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

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Abstract—Electronic Freight Security (EFS) systems are being increasingly 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 an 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. 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.

Index Terms—Smart cargo Monitoring, Mesh, BLE, PLC, IoT, USRP

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 architecture 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 the 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.

The PLC narrowband and broadband communication with existing powerline infrastructure is extensively studied in literature. The works are indicated in [4]–[9]. Anil Kumar et al., proposes combination of PLC network with other wired/wireless networks for data transfer from an aircraft to airport networks. Several patents ([10], [11], [12]) 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 [13]. The work of David et al., [14] 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 [15] 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 [16]. 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 [17] and reliability of service is a major challenge for any individual

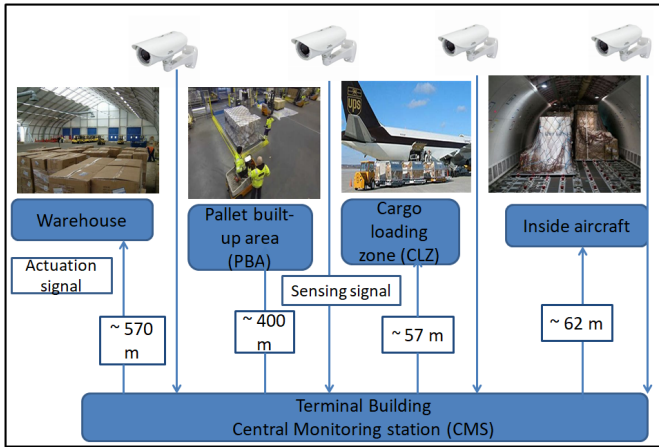


Fig. 1: Typical cargo movement at airport terminal [3]

technology. This paper attempts to overcome this challenge by our heterogeneous network where we combine BLE with PLC network to meet Packet Delivery Ratio (PDR) and latency requirements. Our contributions through this work are as follows:

- 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.
- 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.

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

TABLE I: Smart cargo monitoring application requirements [15]

Application	Max transmission delay(ms)	update time (ms)	Packet loss rate	node density per $10 m^2$
control operations	50-100	100-5000	10^{-4}	1-20
Monitoring	>100	>10000	10^{-4}	1-20

II. 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

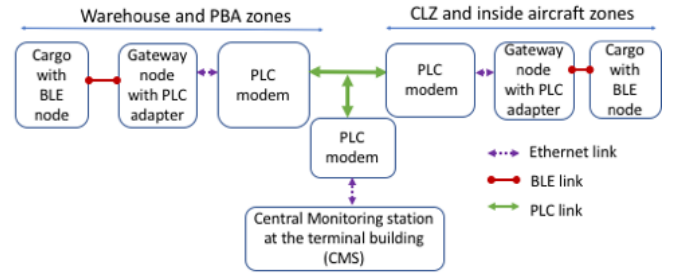


Fig. 2: Proposed architecture for smart cargo monitoring

movement. Initially, cargo enters the warehouse of the airport terminal. Soon after the cargo may be moved to a pallet 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 identifier (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 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 at a zone sends a packet, the slaves in any other zone respond with their source address which passes through the PLC slave modem can be retrieved 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

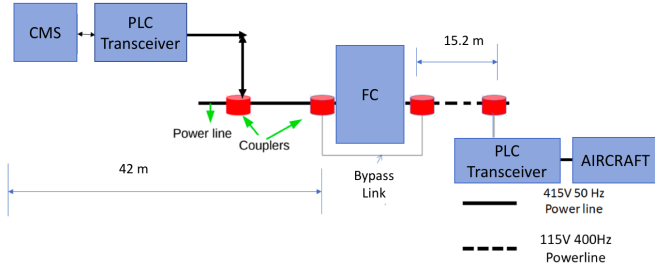


Fig. 3: Bypass architecture to extend power line communication across Frequency Converter (FC)

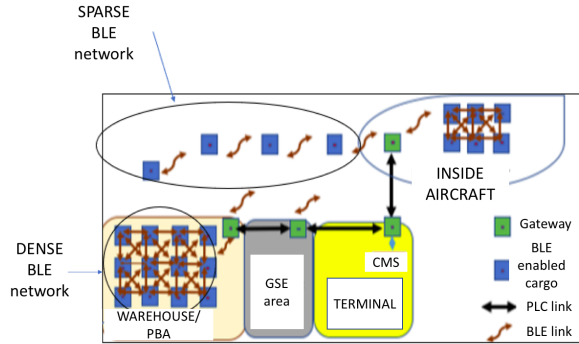


Fig. 4: Dense and Sparsely connected cargo

bypass the frequency converter [18] 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 II depicts typical distances from each zone to cargo monitoring station.

