Wi-Fi 6 Data Transmission over a Low-Voltage Power Line Channel: Implementation and Analysis

K. Ogunyanda [1,*], O. O. Ogunyanda [2], A. D. Familua [2], T. Shongwe [3], T. G. Swart [2], and L. Cheng [4]

[1] Networks, BT Group, London, United Kingdom

[2] Center for Telecommunications, Department of Electrical and Electronic Engineering Science, University of Johannesburg, Johannesburg, South Africa

[3] Department of Electrical and Electronic Engineering Technology, University of Johannesburg, Johannesburg, South Africa

[4] School of Electrical and Information Engineering, University of the Witwatersrand, Johannesburg, South Africa

Email: ogunyanda@gmail.com (K.O.); opeyemiogunyanda@gmail.com (O.O.O.); familuakunle@gmail.com (A.D.F.); tshongwe@uj.ac.za (T.S.); tgswart@uj.ac.za (T.G.S.); ling.cheng@wits.ac.za (L.C.)

*Corresponding Author

Abstract—**The increasing demand for bandwidth-intensive and low-latency applications has made Wi-Fi 6 an essential technology for modern wireless networks. However, the deployment of Wi-Fi 6 often relies on Ethernet cabling, which can be costly and challenging to install, especially in existing structures or where cable routing restrictions apply. This research investigates the integration of Power-Line Communication (PLC) into the Wi-Fi 6 underlay cabling infrastructure, using enterprise-based wireless local area network devices. A direct forwarding method of data transmission was employed to facilitate faster data transfer in the proposed solution. PLC leverages existing electrical wiring to reduce installation costs and simplify deployment in complex environments. The solution enables connectivity for end devices such as computers, phones, and Internet of Things (IoT) devices, either in home environments or within the access layer of hierarchical enterprise-based campus networks, enhancing data transmission where traditional cabling is impractical. Performance analyses, including comparisons with a non-PLC prototype, demonstrate the feasibility and advantages of PLC-Wi-Fi 6 integration as a cost-effective alternative to Ethernet cabling. Wi-Fi 6 was chosen due to its established ecosystem and resource availability at the time of study; however, the proposed PLC framework is adaptable to next-generation technologies like Wi-Fi 7, ensuring future scalability.**

Keywords—**access point, Ethernet network, Ethernet PLC adapter, Internet of Things (IoT), Power-line communications, Wi-Fi 6, Wireless access controller, wireless communications, WLAN technology**

I. Introduction

Originally, Wi-Fi technology served limited scenarios like cafeterias, hotels, and airports. However, the rise of mobile terminals, Internet of Things (IoT), and mobile offices presented new challenges for traditional Wi-Fi. To address these demands, Wi-Fi 6/7 emerged, offering high data rates and compatibility with power-intensive devices [1–3].

Wi-Fi 6, complemented by wireless RF technology, provides widespread coverage and convenience for IoT applications [4]. With diverse connectivity needs, Wi-Fi 6 stands out as a versatile solution capable of addressing varying bandwidth and power requirements [5].

Setting up Wi-Fi networks in medium or large-scale enterprises requires planning and setup involving standard devices like Wireless LAN Controller (WLC), Access Points (APs), Ethernet switches, routers and Ethernet cabling. However, running new Ethernet cables could be challenging in many ways, as later revealed in the subsequent section.

Integrating Power-Line Communication (PLC) with Wi-Fi 6 networks addresses challenges of traditional Ethernet cabling. For example, Ethernet deployment is costly, labor-intensive, and disruptive, especially in retrofit scenarios. Signal degradation over long distances and vulnerability to Electromagnetic Interference (EMI) are common issues. Hence, to address these challenges, this study explores the practical adaptation of power-line channels for Ethernet use in WLAN and Wi-Fi 6 architectures, suitable for enterprise settings.

The objectives of this research are to:

- Evaluate the feasibility of integrating PLC with Wi-Fi 6 networks in enterprise environments.
- Measure the impact of such integration on network performance metrics, including throughput, latency, and packet loss.

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- Assess the applicability of this hybrid system for supporting IoT devices in scenarios where Ethernet cabling is impractical.
- These objectives address key research questions:
- Can PLC provide a reliable alternative to Ethernet for Wi-Fi 6 in enterprises?
- What are the measurable impacts of PLC-Wi-Fi 6 integration on network Quality of Service (QoS) in terms of throughput, latency, and loss?
- Does this integration improve IoT device performance in enterprise environments compared to traditional setups?

The integration capitalizes on both technologies' strengths. It merges PLC's reliability and coverage [6, 7] with Wi-Fi 6's high-speed, low-latency capabilities [8, 9]. This synergy benefits scenarios with challenging Wi-Fi coverage, like multi-story buildings or dense urban areas, enhancing network performance and user experience without extensive cabling or infrastructure upgrades. Wi-Fi 6, as an enabling technology for IoT [1, 2], excels in supporting a vast number of connected devices, making it particularly advantageous in situations where Ethernet cabling is impractical. This capability expands the deployment potential of IoT devices in diverse enterprise and home-based scenarios. While practical implementations of PLC-IoT deployments are still emerging [10], experimental studies, such as those discussed in Ref. [11], demonstrate the potential of PLC in providing a reliable backbone for IoT connectivity. Other benefits and various application scenarios of this integration are further explored in Ref. [12], though practical implementations remain limited.

