Computer Communications 209 (2023) 429–443

Contents lists available at ScienceDirect

Computer Communications

journal homepage: www.elsevier.com/locate/comcom

Empirical evaluation of 5G and Wi-Fi mesh interworking for Integrated Access and Backhaul networking paradigm

Mohamed Khadmaoui-Bichouna [*], Jose M. Alcaraz-Calero, Qi Wang

University of the West of Scotland, Paisley, Renfrewshire, United Kingdom

ARTICLE INFO

Keywords:
IAB(Integrated Access and Backhaul) network
Wi-Fi mesh
5G
Network coverage
Edge

ABSTRACT

The Fifth Generation (5G) of mobile networks and beyond have emerged with ambitions to facilitate the deployment and evolution of a wide spectrum of applications such as Industry 4.0 and 5.0 use cases. Despite this trend of increasing importance to upgrade the networked applications to the next generation, the use of 5G and beyond technologies can be a prohibitive barrier for some business sectors due to the high deployment costs that it can incur. To overcome this obstacle, more cost-effective approaches in networking are entailed. In this work, an innovative approach coupling 5G and Wi-Fi mesh networking is proposed and developed as a promising solution to extend 5G services to the indoor use case scenarios whilst being capable of keeping the capital expenditure of the network infrastructure significantly lower. In order to empirically validate and evaluate this new networking paradigm, a number of experiments have been performed over a testbed with a demanding video application as a representative use case. The experimental results prove the gained benefits from this new approach, especially, video users can be more than twice as far away without compromising the quality of the video consumption experience. Specifically, the results show that users can be 29% further away using a single router, and 100% further away if a second router is added.

1. Introduction

The Fifth Generation (5G) of mobile communications is bringing with it a number of improvements for both individual users and industry [1]. The industrial sector will notice such improvement the most due to the desire to automate as many tasks as possible, making industrialization processes more efficient than before. With 5G, the amount of data that can be transmitted has grown significantly. Not only that, but the speed at which this information is transmitted is also higher. These speeds are expected to be up to 10 Gbps with a minimum guaranteed speed of 100 Mbps [2]. The improvement of these two features has resulted in a decrease in latency enabling 5G technology to appear in various fields of research. An example of this can be found in the use of this technology to bring tasks from user devices to the edge of the network. In [3], it is demonstrated how bringing the task of corrosion detection by an AI to the edge of the 5G network achieves high processing times. Conclusions like this help other authors test different AI platforms for their computationally expensive applications. For example, Martinez et al. [4] could extend the use of 5G network edge instead of the usage of constrained devices.

One obstacle to this new 5G network that may determine its limited use in the industry is that coverage is not as great as other technologies because of the fact that the frequency at which 5G communications work is relatively high. The 5G spectrum is divided into two parts. The first one is the mmWave (millimetre wave) spectrum which has been almost unused in the initial deployment of the 5G network. This region ranges from 17 GHz to 100 GHz while the second part of the spectrum is the sub-6 GHz region which ranges between 3–6 GHz [5]. Using such high frequencies results in the coverage distance not being as large as desired. Therefore, in order to solve this problem, the number of cells must be increased to cover a larger working area.

Another issue facing 5G networks is the potential cost of deploying them. Generally, mobile networks are divided into two sections. The first portion is the wireless zone where the user's equipment is connected, called the access network. The second part is the one that connects the access network to the core, called the backhaul network. This part is usually wired. Large amounts of traffic are handled in this area and therefore, it is safer to be wired. Fibre optic cabling is used in this area as it has been proven to support high traffic capacity. Consequently, increasing the number of 5G cells leads to higher deployment costs since the installation costs of the fibre optics behind the 5G network are high [6]. Eventually, the rising cost means that the deployment of 5G networks will not be as expected and therefore will not reach everyone. This fact has led to Integrated Access and Backhaul (IAB) networks being proposed as a solution.

---

[*] Corresponding author.
E-mail addresses: mohamed.khadmaoui-bichouna@uws.ac.uk (M. Khadmaoui-Bichouna), jose.alcaraz-calero@uws.ac.uk (J.M. Alcaraz-Calero), qi.wang@uws.ac.uk (Q. Wang).

https://doi.org/10.1016/j.comcom.2023.07.007
Received 6 March 2023; Received in revised form 27 May 2023; Accepted 6 July 2023

Table 1
Comparison of this research with the state of the art.

	5G - IAB				WI-FI			Validation	Software			Analysis				Protocol
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
[9]	×	✓	×	✓	×	×	×	Analytical	Unspecified			×	×	×	×	Unspecified
[10]	×	✓	✓	✓	×	×	×	Analytical	×	×	×	✓	✓	×	×	×
[11]	×	✓	×	✓	×	×	×	Analytical	×	×	×	×	×	×	×	×
[12]	×	✓	×	✓	×	×	×	Analytical	×	×	×	×	×	×	×	×
[13]	×	✓	✓	✓	×	×	×	Simulation	NS-3 simulator			×	✓	✓	×	UDP
[14]	×	✓	✓	✓	×	×	×	Simulation	NS-3 simulator			✓	✓	×	×	UDP & TCP
[15]	×	✓	×	✓	×	✓	×	Simulation	MATLAB			✓	×	×	×	×
[16]	✓	✓	✓	✓	×	×	×	Simulation	MATLAB			×	×	×	×	×
[17]	×	✓	✓	✓	×	×	×	Simulation	NS-3 simulator			✓	✓	×	×	UDP
Our	×	×	×	×	✓	✓	✓	Fieldwork	Open Air Interface		TP-LINK	✓	✓	✓	✓	TCP

Table 2
Description of the columns.

			Description
5G/6G - IAB	1	Multi-Donor	Uses more than one IAB Donor
	2	Single-Donor	Uses 1 single IAB Donor
	3	Multi-hop node	Uses more than 1 IAB Nodes
	4	Single-hop node	Uses 1 single IAB node
WiFi	5	Mesh support	Use of WIFI mesh
	6	Single-hop	Uses 1 single hop of WIFI mesh
	7	Multi-hop	Uses more than 1 hop of the WIFI mesh
Validation	8		Type of empirical validation
Software	9	RAN	Software for simulation or emulation of the 5G network and the IAB network
	10	CORE	
	11	IAB	
Analysis	12	Throughput	Amount of data that can be transmitted successfully
	13	Latency	The time it takes for information to get from one point to another
	14	Packet loss	Number of packets that do not arrive successfully at the destination
	15	Jitter	Variety of delays in the arrival of packages
Protocol	16		Transport protocol

IAB networks have been first proposed for LTE technology by 3GPP (Third Generation Partnership Project) [7], but due to the limited valuable spectrum of 4G, this technique did not succeed. With the increase of spectrum in 5G networks, IAB networks have been re-positioned as a transport backhaul solution. IAB networks have been proposed by 3GPP [8] to reduce most of the fibre optic deployment. With this technique, different radio access networks (RAN) communicate with each other wirelessly using the same spectrum as the one being used for UEs. Therefore, in this topology, there will be RAN connected to the core via fibre optics supporting other RAN wirelessly. This increases the number of RAN without increasing the costs due to fibre optics. Hence, there would be two types of backhauling: one wired and the other wirelessly. Making part of the transport network wireless makes the network more flexible and scalable, causing an increase in the distance of coverage.

Integrated access and backhaul networks have been standardized in [18] and the cost savings they produce have been demonstrated.

The challenge of testing whether it is possible to make a 5G network reach a greater distance is what motivated this research work. To this end, it has been decided to create a Wi-Fi mesh network using 5G network resources to increase network coverage. In order to test the proposed network architecture as a suitable real-world networking solution for applications, it has been decided to carry out experiments with video transmission and visualization since they are realistic and demanding use cases. These use cases make it possible to experimentally assess the behaviour of the network under heavy real-time traffic scenarios. Video streaming requires low latency and high bandwidth to achieve satisfactory video quality and is, therefore, a good option for testing the quality of service of the proposed architecture. Therefore, the aim of this paper is to unify 5G networks with Wi-Fi mesh networks in order to empirically emulate the operation of an integrated access and backhaul network. Several network hops have been introduced to study this type of network. And finally, to validate the operation of this network in an empirical way.

According to these contributions, the following set of innovations are provided with respect to the state of the art:

1. A set of new architectural components have been designed to achieve the integration of Wi-Fi technology into the 5G.
2. A set of deployment strategies and scenarios to demonstrate the benefits of the proposed new components.
3. Empirical Validation of the proposed architectural components in a lab-based prototype to demonstrate the feasibility and performance of the approach.

To describe the contribution of this work, the article has been divided into the following sections. Section 2, provides information on the state of the art related to different articles regarding simulated or real IAB network research works. Section 3 contains a comparative between Wi-Fi mesh networks and IAB networks indoors. Section 4 shows an overview of the proposed architecture to achieve the objective. Section 5 provides a vision of the testbed that is used in this research work. Section 6 explains the experiments carried out to test the network created. Section 7 provides the results obtained by studying the operation of this architecture and finally, Section 8 concludes the work and presents possible future work.