TABLE II: Typical distances of each zone from cargo monitoring station (CMS) [19], [20]

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

III. 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 noises for PLC. We inject the impulse noise generated by several emulated electrical

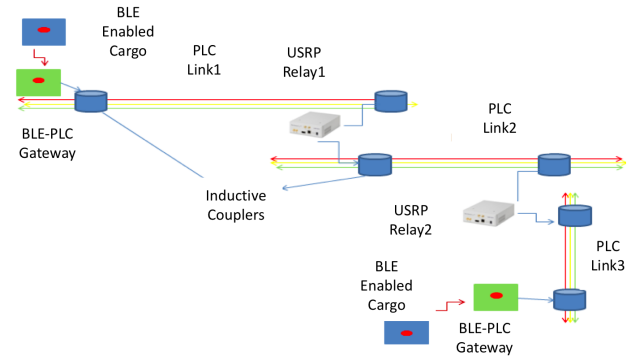


Fig. 5: Testbed for connected cargo with three PLC hops

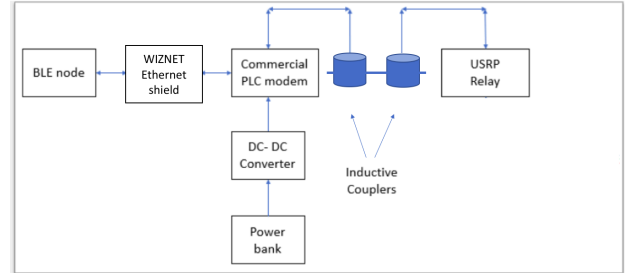


Fig. 6: Gateway node

loads in a PLC network using an open source SDR platform such as the Universal Software Radio Platform (USRP). The 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 System On Chip (SoC) boards [21] 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 [22] 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 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 5 cm diameter. This stinger cable is insulated, flexible and suits all weather conditions for powering an aircraft parked at the gate [10].

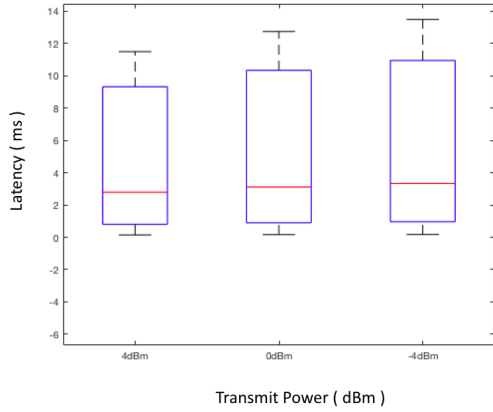


Fig. 7: Transmit power vs Latency in a sparsely connected BLE network. Worst case latency with lowest power -4 dBm is about 13.5 ms and suits a real-time monitoring application

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 [23]. 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

The BLE mesh performance under dense BLE network with and without WiFi hotspots are measured and presented in Table III. The sparse network latency with WiFi interference is measured between two BLE nodes and shown in Fig.7. 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.

E. PLC channel Impulse Noise

In general, 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 by connecting actual electrical devices to the power line as loads. The waveforms generated during ON/OFF operations were recorded using inductive coupler and USRP systems. 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. Later, these waveforms are replayed at the instances of packet communication. Fig. 8 shows a snap shot 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

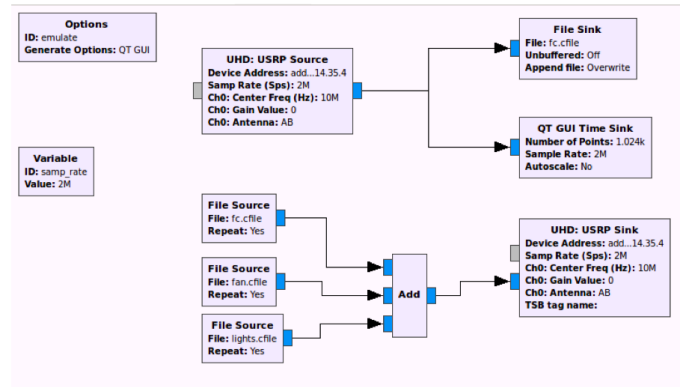


Fig. 8: Emulation flowgraph in GNURadio to generate impulse noise.

time instants. The top part of fig. 9 shows the impulse noise amplitude and inter-arrival times for a frequency converter and bottom part shows BLE data over PLC line.

IV. 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 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 PDR) networks. As latency and reliability are the key performance metrics, we evaluate the system using the latency and PDR. The heterogeneous testbed BLE- PLC network setup is shown in Fig. 5. The evaluation scenarios include with and without the respective channel impairments in both BLE and PLC networks.