II. Power-Line Communications

PLC leverages existing electrical wiring, providing a cost-effective alternative to Ethernet. Studies have demonstrated its scalability and flexibility in network expansion, particularly in IoT applications, without requiring additional wiring [11, 13]. It has been known since 1897, when Routin and Brown were awarded the first patent in PLC in Britain. In 1901, a German engineer called Loubery obtained the second PLC patent [14, 15]. In 1950, town lightning and relay remote control were already being done by single directional transmission before ASCOM (Switzerland) and NORWEN (UK) could register their first bi-directional tests for data transmission over a PLC channel in the late 1990s. These town lightning and relay remote control were done at a frequency of 10 Hz and 10 kW signal power. In France, EDF Research and Development (ERD), together with ASCOM was only able to carry out the test in the year 2000 [16]. Ever since then, PLC has become popular for various uses, some of which are telemetry, monitoring, smart metering, measurement, and rural area communications (where alternative means of communication is difficult to achieve) [17, 18].

Work done with regards to modifying the behavior of PLC channels to make it suitable for data transmission has been widely reported in the literature [19–21]. Efforts applied to implement some of such works have been reported in Refs. [22–24]. Furthermore, recent advancements in PLC technology improve data rates, signal reliability, and interference mitigation, though further development is needed for high-bandwidth applications [25].

Since PLC is no longer new research, our focus in the work reported here is to further explore its advantage for data communication. As such, we have made use of the Ethernet PLC adapter manufactured by Netgear to couple the transmitted data to a low-voltage PLC channel.

III. WLAN Architecture

WLANs are composed of wired (underlay) segments and wireless segments. On the wired side, APs connect to the upper-layer network (the Internet) using the IEEE 802.3 standard for Ethernet connections. On the wireless Side, Stations (STAs) communicate with APs using the IEEE 802.11 standard. The WLAN architecture is composed of basic networking devices connected in such a way as to ensure connectivity between an upper-layer network and the STAs, depending on the method of deployment. Fig. 1 shows a typical WLAN topology comprising of WLC, LAN (network of switches), APs, STAs and upper-layer network.

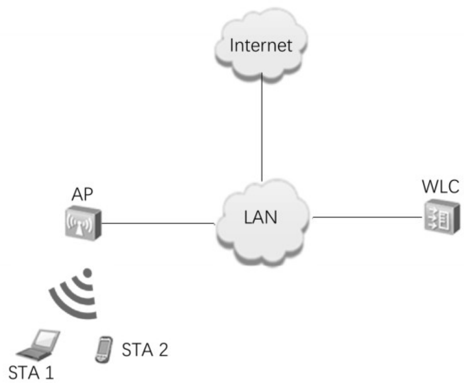


Fig. 1. Typical WLAN topology.

Depending on the deployment requirement, a WLAN solution can transmit data in either tunnel forwarding, direct forwarding or soft Generic Routing Encapsulation (GRE) forwarding mode [26]. These offer different forwarding efficiencies η.

A. Tunnel Forwarding

Tunnel forwarding is also referred to as a centralized forwarding where the WLAN control packets and user data are forwarded through Control and Provisioning of Wireless Access Points (CAPWAP) tunnels. In this mode, the user data is encapsulated in a tunneling protocol (e.g., GRE or IPsec) and then delivered to the WLC, which in turn forwards it to the upper-layer network. This mode is illustrated in Fig. 2. Its forwarding efficiency is given by:

$$\eta_{\text{Tunnel}} = \frac{\text{Number of Tunneled Packets}}{\text{Total Packets}} \times 100\%. \quad (1)$$

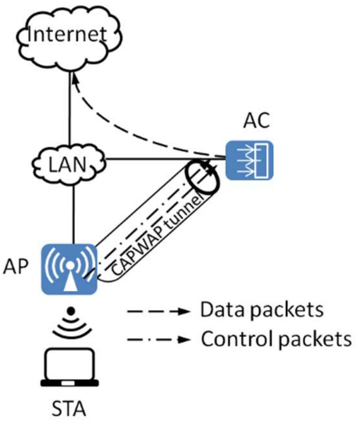


Fig. 2. Tunnel forwarding (adopted from [26]).

B. Direct Forwarding

This is also referred to as local forwarding where the WLAN control packets are forwarded through CAPWAP tunnels, while the user data is directly forwarded to an upper-layer network without any form of CAPWAP tunnel encapsulation. This mode is illustrated in Fig. 3 and its forwarding efficiency is given by

$$\eta_{\text{Tunnel}} = \frac{\text{Number of Direct Packets}}{\text{Total Packets}} \times 100\%. \tag{2}$$

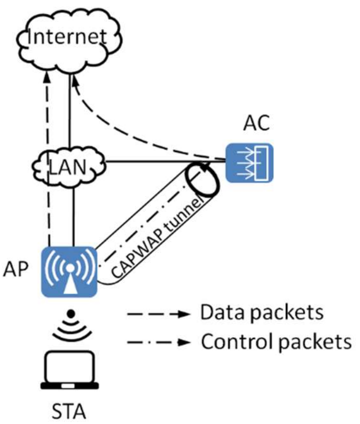


Fig. 3. Direct forwarding (adopted from [26]).