2. Related work

This section shows different journals where IAB networks and their benefits are studied. In Table 1, a comparative summary of the different papers is presented. The columns of Table 1 are labelled with a number and Table 2 provides an explanation of the meaning of such number.

The research works found are divided into 2 categories. These categories will be divided into two different sub-sections for easier presentation.

2.1. Analytical related work

This first category is about papers where the work done is analytical.

In [9], the resource allocation and relay selection in a multi-hop IAB network are investigated. Such work demonstrates how these parameters can affect the mean of UE rates. When testing for numerical results, assumptions are made about possible topologies of the network. Both antenna positions and UE positions are assumed. Even the transmit powers of the antenna and the UE are assumed to be a specific value. A comparison of what the differences would be between adding an IAB network to a 5G network and not is made. The conclusion of the authors is that by adding an IAB network, the coverage and capacity may be increased.

Jaber et al. in [10] proposed a framework that can analyse the performance of a wireless backhaul. A backhaul network with 2 hops is simulated. The Poisson Point Process is used to study how LOS (Loss of signal) can affect the metrics of Throughput, latency, and resilience.

In [11], an analytical framework to study different bandwidth partitioning strategies for the backhaul of an IAB network is developed. The first strategy is allocating the same bandwidth to all base stations, then the bandwidth is divided according to the instantaneous load and finally, dividing the bandwidth among the base stations according to the average load they have. The Monte Carlo method is used to perform these simulations.

The impact of traffic offloading and SBS (Small Cell Base Station) density on data rate on a multi-tier IAB is studied in [12]. The MBSs (Macro Base Stations) are supposed to be the only components that are connected to the fibre backhaul while the SBSs are connected wirelessly. Two strategies to divide the bandwidth are defined with this architecture. In the first one the bandwidth is dynamically split between access and backhaul and in the second one, there is a static split between these 2 parts. An analytical framework has been developed for the study of these configurations. It has been concluded that the excessive user load on SBSs affects the performance of this type of network due to the generation of bottlenecks.

2.2. Simulated related work

The second category contains research works where simulations of IAB networks are performed with software such as MATLAB or emulated using NS-3 Emulator.

Fabian et al. [13] compare various topologies of a 5G network with and without IAB. The delay of transmissions and the rate of packet loss are studied. The conclusion the researchers come to is that adding an IAB topology to a 5G network is beneficial and does not affect the above metrics to any great extent. In addition to this, the coverage distance is increased by adding IABs where the 5G network operates, without having to increase fibre optics for the deployment. For the study of IAB networks, the NS-3 simulator is used. UDP packets have been transmitted from the client to an Internet server for the tests at a constant bit rate.

Pagin et al. in [14], propose a new scheme for IAB networks where the resource allocation it is defined by a partition on the links between backhaul and access. This scheme, based on MWM (Maximum Weighted Matching), receives measurements of L1 and/or L3 and lets the nodes schedule the resources among the connected devices. To achieve this, an algorithm that calculates which backhaul and access partition can be optimal for a function has been developed. This algorithm is based on metrics such the throughput and latency.

In [15], Sahoo et al. consider a coexistence between an IAB network and a Wi-Fi network. The throughput of the downlink has been studied. 3 different scenarios where the access strategies change have been deployed to study these metrics. A network topology using one IAB-donor and several IAB nodes connected to it has been simulated. MATLAB software has been used to carry out the tests and simulations.

In [16] Adare et al. study how modifications to power control can improve the coverage range offered by IAB networks. To be able to do this, a genetic algorithm that can maximize the coverage of the uplink service of the network has been developed. The algorithm consists of selecting possible values that the transmit power can take, calculating the received power for each case, the SINR and the coverage probability. Once this has been done, the set of powers that have achieved the most coverage is selected, the second set of 5 values close to the first set is chosen and the algorithm is iterated once again. The calculations carried out in this work have been done by simulation using MATLAB software.

In [17] the performance of an IAB network simulated with the help of the NS-3 simulator software has been studied. The analysis consisted of creating single-hop and multi-hop IAB networks to study the throughput and latency that may be present in this type of network. All this takes into account possible interferences that may occur in this supposed network. After their work, it has been concluded that IAB networks can be a very good solution to reduce latency between communications and increase network performance.

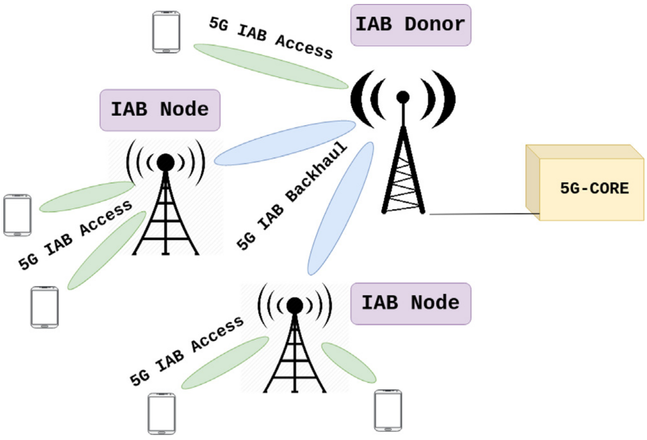

Fig. 1. IAB network Topology.

In [19], an interesting work is proposed where IAB network and Reconfigurable Intelligent Surface (RIS) technologies are brought together to study the advantages that can be achieved. They present a resource management framework that seeks energy efficiency by considering RIS parameters, system bandwidth and transmission powers. To this end, they present a RIS-assisted IAB network and a UAV acting as an IAB node with the objective of improving the overall energy efficiency of the network in the wireless access and backhaul parts. To address this problem, a distributed optimization process based on Stackelberg games is proposed, according to which the network resources are allocated in different stages.

To conclude, many studies have been carried out to corroborate the performance of IAB networks and their benefits. They all come to the same conclusion that the distance of coverage is increased and thus makes it possible for more users to have access to the network without increasing the costs due to the installation of fibre optics. However, all the studies mentioned above perform simulations with programs such as NS-3 or MATLAB to reach these conclusions. Others perform analytical studies. This paper differs from them because it is a field study combining Wi-Fi mesh and 5G technologies. In addition, to corroborate the performance and emulation of these networks, a real use case is presented where a streaming video transmission network is deployed. With the latter, it is possible to give access to a Wi-Fi network to several users using the resources of the 5G network for a single user.

3. Wi-Fi mesh and IAB networks comparison

As seen in the previous section, most of the research works focus on the study of simulated IAB networks in order to achieve a large coverage area. Pursuing the same objective in indoors, our approach is to use a Wi-Fi mesh network instead of an IAB network. In this section, a comparison between a Wi-Fi mesh network and an IAB network is made and it is explained why the first one has been selected to accomplish the objectives of this research work.

3.1. IAB architecture

Fig. 1 describes what an IAB network looks like. This IAB architecture has been developed to replace a high fraction of the optical fibre that connects the antennas to the core in 5G networks. With this topology, the number of antennas wired to the core is reduced. Consequently, the deployment costs are reduced.

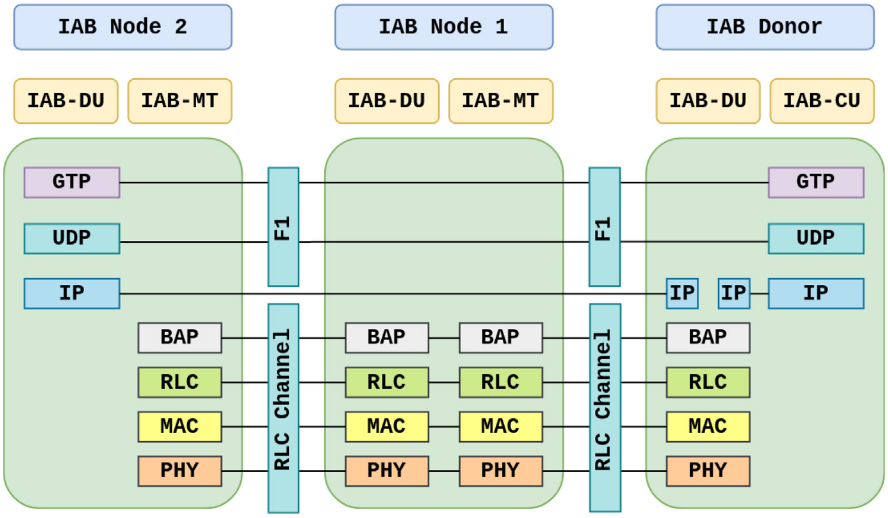

Fig. 2. Protocol stack of an IAB network.