TABLE III: 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

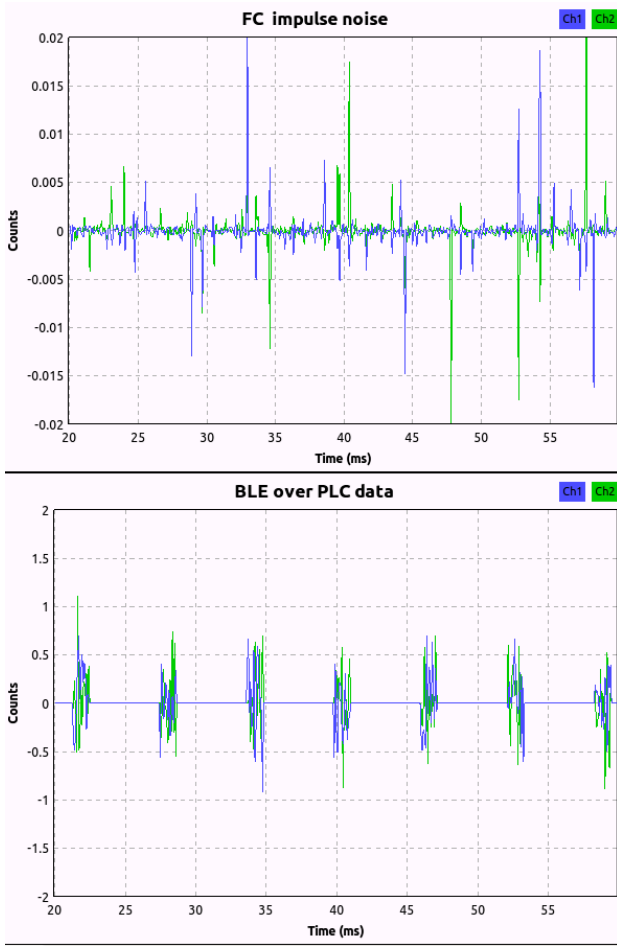


Fig. 9: (top) Impulse noise due to frequency converter and (bottom) ble data over powerline

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. 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, average and best case transmission latencies and 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

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 IV shows a single hop PLC link latency for

TABLE IV: 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.

TABLE V: Worst case end to end transmission 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

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. It is reported in literature that host computer signal processing delay dominates the bus communication latency [24]. 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 [25]. Due to these two overheads, one may wish to revisit Table IV to reevaluate the latency measurements. As an example, 6.9 ms and 10.8 ms will evaluate to $7.54 \mu\text{s}$ and $22.7 \mu\text{s}$ 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.

V. RESULTS AND DISCUSSIONS

We evaluate BLE and PLC technologies in isolation to the other and later we integrate the two technologies and evaluate

the transmission latency. Table III, IV and Fig. 7 shows the evaluation of BLE and PLC network independently. Fig. 7 shows the average, best and worst case latencies between two sparsely located BLE nodes in a mesh network. The distance between the nodes was varied from 5 to 150m to capture cargo in motion from one zone to another. The results indicate that the worst case latency for a 150m inter node distance is 13.54ms for a power level of -4dBm. Table III indicate a dense BLE mesh does well to support a consistent PDR and latency even in the presence of Wi-Fi interference. We use two WiFi hotspots as interference for a 12 node dense BLE mesh network. BLE has inherent Adaptive frequency hopping (AFH) mechanism to choose channels, two WiFi hotspots is not able to disrupt the BLE communication. Thus, one may also conclude that the influence of one or two cargo handler carrying a mobile phone or WiFi access points will not degrade the performance of BLE network. Table V provides end-to-end transmission latency with the integration of BLE with PLC network systems and it is 24.85ms for a 570m separation between cargo in warehouse to CMS. During the testbed evaluation, we observed a $3\times$ reduction in the worst case latencies for BLE networks compared to prior work [15]. 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.

VI. CONCLUSIONS

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 transmission latency of the order of 24.85ms for a distance of 570meters 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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REFERENCES