Since encapsulation or additional processing is not needed in this mode, the forwarding efficiency is typically high because there is minimal delay and overhead introduced by intermediate devices. For the sake of simplicity and faster transmission, this forwarding mode shall be employed in the work reported here.

C. Soft GRE Forwarding

This forwarding mode is similar to that of direct forwarding, but the wireless users are authenticated using legacy broadband remote access server (BRAS) devices in the live network and their data packets are GRE-encapsulated (i.e., Generic Routing Encapsulation). If the encapsulation is done using the IPsec protocols, then it is referred to as *IPsec Forwarding*. This mode is illustrated in Fig. 4 and its forwarding efficiency is given by

$$\eta_{\text{Tunnel}} = \frac{\text{Number of Soft GRE Packets}}{\text{Total Packets}} \times 100\%. \tag{3}$$

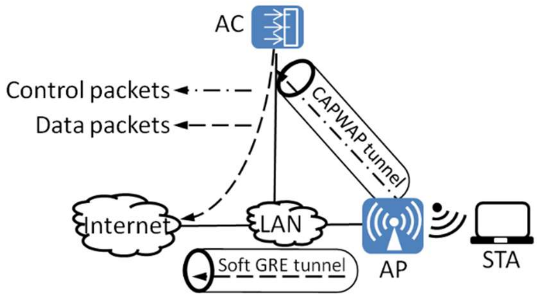


Fig. 4. Soft GRE forwarding (adopted from [26]).

IV. Combining PLC with Wi-Fi

The integration of Power-Line Communication (PLC) and Wi-Fi technologies presents a novel approach to addressing connectivity challenges in enterprise environments. While PLC leverages existing electrical wiring for data transmission, Wi-Fi provides high-speed wireless connectivity, creating a hybrid communication system that combines the strengths of both technologies.

A. Existing Work on Hybrid PLC-Wi-Fi Systems

Previous research has explored both domestic and enterprise applications of hybrid PLC-Wi-Fi systems. For example, Koch [27] focused on hybrid networks for home automation, highlighting PLC's ability to complement Wi-Fi in environments with limited cabling infrastructure.

In enterprise-focused research, Berkman [28] outlines a conceptual framework for PLC-Wi-Fi integration, while Khan *et al.* [29] demonstrated a practical implementation of a Wi-Fi-PLC system using an ordinary broadband modem for an e-health hospital scenario. However, this implementation lacks the use of WLC, a critical component for managing scalable wireless networks in enterprise environments. Furthermore, Alhulayyil *et al.* [30] introduced Priza, a framework for clustering Wi-Fi-PLC extenders into a Distributed Antenna System (DAS) to optimize throughput in dense deployments by improving PLC backhaul sharing. Similarly, Alhulayyil *et al.* [31] proposed WOLT, a framework for optimizing user association with PLC-WiFi extenders to maximize throughput by accounting for both PLC and Wi-Fi link qualities. Both works emphasize network optimization using conceptual frameworks evaluated through simulations and testbed experiments.

While these studies highlight the potential of PLC-Wi-Fi systems, they fall short in addressing practical deployment challenges, particularly the scalability and management frameworks required for robust enterprise networks.

B. Our Contribution

This study expands on previous work by demonstrating the practical deployment of hybrid PLC-Wi-Fi systems in enterprise environments, presenting untapped prospects for ICT vendors and enhancing connectivity within such environments. Using Ethernet PLC adapters integrated with Wi-Fi 6 architectures, we address the scalability and performance challenges of traditional Ethernet cabling. The results demonstrate how this hybrid approach enhances network performance, reduces infrastructure costs, and supports IoT deployment in challenging scenarios, such as multi-story buildings or retrofitted office spaces.

V. Experimental Setup

The experiment carried out in this research work is composed of WLAN devices manufactured by Huawei Technologies Co., Ltd. Table I contains the list of all the devices used, and their detailed physical connections are represented in Fig. 5. The selection of Huawei devices for this experiment was based on several factors, including their availability and the research team's familiarity with their command-line interfaces, which facilitated efficient deployment. Additionally, these devices are compliant with the IEEE 802.11ax standard and are widely used in this part of the World, making the findings relevant for local enterprise deployments. While Huawei devices were chosen for this study, other vendors such as Cisco and Aruba offer similar capabilities, which could be explored in future research to generalize the results across different hardware platforms.