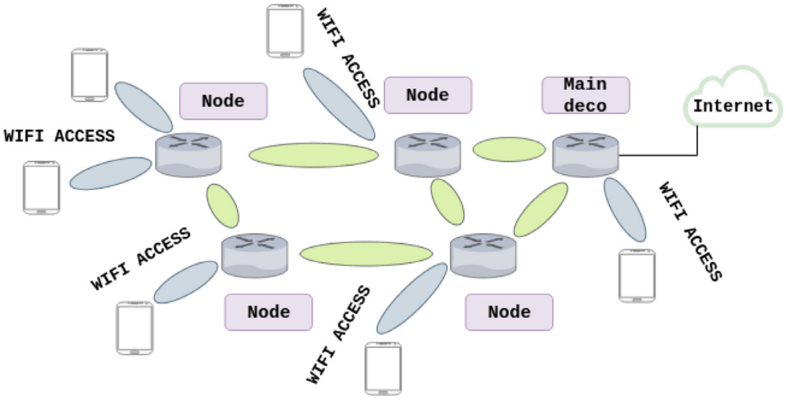

Fig. 3. Wi-Fi mesh network topology.

In an IAB network, there are 2 types of antennas. The first type is the donor antenna (IAB donor). This antenna is wired to the core of the 5G network. This antenna has two types of communications, the first one is with the UEs. This communication is done through a 5G radio access network. The UEs connect to the network as a usual 5G network. The other type of communication is with the second type of antenna, called IAB nodes. The two antennas communicate with each other using the Backhaul Adaptation Protocol (BAP). This protocol is specified by 3GPP in [20]. With this protocol, network traffic is transmitted between the existing hop destinations in the network. This protocol is above the RLC (Radio Link Control) layer. Due to this backhaul adaptation protocol, the IAB donor is able to give support to the other antennas.

With this configuration, a greater distance can be reached by having less antennas (IAB donors) connected to the core network. Therefore, an IAB mesh network is created between the different antennas so that a greater number of users can connect to the network.

The protocol used to carry out this information exchange is described visually in Fig. 2.

The figure shows the communication that exists in a multi-hop IAB node. The IAB donor is composed by two different components. The first one is the IAB-CU which refers to the Centralized Unit of a gNB. This segment is connected to the core of the 5G network and the IAB distributed unit (IAB-DU). To the last one is connected via the F1 interface [21]. The IAB-CU functionalities are the same as the gNB-CU but adding some more to support the IAB network communications between antennas as defined in the technical specification 38.401. The IAB node is divided into two parts: a mobile termination (MT) and a Distributed Unit (DU). The mobile termination is used to communicate the IAB node with the DU part of the other antennas, either the donor antenna or another node antenna. The DU part of the IAB node is responsible for providing service to user devices or communicating with the MT of another IAB node. The MT part of the nodes behaves as if they have been mobile devices for other IAB nodes.

3.2. *Wi-Fi mesh architecture*

Wi-Fi mesh networks are based on specific standards to enable integration and operation of nodes. The primary standard is IEEE 802.11s [22]. IEEE 802.11s defines the protocols needed for creating self-organization mesh networks within the Wi-Fi ecosystem. To ensure efficient routing, IEEE 802.11s incorporates the Hybrid Wireless Mesh Protocol (HWMP). This protocol enables dynamic routing decisions based on the optimal paths for forwarding the network traffic. The standard also defines how node discovery and synchronization between the nodes are managed. Furthermore, this standard works with other standards such as 802.11a/b/g/n/ac/ax to provide Wi-Fi service with higher or lower quality of service.

In a Wi-Fi mesh network, several access points create a Wi-Fi network to increase the coverage radius. Each access point is called a node and all are connected to, at least, another one. The objective of using this technology is to reduce the number of access points connected in a wired way and to reduce the cost of deployment. An example of a Wi-Fi mesh topology is shown in Fig. 3.

The different nodes in the network use a backhaul Wi-Fi network to communicate with each other. With this network, the traffic is

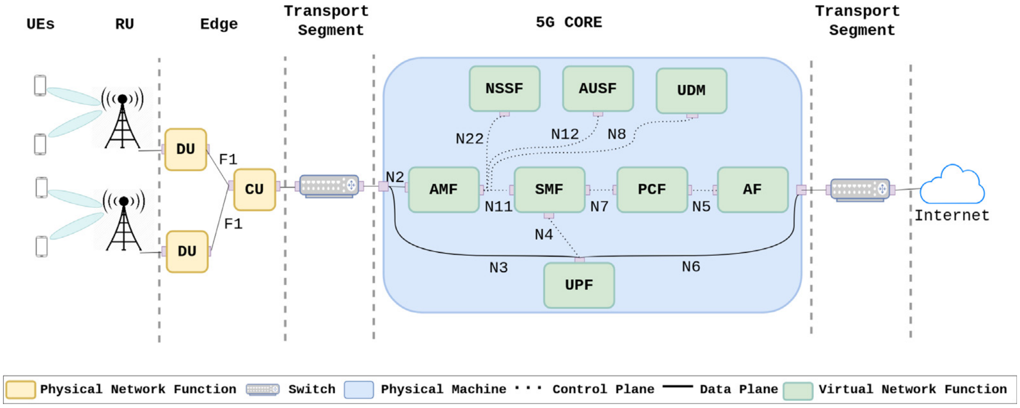

Fig. 4. 5G Architecture.

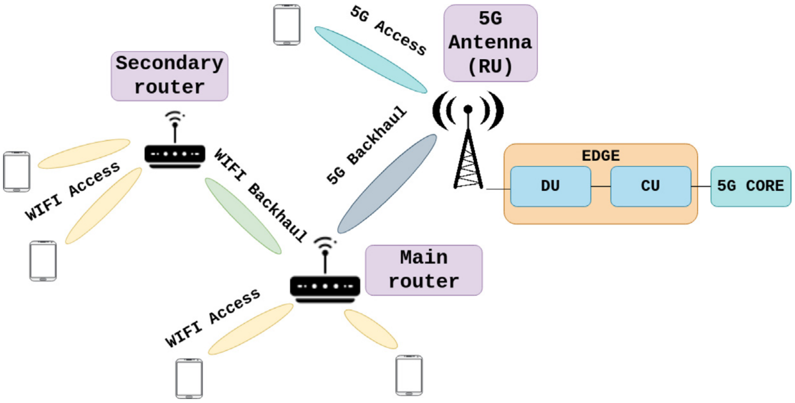

Fig. 5. Proposed integrated 5G and Wi-Fi mesh network architecture.

redirected until it reaches the final destination. An important feature of this network is that there is a default organization so that traffic is always redirected along the best path. This ensures a high quality of service for the user. As the network created between these nodes is the same Wi-Fi network, if a user have been to disconnect from one node, it would automatically reconnect to another one without losing the Wi-Fi connection.

Finally, this type of network allows great scalability since it would only be necessary to add more nodes to the network to be able to take the coverage to other places and to be able to give service to more users. Notice in Fig. 3 how there is a node labelled as “Main Deco” which is the one that is truly connected to the wired network.

3.3. *Wi-Fi mesh vs. IAB networks in indoors*

Looking at the two architectures, it can be said that both offer great advantages for expanding coverage and offering service to more users. However, for Industry 4.0 and 5.0 where the intention is to bring 5G technology indoors, choosing Wi-Fi mesh over an IAB network would make sense as the former operates in lower frequencies than the latter one and thus it makes a significant difference in industrial scenarios with high electromagnetic interference.

The cost of deployment is much lower if a Wi-Fi mesh network is chosen instead of an IAB network in indoors. This fact is because Wi-Fi mesh only needs routers that support this technology whereas IAB networks requires more specialized hardware such expensive antennas to transmit and receive signals in a specific bands. IAB networks utilize millimeter-wave wireless links for backhaul connectivity, so the need of these links is present. Other example of requirements is the power infrastructure needed to supply the hardware.

The ease of deployment is also greater. It would not be necessary to develop anything to make these networks work since having the routers, they configure themselves to create the network. However, an IAB network needs the maintenance of the BAP protocol and deeper knowledge.

Last but not least, one of the most important features for choosing Wi-Fi mesh network is the compatibility of the devices. There are many more devices equipped to work with Wi-Fi technology rather than devices with 5G chips. This also influences the costs of deploying them in industry.

4. Proposed architectures

This section provides information to explain the architecture that has been followed in order to amplify the network coverage. Two figures will be used to explain the architecture followed in order to achieve this. Fig. 4 depicts the 5G architecture. Fig. 5, additionally, shows the topology of a Wi-Fi mesh network used in this research work. Each part is explained in detail in the following subsections.