- [1] <https://www.iata.org/whatwedo/cargo/Documents/cargo-strategy.pdf>. Accessed: 2019-02-24.
- [2] Yoon Seok Chang, Min Gyu Son, and Chang Heun Oh. Design and implementation of rfid based air-cargo monitoring system. *Advanced Engineering Informatics*, 25(1):41–52, 2011.
- [3] Rathinamala Vijay, Harshpal Singh, TV Prabhakar, Vinod Hegde, and Pavan Shigehalli. Air cargo monitoring: A robust tamper detection and reliable communication system. In *2018 IEEE 13th International Symposium on Industrial Embedded Systems (SIES)*, pages 1–4. IEEE, 2018.
- [4] Lutz Lampe. *Power Line Communications: Principles, Standards and Applications from multimedia to smart grid*. John Wiley & Sons, 2016.
- [5] Federico Passerini, Davide Righini, and Andrea M Tonello. A bottom-up plc channel model that includes radiation effects. In *2018 IEEE International Symposium on Power Line Communications and its Applications (ISPLC)*, pages 1–6. IEEE, 2018.
- [6] Manfred Zimmermann and Klaus Dostert. A multipath model for the powerline channel. *IEEE Transactions on communications*, 50(4):553–559, 2002.
- [7] Khaled M Rabie, Bamidele Adebisi, Haris Gacanin, and Serhan Yarkan. Energy-per-bit performance analysis of relay-assisted power line communication systems. *IEEE Transactions on Green Communications and Networking*, 2(2):360–368, 2018.
- [8] Davide Righini, Federico Passerini, and Andrea M Tonello. Modeling transmission and radiation effects when exploiting power line networks for communication. *IEEE Transactions on Electromagnetic Compatibility*, 60(1):59–67, 2018.
- [9] V Sessa Raghav, Varun Gowtham, HS Jamadagni, and TV Prabhakar. Data throughput maximization for broadband over power line. In *2014 Sixth International Conference on Communication Systems and Networks (COMSNETS)*, pages 1–6. IEEE, 2014.
- [10] Donald B Lee, Anil Kumar, Nha Thanh Nguyen, and Timothy McNally Mitchel. Methods and systems for vehicle broadband connection to a data network, February 3 2015. US Patent 8,948,934.
- [11] Anil Kumar, Arun Ayyagari, and Timothy M Mitchell. Secure aircraft data transmission using multiple communication channels, March 22 2016. US Patent 9,295,032.
- [12] Nha Thanh Nguyen, Anil Kumar, Timothy M Mitchell, Radhakrishna G Sampigethaya, Arun Ayyagari, and Sudhakar S Shetty. Aircraft data transmission using phase separation, May 30 2017. US Patent 9,667,316.
- [13] Yinjia Huo, Gautham Prasad, Lazar Atanackovic, Lutz Lampe, and Victor CM Leung. Grid surveillance and diagnostics using power line communications. In *2018 IEEE International Symposium on Power Line Communications and its Applications (ISPLC)*, pages 1–6. IEEE, 2018.
- [14] David Cenizal and Rahul Anilkumar. Power line communication monitor, May 17 2016. US Patent 9,344,151.
- [15] Raúl Rondón, Mikael Gidlund, and Krister Landernäs. Evaluating bluetooth low energy suitability for time-critical industrial iot applications. *International Journal of Wireless Information Networks*, 24(3):278–290, 2017.
- [16] Alessandro Chiumento, Brecht Reynders, Yuri Murillo, and Sofie Pollin. Building a connected ble mesh: A network inference study. In *2018 IEEE Wireless Communications and Networking Conference Workshops (WCNCW)*, pages 296–301. IEEE, 2018.
- [17] Chayan Sarkar, SN Akshay Uttama Nambi, R Venkatesha Prasad, and Abdur Rahim. A scalable distributed architecture towards unifying iot applications. In *2014 IEEE World Forum on Internet of Things (WF-IoT)*, pages 508–513. IEEE, 2014.
- [18] William H Berkman and David Stanley Yaney. Wireless link for power line communications system, March 24 2009. US Patent 7,508,834.
- [19] Robert Horonjeff, Francis X McKelvey, William Sproule, and Seth Young. *Planning and design of airports*, volume 4. McGraw-Hill New York, 1962.
- [20] Mike Maynard, Dave Clawson, Marc Cocanougher, David Walter, Michael Webber, Rich Janise, Ray Brimble, Kitty Freidheim, and Robert Miller. Air cargo facility planning and development. Technical report, 2015.
- [21] <https://www.nordicsemi.com/Products/Low-power-short-range-wireless/nRF52832>. Accessed: 2019-02-24.
- [22] T Samakande, T Shongwe, AS de Beer, and HC Ferreira. The effect of coupling circuits on impulsive noise in power line communication. In *2018 IEEE International Symposium on Power Line Communications and its Applications (ISPLC)*, pages 1–5. IEEE, 2018.
- [23] <https://www.wiznet.io/product-item/w5500>. Accessed: 2019-02-24.
- [24] Nguyen B Truong, Young-Joo Suh, and Chansu Yu. Latency analysis in gnu radio/usrp-based software radio platforms. In *MILCOM 2013-2013 IEEE Military Communications Conference*, pages 305–310. IEEE, 2013.
- [25] Roece Bar. *In-vehicle powerline communication using software-defined radio*. PhD thesis, University of British Columbia, 2016.