PLC hops to reach CMS

Distance of each Zone from CMS (m)		BLE to Gateway Latency (ms)		Number of PLC hops	Multi-hop PLC Latency (ms)	End to End Latency (ms)
		Dense (0.6 m)	Sparse (150 m)			
CLZ	57	8.4	13.54	2	7.56*	21.10
Inside aircraft	62.7	8.4	13.54	2	7.56*	21.10
PBA	300	8.4	13.54	3	3.77	17.31
Ware house	570	8.4	13.54	6	11.31**	24.85

* Latency over two PLC hops. First hop: CMS to input of FC (415V 50Hz link). Second hop: Output of FC to CLZ/Aircraft (115V 400Hz link),

** Calculated latency based on 1,2 and 3 hop PLC link experiments

It is reported in literature that host computer signal processing delay dominates the bus communication latency [27]. The authors presented that the application latency, GNURadio latency and hardware latency is calculated to be around 4.259 ms, 0.256 ms and 0.61ms respectively. The total latency due to USRP/GNURadio platforms approximate to 5.125 ms. Further, we used a 4MHz effective sampling rate (2MHz sampling rate at USRP) which is less than the specified 100 MHz in IEEE 1901 [28]. Due to these two overheads, one may wish to revisit Table III to revaluate the latency measurements. As an example, 6.9 ms and 10.8 ms will evaluate to 7.54 μs and 22.7 μs respectively.

C. Hetnet Evaluation

BLE communication as an independent technology is impacted by Wi-Fi interference under sparse mesh network, whereas PLC data communication throughput is disrupted by impulse noise generated by switching loads. However, if one combines the two technologies, we expect that the integrated solution will perhaps provide a QoS higher than either protocol. BLE measurements in Fig. 7 reveal that when two nodes are in 150 m apart the worst case latency is 13.45 ms.

VI. RESULTS AND DISCUSSIONS

Our study begins with evaluation of individual technologies in isolation to the other. Table II, III and Fig. 7 shows the evaluation of BLE and PLC network independently. Table II shows the Packet Delivery Ratio (PDR) and worst case latency for three transmission powers for a 12 node BLE mesh network. The packet size chosen is 32 B including the header. The table also shows the impact of Wi-Fi interference on the mesh network. Results from this table indicate a dense BLE mesh does well to support a consistent PDR and latency even in the presence of Wi-Fi interference. Thus, one may also conclude that the influence of a cargo handler carrying a mobile phone will not degrade the performance of the cargo.

The packet size for PLC communication considered is 136 B. We obtained the worst case latency as 1.885 ms for a PLC length of 100 m for a transmit power of 20 dBm. The worst case end-to-end latency for 570 m (Table IV) is 24.85 ms. Fig. 7 shows the average, best and worst case latencies between two BLE nodes in a mesh network. The distance between the nodes was varied from 5 to 150 m to capture cargo in motion from one zone to another. The results indicate that the worst case latency for a 150 m inter node distance is 13.54 ms for a power level of -4 dBm. Table IV provides end-to-end latency with the integration of BLE with PLC network systems. These results clearly indicate that PLC channel with low latency with adaptive packet sizes, transmit power and transmit frequencies forms a range extension technology for the widely adopted low power BLE network. The joint working of BLE and PLC is demonstrated with the help of this testbed. Though the application demonstrated is smart cargo monitoring, this testbed can be used for many applications pertaining to real time status retrieval. During the testbed evaluation, we observed a 2× reduction in the worst case latencies for BLE networks compared to prior work [16].

VII. CONCLUSION

This paper explained the design, implementation and lab based field trials of BLE-PLC network for smart cargo monitoring to evaluate PDRs and latencies. A latency of the order of 24.85 ms for a distance of 570 meters and Packet delivery ratio of the order 87.6 % with a significant range coverage was observed. The measurement results in this paper will help in network planning for several smart applications scenarios such as Industrial automation, asset tracking, intrusion detection and many other scenarios where the sensor nodes are spread across multiple floors or over long range to support a reliable communication between nodes.

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