4.1. *5G architecture*

Fig. 4 shows all the necessary resources to be able to have a 5G network properly deployed, either in physical resources or virtual resources. For the description of this architecture, the rightmost components will be explained first and then move on to the left until the part where the user devices are located. The first thing to be found is the Internet part. The core is connected to this network via the UPF (User Plane Function) component. The core of the 5G network divides the data plane and the control plane. These two planes are differentiated by the functionality carried in them. In a nutshell, the

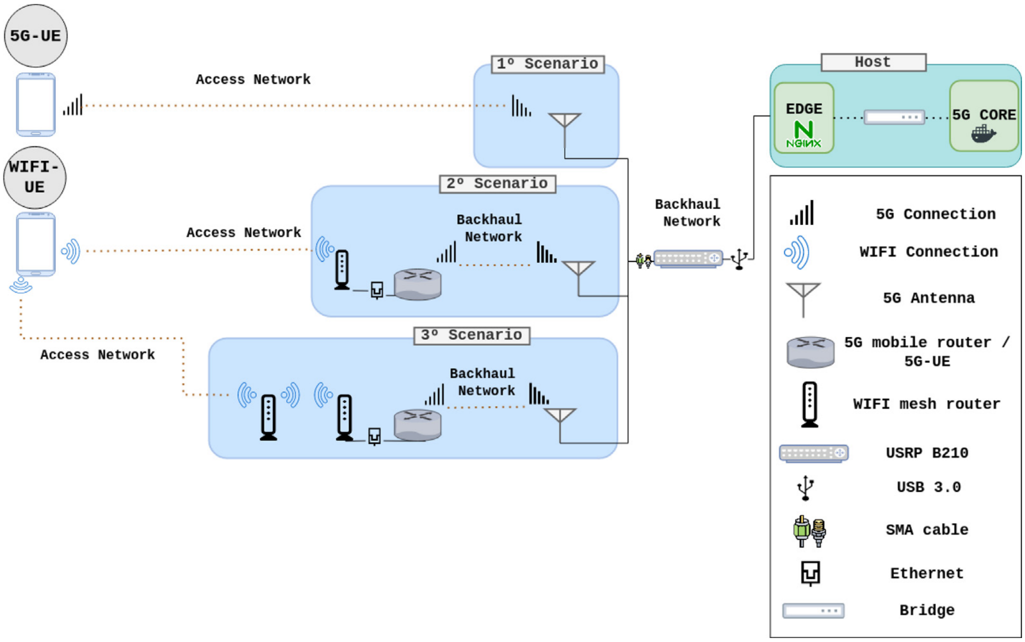

Fig. 6. The different scenarios that have been carried out to emulate an IAB network.

control plane is responsible for defining how the data packets will behave, how they will be transmitted and the authentication of the various devices that can connect to the network. In contrast, the data plane transmits these packets between the user and the Internet. The UPF is located in this plane. This component is responsible for routing and forwarding the packets. After authenticating themselves on the network, devices establish communication with this component to obtain internet connectivity.

On the other side, at the top of the figure, in the core, is the control plane. The components found in this plane are The Access and Mobility Management function (AMF) in charge of the management of the registers of the different devices, the connection with the device and its mobility. The Network Slice Selection Function (NSSF) is responsible for the selection of the slices to serve the devices. The Session Management Function (SMF) is responsible for managing device sessions. The Authentication Server Function (AUSF) is responsible for device authentication to maintain security in the 5G network. The Policy Control Function (PCF) component describes how the rules for enforcing control plane functions will be implemented. The Unified Data Management (UDM) is responsible for credentials for user authentication. And finally, there is the Application Function (AF) component responsible for providing information about the existing session [23]. All these components are described together with their functionalities in 3GPP.

The interfaces with which the core components communicate are also described in the figure.

The core of the 5G network is connected to the edge via the transport segment. The aim of this generation of telecommunication is to bring some functionalities closer to the user. This makes the network faster and therefore lower latency than previous generations. As a result, the edge part has been developed. The fifth generation of mobile communications is the first to present the edge as a part of the network. At the edge, there are two components: The Centralized Unit (CU) and the Distributed Unit (DU) [24]. For each Next-Generation Node B (gNB) there is a CU and one or more DU. These components are responsible for forwarding traffic and maintaining the connection between the antenna and the core. For each DU there is a radio unit (RU) in charge of creating wireless communication between the user equipment (UE) and the 5G network.

4.2. 5G network and Wi-Fi mesh integration

Increasing the coverage of such wireless communication is what this research work seeks. Therefore, to the architecture presented in Fig. 4, an additional sector with Wi-Fi connectivity is added. The new architecture is shown in Fig. 5. To the 5G antenna that is connected to the DU of the 5G network, a device is connected that serves as a gateway for the Wi-Fi technology. This bridge is a 5G router capable of creating a Wi-Fi network. To this device, both end-devices (e.g. mobile phones, IoT devices, laptops etc...) and other routers can be connected. In this way, a Wi-Fi mesh network is developed with the resources of a 5G network. The topology conceived has two Wi-Fi mesh routers, where one of them is connected to the 5G network acting as 5G-UE. The other router serves as another Wi-Fi access point to which devices can connect. Its main function is to make the network reach further.

As a result of this new topology, both technologies can be used by end users. This results in an increase in the number of end-users able to connect to the network. Without the Wi-Fi mesh network sector, only 5G devices could connect. With it, all devices capable of connecting to a Wi-Fi network are added.

5. Measurement setup

This section explains in detail the testbed used to conduct the experiments that have been carried out to demonstrate how unifying 5G and Wi-Fi mesh can lead to greater reach. It is divided into several subsections to a better description of the different parts of the testbed.

5.1. 5G network

Fig. 6 shows a visual depiction of the real scenario where the experiments have been carried out.

The OpenAirInterface [25] open-source software has been used for the deployment of the 5G network, having the software for the core and the radio access network. The core and the RAN have been deployed on the same host. This device is a Dell computer with an Intel Xeon(R) CPU E5-2630 v4 @2.20 GHz x 10 processors and 32 GB of RAM. The operating system running on this computer has been UBUNTU 20.04 with a 5.4.0-120-low-latency kernel.

The 5G core designed by OpenAirInterface has been designed following the definitions carried out by 3GPP definitions. It is composed of the different components that form the 5G core, called Network Functions (NFs). The separation between the control plane and the data plane also exists to provide access to greater scalability and independence between the different components. It matches exactly the architecture depicted in Fig. 4.

The OpenAirInterface 5G core supports 3 types of deployments. The first deployment uses virtual machines. For the second deployment, each NF is hosted in a Docker container and deployed with the Docker-Compose utility. Finally, in the third one, cloud deployment can be used making use of OpenShift or Kubernetes. For this work, the second deployment has been used where each component is a CNF (Cloud Native Function) deployed in a Docker container.

For the RAN, OpenAirInterface software currently allows users to deploy two types of 5G: 5G NSA and 5G SA. The main difference between these 2 types is the core behind the network. For 5G NSA, a 4G core is needed. On the other hand, for 5G SA, a 5G core is used.

For this work, a real 5G network has been needed in order to make it as similar as possible to a real scenario. This is why a 5G SA network has been chosen. This 5G RAN is a VNF that is deployed on a host and needs a core to connect to in order to provide services to a device.

There are two ways to deploy the RAN. The first way is to split it into 2 parts in order to have CU/DU functionalities and the second way is to deploy it in monolithic mode. With this last method, the 2 functionalities are united in 1. Selecting this way, it is not possible to have more than one DU connected on the same edge. In our case, the deployment has been done in monolithic mode.

For the radio unit (RU), a Universal Software Radio Peripheral (USRP) and an antenna operating on 5G frequencies is required. For the USRP it has been decided to use the USRP B210 from Ettus. It is a dual-channel transmitter operating on the frequencies 70 MHz and 6 GHz. It provides a real-time bandwidth of up to 56 MHz. It is designed to perform low-cost experiments and test different radio applications. The connection of this device to the computer hosting the RAN is made via USB 3.0 in order to serve high data rates.

The antenna used is a BLUESPOT mini antenna. A directional antenna capable of working in the frequency range of 3400–3800 MHz. The connection between the antenna and the USRP is made via SMA (SubMiniature version A) cables.

For the 5G signal, a configuration of 106 Physical Resource Blocks (PRB) has been used, giving a bandwidth of 40 MHz. Band 7 has been used, specifically the frequency 3650 MHz. This decision of using such band is because the antenna used to develop this work supports the frequency range of band 7.

5.2. Wi-Fi network

For the deployment of the Wi-Fi mesh network, a ZTE 5G CPE MC801 A router has been used. With this 5G mobile router, the 5G network can be converted into a Wi-Fi network. With this router, it is not possible to create a Wi-Fi mesh network. Then, what it has been done is to disable the Wi-Fi capabilities provided by such ZTE device and use instead a wired cable to connect it to a Wi-Fi mesh capable access point. This setup creates a logical component with 5G connectivity in one end and Wi-Fi mesh connectivity in the other end. Thus, two additional Wi-Fi mesh routers have been used. These are the TP-Link E4 routers. Based on the specifications of the manufacturer, the Wi-Fi standards supported by these models of devices deployed in the tests are the IEEE 802.11ac/n/a for the 5 GHz and the IEEE 802.11n/b/g for the 2.4 GHz band. This allows the development of a Wi-Fi 5 network with a maximum theoretical throughput of 1300 Mbps [26] . On the manufacturer's website it does say that these devices can reach peaks of 1167 Mbps, but in the 5 GHz band, the expected speed is 867 Mbps [27] . The maximum rate obtained in the 5G network of the testbed is 120 Mbps in downlink and 8 Mbps in uplink. The Wi-Fi technology is used to extend the resources of the 5G network. The results obtained on network speeds will be discussed later in the document.

TP-Link provides a mobile application to configure the Wi-Fi mesh network created with their routers. With this application, a user can see which devices are connected to which routers and therefore, be able to monitor and ensure that a device is connected to a particular router. This is important especially if experiments are wanted to be performed. In addition, it is possible to track the throughput of a device in real-time, block devices from connecting by specifying their MAC address, create slices, etcetera.