TABLE I. WLAN Devices Details

Device	Model	Software Version	Qty
WLAC	AC6500	V200R021C00	1
LAN Switch	S5700	V200R021C00	1
AP (Wi-Fi 6)	AirEngine 6761	V200R021C00	2
PLC adapter	Netgear HDX101	1.0.1.98	2

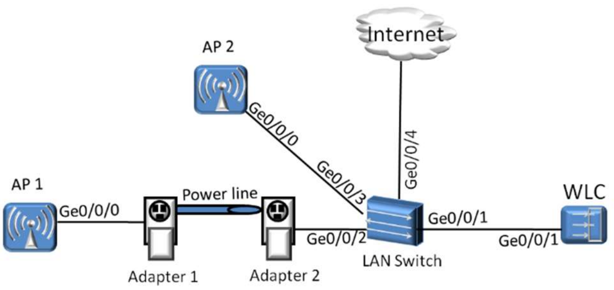


Fig. 5. Physical topology.

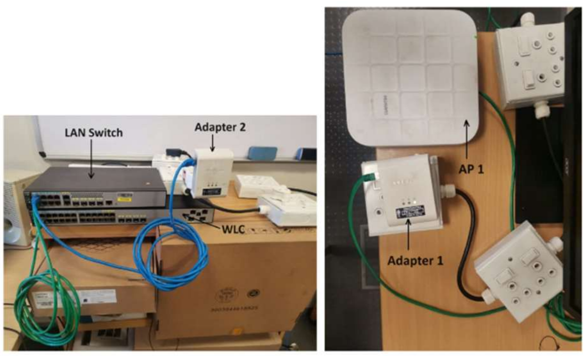


Fig. 6. Experimental setup.

All device specifications are accessible from [32–34]. The actual laboratory setup is as shown in Fig. 6. To the best of our knowledge, this is the first time such vendor devices are integrated with a PLC environment for the purpose of providing Wi-Fi 6 coverage for enterprises.

As shown in Fig. 5 the PLC channel is introduced between AP1 and the LAN switch. AP2 connects to the LAN with a Cat-6 Ethernet cable. The LAN switch is PoE enabled. As such, it is capable of powering up the APs without the need for an external power source.

Table II contains all the configuration parameters used in this work.

TABLE II. Configuration Parameters

Item	Value/Data
AP management VLAN	VLAN 11
STA service VLAN	VLAN 10
IP pool for STAs	10.10.10.1-10.10.10.254/24
IP pool for APs	11.11.11.1-11.11.11.254/24
DHCP server gateway	STAs default gateway: 10.10.10.1/24
CAPWAP source IP	11.11.11.1/24
AP group	Name: Test
SSID	Name: Test
Security policy	WPA PSK with AES encryption
VAP profile	Forwarding mode: direct

A. *Networking Specifications*

The following were assumed to set up the Wi-Fi 6 environment:

- The WLC acts as a DHCP server to assign IP addresses to the APs using a management VLAN 11.
- The WLC acts as a DHCP server to assign IP addresses to the STAs using a service VLAN 10.
- Direct forwarding mode is employed to forward user data.

B. *Configuration Roadmap*

Below are the steps followed to set up the Wi-Fi 6 network and get it up and running. Details about the LAN switch and WLC command lines can be sourced from [32, 33].

- Configure reachability between the WLC, APs and the LAN switch.
- Configure the WLC to onboard the APs by creating the AP group, and other WLC parameters (see Table II).
- Configure service parameters from the WLAN configuration mode so STAs can access the network (see Table II).

C. *Voltage Measurement*

In order to enhance the anti-interference capability of LAN switches, their Ethernet ports are equipped with PHY chips which need to be isolated from external devices. Electrical isolation is therefore pertinent in order to protect these PHY chips. To ensure that the electrical power line is completely isolated from the APs and the LAN switch, a series of voltage measurements were carried out before coupling them to the low-voltage power line. As such, output voltages on the Ethernet/LAN cables protruding from the Ethernet adapters were measured using a voltmeter.

According to the IEEE 802.3 standard, the AC component of the common-mode output voltage of a pair of matched 39 Ω ± 1% resistors and circuit VC should not exceed 2.5 V (30−40 Hz) and 160 mV (40 kHz-BR) [35]. The measured voltages between the eight copper wires of the LAN cables were approximately zero volt as expected. Similar values were observed between the ground and each of the wires.

D. Performance Measurement

For comparing with conventional Wi-Fi 6 setups, we utilized graphical frontend network performance testing tools, namely Ookla and *jPerf* (Java PerfMeter), to assess the Quality of Service (QoS) of the network in real-time.

Ookla functions by transmitting a series of data packets from the test PC to any of the selected globally distributed speed test servers and measures the round-trip time for these packets [36]. It is also capable of recording packet losses.

Similar to *iPerf*3 (Internet Protocol Performance), *jPerf* measures the maximum IP network bandwidth by adjusting parameters such as timing, buffers, and protocols (TCP, UDP, SCTP for both IPv4 and IPv6). It reports key metrics such as bandwidth, jitter, and loss. In this study, the focus is on assessing throughput performance and datagram loss as key QoS parameters.

jPerf is built using Java to provide a graphical front-end for displaying measurements in the form of graphs. It also has an output window whose contents can be exported in .txt format for further processing. The two operational modes of *jPerf*, which are the client and the server modes, were employed in the measurement exercises carried out in this work. The server mode was set up on one computer (PC) by executing the *jPerf*.bat (batch) file in the *jPerf* package folder. This opens up a graphical user interface, from where the server role was selected (activated) as can be seen in Fig. 7. In a likewise manner, the client mode was setup on the other PC by selecting the client role, but the server's IP address needed to be provided on the server address tab.

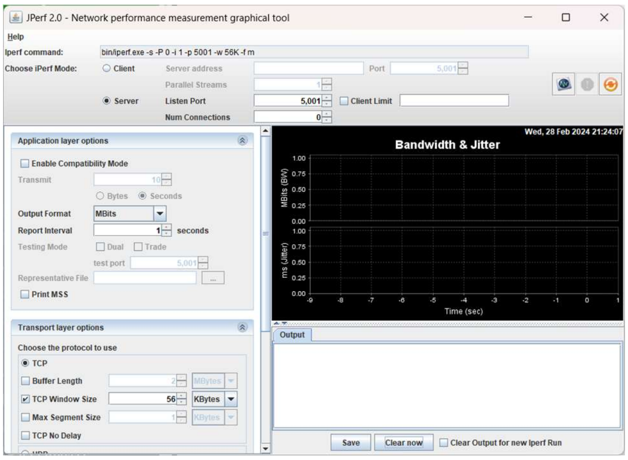


Fig. 7. *jPerf* graphical interface.

The Wi-Fi environment is inherently susceptible to latency, corruption and packet duplication caused by factors such as signal interference, collisions, and retransmissions [37–39]. To accurately assess the impact of these issues on the network's throughput and reliability, we employed the SoftPerfect connection emulator. This tool allows for the artificial introduction of latency, corruption and packet duplication into the channel, enabling us to observe its effects on the overall performance of the proposed Wi-Fi network.

VI. Results and Analyses

To test the functionality of the Ethernet network, both the *jPerf* server and the client, whose properties are displayed in Table III, were first plugged into the Ethernet switch using Cat-6 LAN cables. The tool conducted a 60-second test, with the server listening on TCP port 5001 and utilizing a TCP window size of 256. Fig. 8 illustrates the bandwidth measurements over 5-second intervals, revealing a consistent bandwidth between 941 and 948 Mbps.

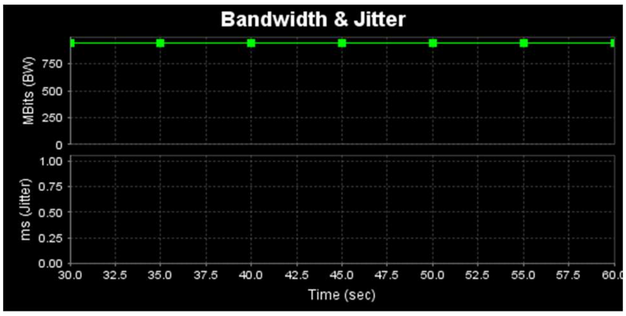


Fig. 8. Underlay network bandwidth.

The robust network performance observed, averaging approximately 944 Mbps, highlights the efficiency of the Ethernet infrastructure. Enhanced by the utilization of Cat-6 LAN cables and optimized adapter properties in both server and client PCs, including network speeds and driver versions, the experiment thus demonstrates the reliability of the underlay network used for the Wi-Fi solutions analyzed in this work.

TABLE III. Ethernet Adapter Properties of the Server and the Client PCs

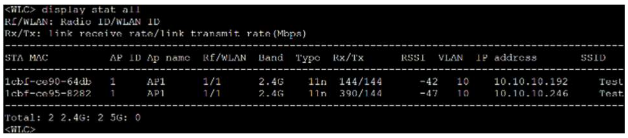
Properties	Server	Client
Manufacturer	Realtek	Realtek
Description	Intel(R) Ethernet Connection (4) I219-LM	Realtek USB GbE Family Controller
Driver Version	12.19.1.37	10.50.211.2022

TABLE IV. Wireless Adapter Properties of the Server and the Client PCs

Properties	Server	Client
Manufacturer	Realtek	Realtek
Description	Intel Dual Band Wireless-AC8265	Realtek 8812BU Wireless LAN 802.11ac USB
Driver Version	20.70.30.1	NIC1030.38.712.2019

According to Fig. 5, AP1 acts as the test AP for the proposed solution, while AP2 serves as the conventional AP without the introduction of any PLC line. Henceforth, the two cases are referred to as Case 1 and Case 2 respectively. To avoid co-channel interference, the two APs were tested one after the other. The two test PCs hosting the *jPerf* server and client were associated with the Test SSID and were successfully authenticated using either AP. Their wireless adapter properties are as shown in Table IV.