One problem encountered during the configuration of the Wi-Fi network has been that these devices do not allow modification of the Wi-Fi channel to which the devices are connected. Therefore, selecting channels based on the existing traffic has not been possible. However, the experiments have been carried out with the devices connected to the same channel. Even if it is not possible to choose the channel to which they are connected, it has been tried that, at least, they are on the same channel.

5.3. User equipment

Several UEs have been used to connect to the generated networks. A 5G mobile router and a ONE PLUS 8T mobile phone has been used as 5G user equipment. For the Wi-Fi devices, 2 mobile phones have been used: ONE PLUS 8T and POCO F3 and 2 laptops with WINDOWS 10 as the operating system.

5.4. Application use case

The proposed architecture explained in Figs. 4 and 5 could bring the 5G technology indoors in industries 4.0 and 5.0. For the experiments of this research work, a factory has been emulated. In such factory, the processes have to be monitored by cameras. The videos recorded by the cameras are published on a server located at the edge of the network. On the other hand, such videos are consumed in real-time by different devices around the factory for security purposes. The proposed application use case revolves around an indoor industrial environment where real-time video monitoring is essential for operational efficiency and safety. Monitoring processes, equipment or even personnel through a network of cameras during work can assure the working environment in case of unexpected events and ensure that action can be taken quickly. The aim is to leverage the benefits of integrating a 5G network and a Wi-Fi mesh network to enhance video transmission, real-time analytic, and decision-making within the industrial setting. For this purpose, the metrics selected for study are related to video streaming using the new hybrid network architecture created with 5G and Wi-Fi mesh. The video transmission quality is one of the Key Performance Indicators (KPI) chosen, studying the frame rate, resolution and latency. Another KPI is the network reliability. With this, the evaluation of the 5G and Wi-Fi mesh networks are studied measuring the packet loss, connection time, round-trip time and jitter. Finally the scalability is also considered by adding users to the network. The different scenarios are explained in the next subsection.

5.5. Video server deployment

The server deployed for the experiments consists of a docker deployed in the edge of the 5G network. This docker contains a service listening to petitions from users in different paths. Each path contains a video. To be able to play the video, the user introduces the IP address of the video server, the port at which the server is listening and the path that contains the video desired. After that, the video will start playing on the user device from the beginning. The type of video streaming app chosen for the experiments was video on demand (VoD) because it makes it easier to synchronize the users to play the videos and

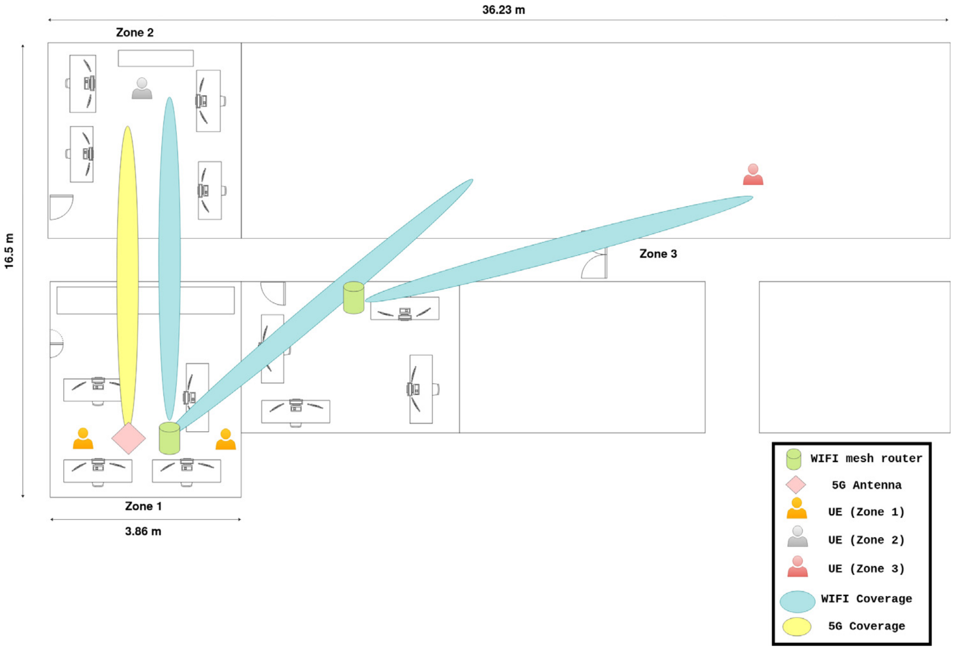

Fig. 7. Zones for the experiments.

thus makes the experiment last as long as possible for everyone. The protocol used for video transmission was Real Time Streaming Protocol (RTSP), using Transmission Control Protocol (TCP) as the transport protocol. The selection of this protocol was due to the fact that TCP dominates the Internet video streaming and brings facilities to calculate the concerned metrics such as latency, packet retransmissions and so on.

5.6. Integration and deployment scenarios for integrated access and backhaul networking

Fig. 6 shows the three scenarios that have been carried out to develop the experiments. There are several common elements in all 3 scenarios. The first one is the host where both the core and the RAN of the 5G network are deployed. The NGINX server is also located as a VNF in a docker outside the network core so it is at the network's edge. For experiments, everything has been installed in one place but the core and the edge of the network could be installed on different servers connected in some way. The host is connected via USB 3.0 to the USRP B210, which generates the signal and transmits it to the 5G antenna via SMA cables. On the other side, is the mobile device that will receive this signal and communicate with the service to play the video. In all 3 scenarios, we have these elements and the objective is the same. What changes in every one of them is the signal to which the mobile device is connected.

In scenario 1, the UE is a 5G-UE. This means it will connect to the 5G signal directly via the access network. This will emulate that the device is connected to the IAB Donor. Fig. 5 shows what this connection would look like in a simpler way. In scenario 2, the UE where the video is received will be a Wi-Fi-UE. The signal to which the UE will connect is the Wi-Fi network created by the 5G mobile router and the Wi-Fi mesh main router. In this scenario, the 5G-UE is the 5G mobile router. It contains a SIM to establish a wireless connection to the antenna. Once connected it deploys a Wi-Fi or LAN (Local Area Network). For these experiments, the desired network is the LAN network as we want to connect the Wi-Fi mesh router so that it can create a Wi-Fi mesh network. Therefore, this 5G mobile router and Wi-Fi mesh router connection will act as an IAB Node. The access network for this scenario will be Wi-Fi and the UE device will be connected to it in order to display the video.

In scenario 3, a second Wi-Fi mesh router is added to communicate with the main router via the Wi-Fi network. The Wi-Fi-UE will be connected to the second router. This is done to meet the objective of this work, which is that a longer coverage distance can be reached with the same resources as in scenario 1.

These three configurations present the different topologies that can be implemented in a Wi-Fi mesh network. The device is first connected to a 5G antenna, then the first Wi-Fi mesh router is added and finally, a second Wi-Fi mesh router is connected to the first one.

Fig. 6 also shows the legend detailing all the elements necessary to create these scenarios.

6. Experiments

This section explains the experiments carried out to test the network, check its operation and prove the assumptions made in Section 1. To run the experiments, a streaming video server has been deployed with the help of an NGINX server. This server has been deployed at the edge of the network. It had a video-on-demand which can be accessed by any user for real-time reproduction. Thanks to this video streaming, it has been possible to check the performance of the network and therefore, to corroborate if the assumptions of the paper are correct.

The experiments have been divided into three parts which will be detailed in more detail in the following subsections.

6.1. Study of the topology

The first experiment carried out consisted of finding out if the topology that has been developed, where both Wi-Fi and 5G technologies are combined, really increases the coverage distance. To do this, the final network (Wi-Fi-5G), represented by scenario 3 has been deployed with the 5G antenna, the 5G mobile router and the 2 Wi-Fi mesh routers.

Fig. 7 shows the real topology created with this architecture which represents the BEYOND 5G HUB premises at the University of the West of Scotland. Measurements of the offices, where the antennas and routers are located, have been done to be able to obtain accurate results. Three zones were used to perform the experiments. 5G antenna and the principal Wi-Fi mesh router are located in zone 1. Zone 2 is located at a distance of 16 m. Finally, zone 3 starts at a distance of 20 meters from zone 1. Between zone 1 and zone 3, a secondary Wi-Fi mesh router is located. This one is located at a distance of 13 meters from zone 1. The reason to have a second Wi-Fi mesh router is to create a second Wi-Fi point access. With this, users can have access being in zone 3. The distance of each zone have been selected based on the Wi-Fi mesh manufacturer guidance [27] . This is 2800 square feet which is 260 square meters. Therefore, the distances had to be within this imposed area. However, the distances selected for the experiments were chosen based on the performance of the devices connected to the network. Devices could be placed at longer distances than described but their connectivity was not optimal for use. Therefore, a balance was sought between connectivity and the distance suggested by the manufacturer. So, the distances have been selected to be similar for both technologies so that the experiments can be compared for fairness.

To make this selection, first, the throughput has been calculated using only the 5G network and moving the mobile away until it lost the signal and could not recover it. Once this has been done, the same UE has been connected to the Wi-Fi signal and the same test has been performed again. Finally, the tests have been carried out again but this time connecting the UE to the second Wi-Fi mesh router. By doing these tests, it has been possible to know the distance that can be reached using both technologies. Once the distance that the network can reach has been verified, video playback experiments have been possible to start in order to test the network.

For this experiment, it has been not only taken into account whether the device could connect to the network but also the RSRP parameter (Reference signal Received Power). This parameter indicates the quality with which the signal reaches its destination in a mobile LTE/5G communication. With the OpenAirInterface software, it is possible to take measurements of this value on the host where the RAN is hosted to know how the signal sent by the UE arrives. In the user's device it is also possible to know the quality of the signal by looking at this parameter, which is provided by the devices themselves. For a good signal quality, this parameter should have a value higher than −80 dB. A value lower than −100 dB indicates that the signal is not high-quality. This means that the communication will not be good and therefore the communication will not be optimal.

The experiments have been carried out by making the RSRP value less than −100 dB. For the 5G-UE experiments, it has been taken into account the value on the user's device and on the edge itself. On the other hand, when the device has been Wi-Fi-UE, this parameter does not appear in the device because the connection is via Wi-Fi. Nevertheless, it does appear in the 5G mobile router (5G-UE) and in the RAN. In the scenarios where Wi-Fi has been used, the RSRP value has been always maintained at values of approximately −75 dB as the router has been always at the same distance from the 5G antenna. Therefore, for these scenarios, only if there has been a connection between the Wi-Fi-UE and the Wi-Fi mesh routers has been taken into account.

The following 2 experiments has been carried out to test the performance of the network. This required the NGINX server to be deployed on the edge. They differ in the number of devices that have been connected to the server and requested to watch the video.

6.2. Experiments with one UE

In the first part, a single UE has been used as a video receiver. First, experiments have been carried out with the normal 5G network. The device, connected to the 5G network, has been connected to the NGINX server in order to receive the video. This procedure has been performed in both zone 1 and zone 2 of Fig. 7. It could not be performed in zone 3 as the 5G signal has been unable to reach it. During the video playback, the tshark tool has been running on the edge in order to capture the transmitted and received packets that go through the network.

Once the experiments with the 5G network have been completed, we proceeded to connect the 5G mobile router to the 5G network and the Wi-Fi mesh router to this router in order to create the Wi-Fi mesh network.

With the Wi-Fi mesh network up, the same UE has been used and the video has been replayed in zone 1, zone 2 and zone 3, collecting the packets at the edge as before. In zone 1 and zone 2, the UE has been connected to the main router located next to the 5G antenna in order to compare the results obtained in the 2 scenarios equally. In zone 3, the device has been connected to the secondary router.

6.3. Experiment with multiple UEs

The approach of these experiments has been as follows. First, only two UEs have been connected to the main router located in zone 1 of Fig. 7. These UEs have been also located in zone 1. The two UEs made the query to the NGINX server simultaneously so they received the video at the same time. After these tests, a third UE located in zone 2 has been added. Again, the request to the server has been made at the same time by all 3 UEs. All 3 have been connected to the main router. Finally, a third UE has been added in zone 3, which has been connected to the second router.

These experiments have been carried out in order to demonstrate that the network created can support more than one UE connected at the same time. It has been also wanted to prove that the video can be played smoothly on all 4 devices.

6.4. Metrics

The metrics that have been studied to analyse network behaviour are connection time, jitter, re-transmissions and round-trip time. These metrics have been chosen because of the use case being emulated. When a user wants to watch a video in real-time, the user usually looks at two characteristics. The first one is the time it takes to start watching the video. This feature is indicated by the connection time. As a second characteristic, the user expects the video to be displayed smoothly with no loss of information. This property can be studied with the jitter and the number of re-transmissions that occur during the broadcast, notice the directly relationship between re-transmissions and packet loss. Finally, the latency that exists during video transmission between the server and the client has also been studied.

6.4.1. Connection time

This metric is used to check how long the UE and the Edge took to make the 3-way handshake to start transmitting the video. This time is calculated as the time in which the "SYN" is transmitted and its "ACK" is transmitted. With this measurement, it is possible to estimate the latency of the network.

6.4.2. Jitter

It is a phenomenon that is defined as the variance between the delays experienced by different packets as they are transmitted. In video transmissions, this metric is highly relevant as it is related to the quality of the video received.

6.4.3. Retransmissions

By analysing the PCAP file generated with the video transmission from the edge to the UE and because TCP is used as the communication protocol, it is possible to analyse how many re-transmissions there have been during the process. This metric has been selected as it can be used to deduce the packets lost during the transmission.

6.4.4. Round-trip time

This parameter indicates the time it takes for a packet to go to a location and return. In this research work, this metric has been calculated as the time it takes to receive the ACK of a packet in the edge. With this data it is possible to know the delay of the packets to reach the client. Simply divide this parameter by 2.

Table 3
Video information.

Video codec	H.264
Width	1920
Height	1080
Display aspect radio	16:9
Pixel format	yuv420p
Duration	634.53 s
Bitrate	4 001 453 bits
Number of frames	38 072

Table 4
Throughput measurements.

	Technology	DL throughput (Mbps)	UL throughput (Mbps)
Zone 1	Wi-Fi mesh	120	8
	5G	120	8
Zone 2	Wi-Fi mesh	70	3.5
	5G	40	5.2
Zone 3	Wi-Fi mesh	40	2.5
	5G	–	–

6.5. Video application

The video “Big Buck Bunny” with h.264 encoding and a resolution of 1920 × 1080p has been used for the experiments. All the characteristics of the streamed video are shown in the Table 3. This information has been obtained with the ffmpeg tool.

7. Empirical results

This section will show the results obtained in the experiments explained in the previous section. For all the results shown, a total of 10 tests have been performed. Then, the average of these results has been obtained to show the trend of behaviour. It will be divided into 3 subsections: first, the coverage results are presented along with the throughput achieved by the different UEs. Then, the network performance results are exposed, which includes the results with one UE and with multiple UEs.

7.1. Coverage results

To show the results the help of Fig. 7 will be used. The figure shows the maximum distance at which the tests could be carried out without connection problems. The yellow colour represents the coverage distance achieved using the 5G antenna alone. The blue colour represents the coverage distance achieved using Wi-Fi mesh technology.

Table 4 shows the maximum speeds obtained in the different areas where the measurements have been taken.

Using the IPerf3 tool and a mobile device, measurements have been made in the different zones, increasing the distance. Table 5 shows the results obtained at the distance at which the highest speed was obtained. In zone 1, the results obtained using only 5G and the extension with Wi-Fi are similar because the users were at the same distance and had the same resources. The signal was not affected by external agents generating interference, so similar results were to be expected. The main difference found in the results has been in zone 3. In this zone, the UEs did not find the 5G signal and could not connect to it. The limit found using this technology, with the hardware specified in Section 5, has been about 17 m. Beyond this distance, the UEs used have been unable to locate the signal. In contrast, using Wi-Fi mesh technology, UEs have been able to connect even beyond 34 m. The limit has been found at approximately 40 m when the UE is connected to the secondary router. At this distance, the UEs have been able to see the Wi-Fi signal but the stability was poor.

Connected to the main router, the UE was able to reach up to 22 m with good network stability. See Table 4.

Table 5
Distance measurements.

Technology	Distance
5G	<17 m
Wi-Fi mesh (main router)	<24 m
Wi-Fi mesh (Two routers)	<40 m

In zone 2 the results obtained for both technologies differ in both downlink and uplink. In downlink, the Wi-Fi mesh network provides more rate while in uplink, the 5G network brings better results. this may occur due to congestion on the Wi-Fi uplink channel. It should be noted that with the Wi-Fi mesh devices used, it was not possible to select the optimal Wi-Fi channel. This selection is done automatically. Therefore, when performing the experiments, if there is a high congestion in the channel, the results will be affected.

With these results, Wi-Fi mesh technology achieves a 29% improvement in distance using a single router and a 100% improvement if a second router is added.

7.2. Results with one UE

7.2.1. Connection time

Fig. 8 shows the connection time obtained by placing the UE in the different areas studied and with the 2 different technologies. As mentioned before, The connection time has been determined by calculating the time taken by the UE to send the ACK of the SYN packet sent in the first instance.

The clearest difference is that, when Wi-Fi is used as the connection technology, the connection time increases compared to 5G. The reason for this is that, when the device is connected to the Wi-Fi mesh router, there is an additional hop between the UE and the edge. As a result of this hop, there is an added time which is the node processing time of the packets. The time it takes for the router to receive the packet, re-route and re-transmit it, causes an increase in the total time.

The results clearly show an increment of this measurement, to a lesser extent, as the UE move away from the edge. The best results are those where the 5G network is used directly, but it should not be forgotten that the aim of this work is to be able to have a greater coverage distance using 5G resources. Hence, although a shorter connection time is achieved by subtracting the hops added by the Wi-Fi mesh network, the coverage distance is shorter.