In our comparisons, we first focused on the 2.4 GHz network band. Fig. 9 displays the CLI output from the WLC, confirming the association of STAs with the 2.4 GHz frequency band. The outcomes of testing both transmitting and receiving PCs for both Case 1 and Case 2 are depicted in Fig. 10. These plots represent multiple parallel streams (4, 5, 6,…, 64), reflecting various connections, with the cumulative sum of average throughput (in Mbps) computed for each. Despite minor variations, both Case 1 and Case 2 demonstrate relatively similar throughputs.



```
<WLC> display stat all
Rf/WLAN: Radio ID/WLAN ID
Rx/Tx: link receive rate/link transmit rate(Mbps)
------------------------------------------------------------------------------------------
STA MAC          AP ID Ap name  Rf/WLAN  Band  Type  Rx/Tx      RSSI  VLAN  IP address     SSID
------------------------------------------------------------------------------------------
1cbf-ce90-64db   1     AP1      1/1      2.4G   11n  144/144     -42   10    10.10.10.192   Test
1cbf-ce95-8282   1     AP1      1/1      2.4G   11n  390/144     -47   10    10.10.10.246   Test
------------------------------------------------------------------------------------------
Total: 2 2.4G: 2 5G: 0
<WLC>
```

Fig. 9. CLI output for 2.4 GHz STA association.

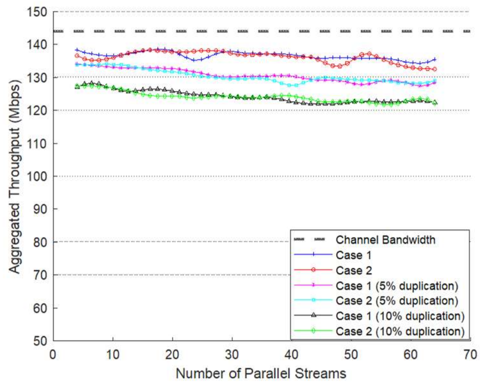


Fig. 10. Aggregated throughput for different parallel streams for 2.4 GHz band (Case 1 and Case 2).

To examine the impact of packet duplication on throughput, we introduced packet duplication into the channel, and the effect is shown in Fig. 10. It is evident that as packet duplication increases, the bandwidth becomes more congested. This congestion arises due to the redundancy introduced in transmissions with data duplication, resulting in increased network traffic and decreased efficiency.

To further analyze the results, the number of streams is plotted against the average Mbps for both cases as shown in Fig. 11. In both cases, the throughput decreases as the number of connections increases, which is expected due to limited available bandwidth that needs to be shared among more users. However, the decrease is not linear; there are fluctuations in throughput values. This might be due to varying network conditions, congestion, or other factors affecting individual connections differently. Remarkably, the two cases behave in the same manner in terms of their average Mbps when subjected to similar conditions (i.e., with and without duplications) as seen in Fig. 11. Similarly, the average Mbps decreases with increasing packet duplication.

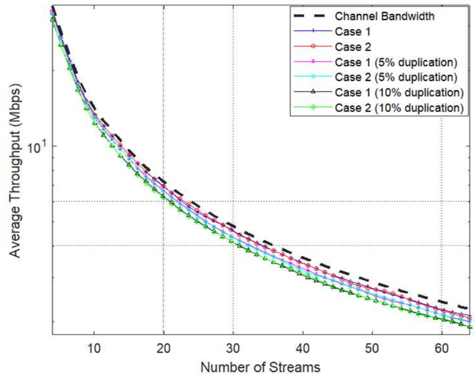
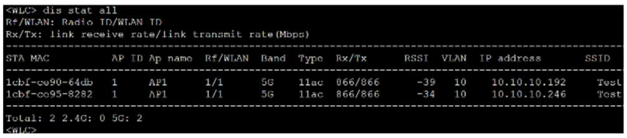


Fig. 11. Average Mbps curves for 2.4 GHz band (Case 1 and Case 2).

The 5 GHz band was also tested using the same STAs. Fig. 12 is the CLI output from the WLC which confirms that the STAs were associated with the 5 GHz frequency band. The outcomes are as shown in Figs. 13 and 14. Both Case 1 and Case 2 exhibit overlapping aggregated and average throughput under the 5 GHz band. Throughput degradation is observed when packet duplication is introduced, impacting both Case 1 and Case 2 under the 5 GHz band.



```
<WLC> dis stat all
Rf/WLAN: Radio ID/WLAN ID
Rx/Tx: link receive rate/link transmit rate(Mbps)
------------------------------------------------------------------------------------------
STA MAC          AP ID Ap name  Rf/WLAN  Band  Type  Rx/Tx      RSSI  VLAN  IP address     SSID
------------------------------------------------------------------------------------------
1cbf-ce90-64db   1     AP1      1/1      5G    11ac  866/866     -39   10    10.10.10.192   Test
1cbf-ce95-8282   1     AP1      1/1      5G    11ac  866/866     -34   10    10.10.10.246   Test
------------------------------------------------------------------------------------------
Total: 2 2.4G: 0 5G: 2
<WLC>
```

Fig. 12. CLI output for 5 GHz STA association.

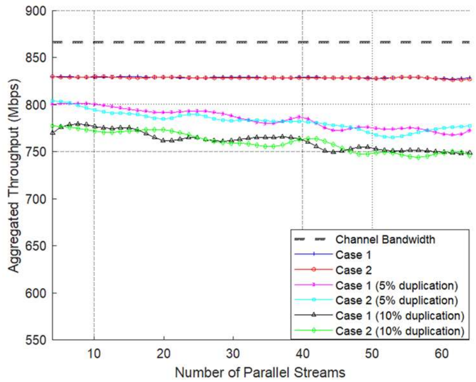


Fig. 13. Aggregated throughput for different parallel streams for 5 GHz band (Case 1 and Case 2).