Finally, the connection time has a variance of 4 ms between a zone closer to the edge and the furthest one using the Wi-Fi mesh network. This reaffirms that the additional time compared to 5G is due to the added hops.

This metric has increased by 65% by adding Wi-Fi mesh to the 5G topology, in exchange for reaching further distances.

7.2.2. Jitter

Ideally, this metric should be zero. This would mean that the transmission time is always the same and does not vary. Therefore, the lower the value of this parameter, the better. A high value would indicate that the video is not being displayed smoothly because the packets take a long time to arrive. Fig. 9 shows the jitter value obtained in the different zones and with the different technologies. For video streaming, the jitter value for smooth video playback has to be less than 25 ms. In all the zones that have been studied for this work, the jitter value does not exceed 2 ms. Between adding Wi-Fi mesh to the infrastructure and not adding it there is only a 6% increase.

In zone 3, the results improve compared to zone 2, and this is due to the fact that there is a second router that helps the network to be more stable (see Fig. 9).

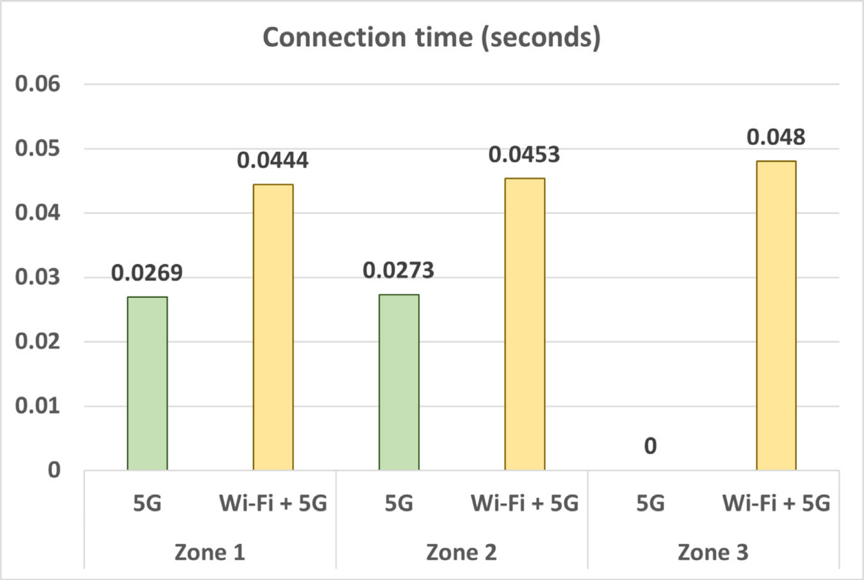

Fig. 8. Connection time for 1 UE (in seconds).

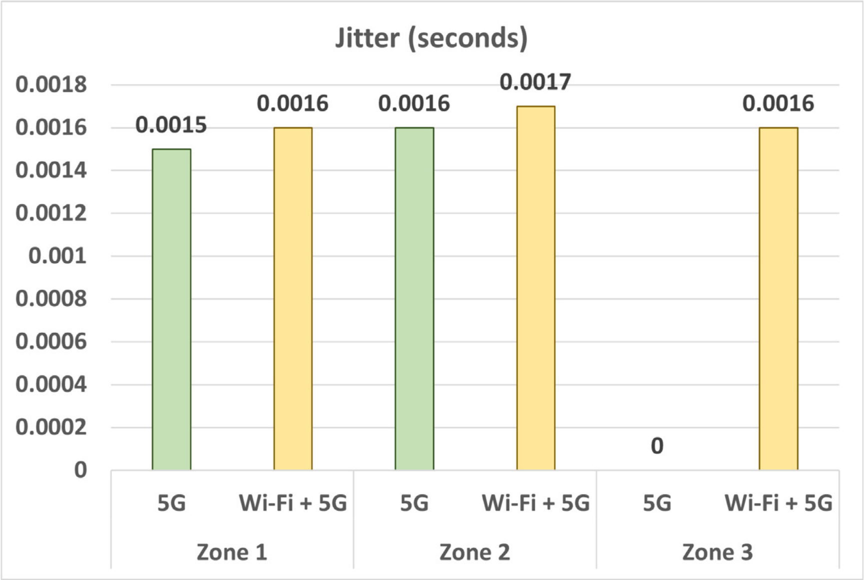

Fig. 9. Jitter for 1 UE (in seconds).

7.2.3. *Retransmissions*

The number of retransmissions calculated is relative to the number of total packets that have been transmitted. In all tests performed, the percentage of retransmissions obtained is less than 1%. Higher retransmissions have been obtained in zone 2, both in Wi-Fi mesh and 5G. This is due to the distance between the UE and the edge.

As mentioned above, with this metric, the amount of information that is lost during video transmission can be analysed. By using TCP as a transport protocol, there will be no lost packets because these lost packets can be retransmitted. Therefore, it is possible to know the amount of information that does not reach the receiver when it should. This phenomenon would lead to interruptions during video streaming. The results show that the video streaming has been done correctly so that the user does not notice if packets have been lost.

In the zone where there have been most retransmissions (zone 2), There has been an increase of 26% from 0.206% (total packets) to 0.2614% (total packets). Even so, this increase does not bring the total number of retransmissions to 1% of the packets sent (see Fig. 10).

7.2.4. *Round-trip time*

Fig. 11 shows the average time difference between sending a packet and receiving its ACK. The round-trip time resulting from the experiments with both technologies only differs by 6 ms. Using Wi-Fi mesh technology there is a difference of fewer than 4 ms between zone 1 and zone 3. In the scenario where only 5G technology is used, there is no data in zone 3 because the devices did not connect.

With this metric, there is an 18% increase in zone 1 and an 11% increase in zone 2 (see Fig. 11).

7.3. *Results with multiple UEs*

This subsection will show the results obtained by connecting several UEs to the Wi-Fi mesh network generated with the architecture proposed in this work. The parameters studied are the same as using a single UE.

The figures presented here showing the results obtained contain the results of the experiments with two, three and four UEs. In green are

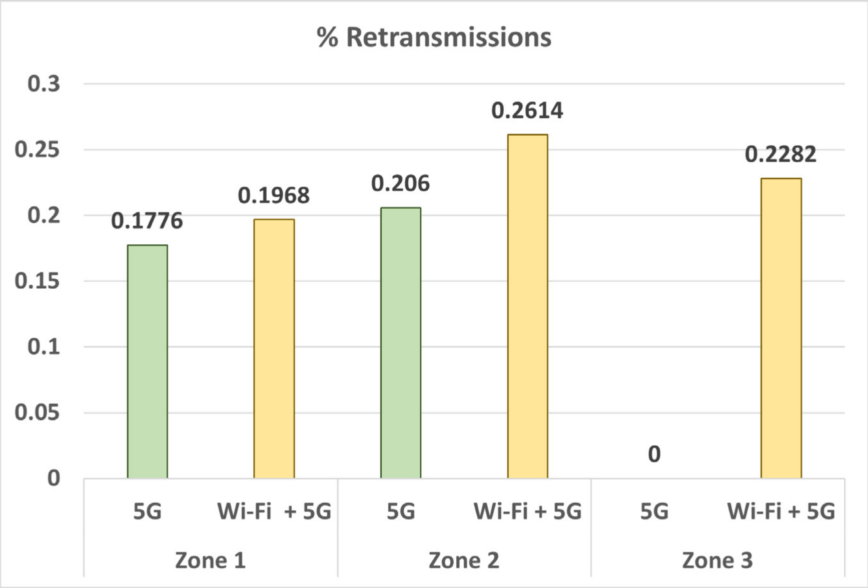

Fig. 10. Retransmissions for 1 UE.

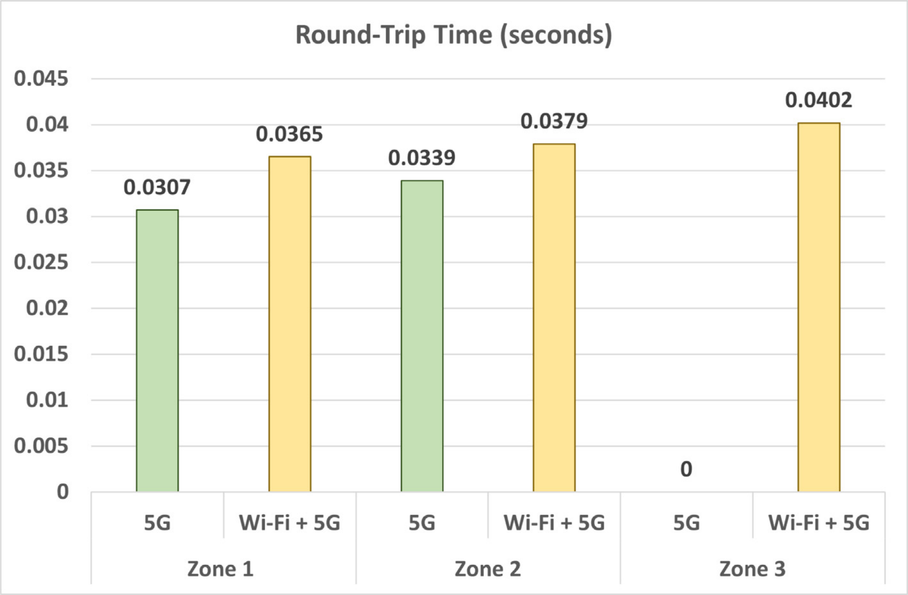

Fig. 11. Round-Trip time for 1 UE (in seconds).

the results obtained when only two UEs are connected, in yellow when there are three UEs and finally, in blue when there are four UEs in the network receiving the video. These UEs have been differentiated using the port with which the communication has been being established.