In order to observe the robustness of Wi-Fi setups in Case 1 and Case 2, we introduced packet duplication into the channel, followed by UDP *jPerf* experiments to record datagram losses. As seen in Fig. 15, both Case 1 and Case 2 exhibit varying degrees of susceptibility to packet duplication, with the percentage of duplicated packets increasing from 0 to 10%. This resulted in a general increase in datagram losses across both cases and Wi-Fi bands, as expected due to the introduction of redundancy in transmissions. In the 2.4 GHz band, loss differences ranged from 0 to 10.44% and 0 to 10.34% in

Case 1 and Case 2, respectively, while in the 5 GHz band, differences ranged from 0 to 10.49% and 0 to 10.39%.

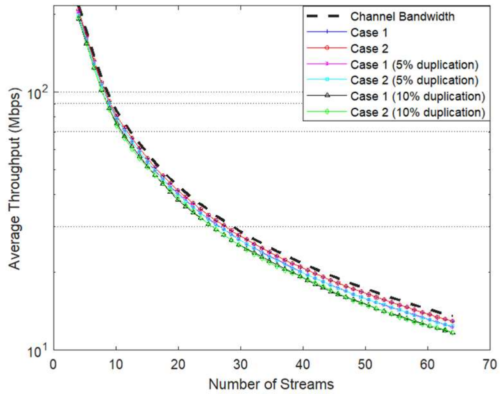


Fig. 14. Average Mbps curves for 5 GHz band (Case 1 and Case 2).

Since the two STAs (i.e., the client and server PCs) are situated within the same IP subnet (VLAN 10), as planned according to Table II, Internet-based data exchange between them does not traverse the upper-layer network, establishing a peer-to-peer connection in an ad-hoc network. Consequently, the test outcomes reported in Figs. 10−15 primarily involved control packet exchanges between the WLC and the AP via the CAPWAP interface, with user data exclusively passing through the AP without utilizing the LAN infrastructure. Therefore, this scenario validates the PLC's capability in sustaining control packet exchanges, facilitating efficient WLC onboarding and AP management.

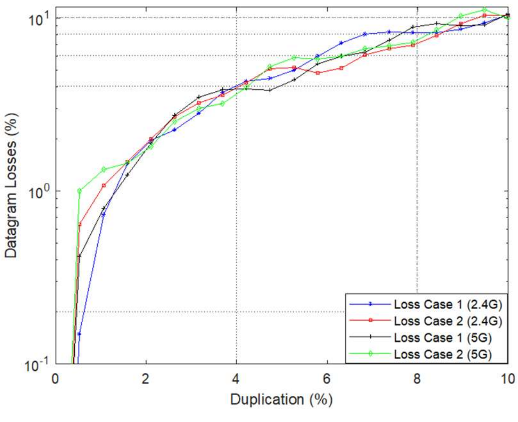


Fig. 15. Effect of packet duplication in the 2.4 GHz and 5 GHz bands (Case 1 and Case 2).

To integrate the LAN segment into user data transmission, we conducted tests involving Internet-based traffic. Due to resource constraints, mobile broadband served as the Internet source in the upper layer, while the client PC was employed for data loss tests using the Ookla platform. In this setup, the SoftPerfect tool introduced corruption into the WiFi link, allowing us to assess the robustness of setups in both Case 1 and Case 2 regarding data loss. Fig. 16 illustrates the test outcomes, revealing minimal disparities in the effects of introduced corruption in both cases, with packet loss escalating as the level of corruption increases. Losses in Case 1 and Case 2 range from 0 to 9.8% and 0 to 10% in the 2.4 GHz band, respectively, and from 0 to 9.1% and 0 to 9% in the 5 GHz band.

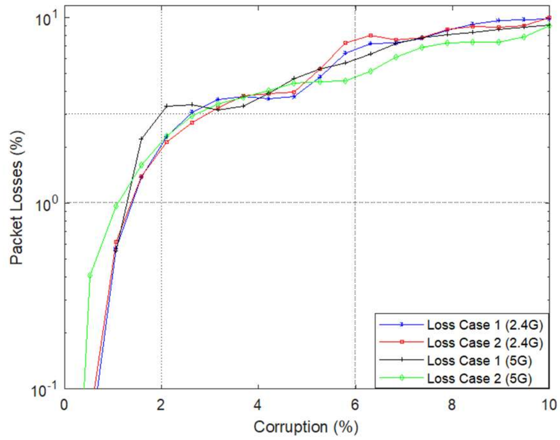


Fig. 16. Effect of corruption on transmitted user data in the 2.4 GHz and 5 GHz bands (Case 1 and Case 2).

To assess the reliability of the observed differences between Case 1 and Case 2, 95% confidence intervals were calculated for the data presented in Figs. 10 to 11 and Figs. 13−16. These intervals represent the range within which the true values are expected to lie with 95% certainty. The substantial overlap of the confidence intervals, as shown in Table V, indicates that the differences between Case 1 and Case 2 are statistically insignificant, suggesting that any observed variations are unlikely to be practically meaningful.

It is worth noting that AirEngine 6761 is capable of 575 Mbps (in the 2.4 GHz band), 1.2 Gbps (in the 5 GHz band) and 4.8 Gbps (in the 6 GHz band) [40]. However, the channel bandwidths for the 2.4 GHz and 5 GHz bands in the ad-hoc situation were restricted to 144 Mbps and 866 Mbps, respectively, due to the adapters' properties of the PCs used. These are indicated as dotted lines in Figs. 10−13. In either case, the bandwidths are not fully utilized or exceeded due to various factors such as the network latency (round-trip time), the TCP window size, and the network conditions.

According to the results obtained from all test cases, it can be inferred that integrating a PLC network with WLAN does not lead to significant performance degradation. Our analysis demonstrates that the system maintains robust performance even as the network size increases. Throughput and latency metrics were monitored in scenarios with varying numbers of connected devices, showing that the network can handle increased loads with minimal degradation. In larger enterprise environments, software-defined platforms such as Huawei CloudCampus, Ruckus Cloud, Meraki Dashboard, and Cisco DNA Center, which integrate WLC functionalities, are employed to manage multiple access points [41–44]. These platforms enhance network scalability, flexibility, security, and overall efficiency. Given the successful integration of PLC within a WLAN environment using WLC, the proposed system is well-suited for deployment in such software-defined platforms, ensuring scalability in larger, more complex networks.

TABLE V. CONFIDENCE INTERVALS FOR RESULTS IN FIGS. 10 TO 11 AND 13 TO 16

Figure	Band	% Duplication	Measurement Type	Case 1	Case 2
Fig. 10	2.4 GHz	0	Aggregated Mbps	[136.28,1 36.89]	[135.70, 136.65]
Fig. 10	2.4 GHz	5	Aggregated Mbps	[130.06, 131.14]	[129.85, 130.93]
Fig. 10	2.4 GHz	10	Aggregated Mbps	[123.72, 124.75]	[123.69, 124.54]
Fig. 11	2.4 GHz	0	Average Mbps	[4.78, 8.45]	[4.77, 8.40]
Fig. 11	2.4 GHz	5	Average Mbps	[4.58, 8.16]	[4.57, 8.16]
Fig. 11	2.4 GHz	10	Average Mbps	[4.36, 7.77]	[4.35,7.76]
Fig. 13	5 GHz	0	Aggregated Mbps	[828.74, 829.06]	[828.49, 828.90]
Fig. 13	5 GHz	5	Aggregated Mbps	[782.01, 787.91]	[780.22, 785.52]
Fig. 13	5 GHz	10	Aggregated Mbps	[759.09, 764.47]	[757.68, 763.49]
Fig. 14	5 GHz	0	Average Mbps	[28.96, 51.07]	[28.95, 51.06]
Fig. 14	5 GHz	5	Average Mbps	[27.99, 49.66]	[27.97, 49.43]
Fig. 14	5 GHz	10	Average Mbps	[26.71, 47.39]	[26.61, 47.37]
Fig. 15	2.4 GHz	0−10	Datagram Loss (%)	[3.60, 6.52]	[3.48, 6.20]
Fig. 15	5 GHz	0−10	Datagram Loss (%)	[3.48, 6.35]	[3.64, 6.54]
Fig. 16	2.4GHz	0−10	Datagram Loss (%) (with broadband)	[3.64, 6.59]	[3.68, 6.61]
Fig. 16	5 GHz	0−10	Datagram Loss (%) (with broadband)	[3.62, 6.28]	[3.64, 6.19]

While PLC networks offer numerous benefits, they are not without security risks. Data transmitted over PLC networks may be more vulnerable to eavesdropping compared to traditional Ethernet. To address this security concern, unauthorized network access was restricted through the use of secure authentication mechanisms configured in the security policy and AP group profiles specified in Table II. Additionally, employing secure forwarding modes with tunneling protocols could further enhance security, although this is beyond the scope of the current study.

VII. CONCLUSION

This study has demonstrated the successful integration of PLC networks with Wi-Fi 6, showing that the hybrid PLC-Ethernet setup maintains robust network performance with minimal degradation, even in complex scenarios. This highlights PLC's practicality as a cost-effective and scalable complement to Ethernet in modern WLAN deployments.

The integration holds particular significance for the IoT landscape, enhancing connectivity for IoT devices in environments where traditional cabling is impractical. Moreover, while Wi-Fi 6 was evaluated due to its maturity and availability during this study, the proposed PLC integration framework is adaptable to future technologies like Wi-Fi 7, ensuring long-term scalability. Future research can explore secure forwarding modes and advanced optimizations for integrated PLC-Wi-Fi architectures to further enhance their efficiency and security.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHOR CONTRIBUTIONS

K. Ogunyanda and A.D. Familua conducted the research; O.O. Ogunyanda wrote the paper; T. Shongwe supervised the work; T.G. Swart and L. Cheng analyzed the results; all authors had approved the final revision before submission.

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