When conducting experiments with several devices, the bandwidth allocated to each device was controlled by the Wi-Fi mesh network itself. This allocation was made depending on the resources required by each UE.

Fig. 12 shows the results of the connection time for each UE in the different tests. The connection time obtained for each UE is practically the same. In the test where four UEs have been connected, there is a slight increase in this value because the traffic has been higher. But it is still within the margins presented in the results with only one UE. Therefore, increasing the number of UEs does not lead to a raise in connection time, so it can be proved that the network has been not congested. This indicates that the presented Wi-Fi mesh network can support more than 4 devices connected at the same time handling traffic.

Once the time taken by the devices to receive the video has been analysed, it will be shown how good the video looks with the jitter and retransmission parameters.

First, jitter is shown. Fig. 13 shows the jitter results for each UE in the 3 tests performed. The results show that the jitter obtained for the UEs is practically the same. Approximately, it has a value of 3 ms so that the packets arrive constant without being lost along the way. This is also demonstrated by the number of retransmissions. The video flow has therefore been good for all UEs, so that users can play the video without any video smoothness problems.

Finally, Fig. 14 shows the results obtained for the retransmissions. For all tests, the percentage of retransmitted packets is less than 1%. This indicates that the amount of lost packets is practically non-existent making the amount of information sent from the NGINX server almost completely received by the user devices.

At last, Fig. 15 shows the round-trip time obtained when performing the experiments with several UEs. Adding several devices to the network makes the RTT go up. But the results show that this parameter

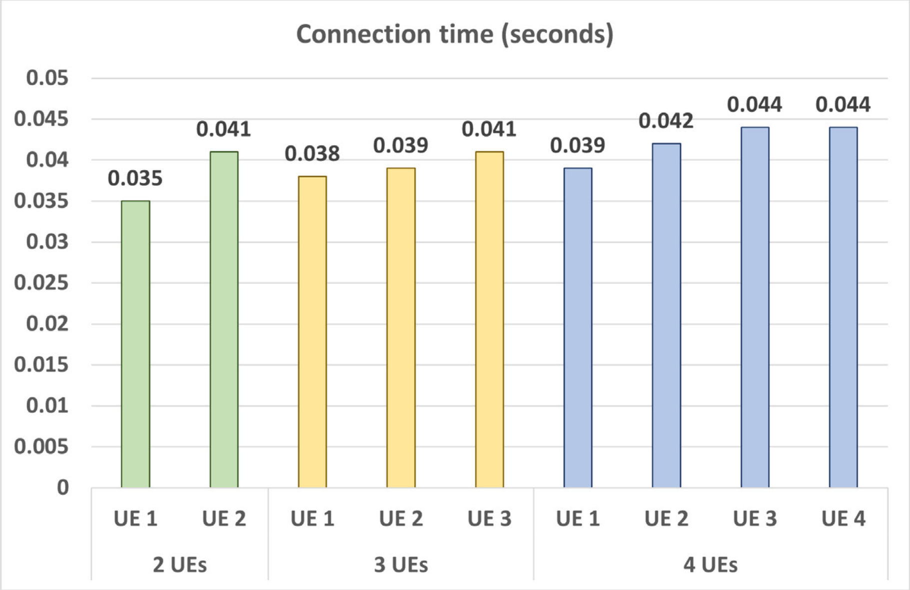

Fig. 12. Connection time for different number of UEs (in seconds).

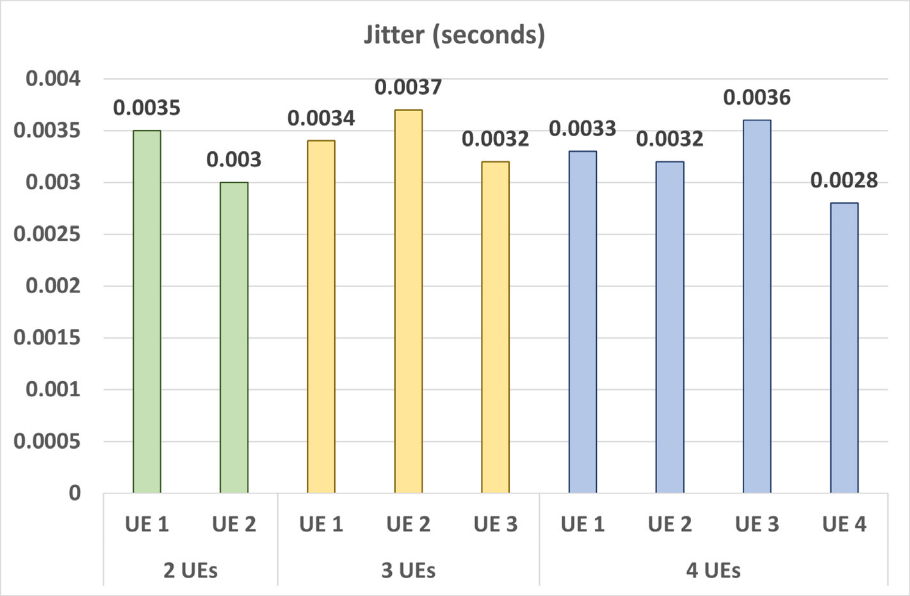

Fig. 13. Jitter for different number of UEs (in seconds).

varies around 50 ms. This, as mentioned before, results in a video transmission delay of about 25 ms on average in the different scenarios to get from the server to the end user.

8. Conclusions

This paper presents a solution to increase the coverage distance of 5G technology in industrial environments. It combines 5G and Wi-Fi mesh technologies. For this reason, a real 5G infrastructure deployed with OpenAirInterface software has been used together with a 5G mobile router and Wi-Fi mesh routers to develop a Wi-Fi mesh network. Once this new network topology has been obtained, several field experiments have been carried out to test the operation of the network and to check if the 5G network resources can really be taken further wirelessly without having to deploy several cores. The experiments have been based on a real-world use case emulating a video streaming platform where the NGINX video server has been deployed at the edge of the network. Users, connected to this network, communicated with this server and requested to play the video on their devices. The results showed how the video could be played in more distant areas than when using the 5G network alone. In particular, the results show that users can be placed at a 100% greater distance using this new topology. Also, results have been presented showing that the Wi-Fi mesh network created is not impaired at any time. The total retransmissions and jitter have been not affected, making the video playback smooth. The increase in the percentage of retransmissions has been 26% in the worst case. Even with this increase, the total number of retransmissions is not even close to 1% of the total number of packages. So the user still did not lose any information when watching the video. Regarding jitter, the results were increased by 6%. But as in the previous case, the video still plays perfectly. The connection time has increased in this network due to the number of hops added to move from 5G to Wi-Fi. There was a 65% increase. Finally, the use of Wi-Fi mesh technology causes an increase in packet transmission delay but does not affect the service. A

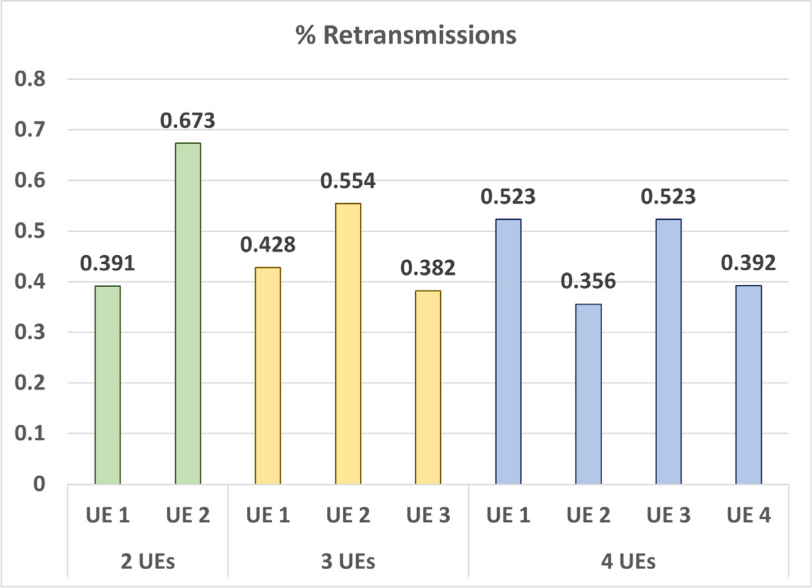

Fig. 14. Retransmissions for different number of UEs.

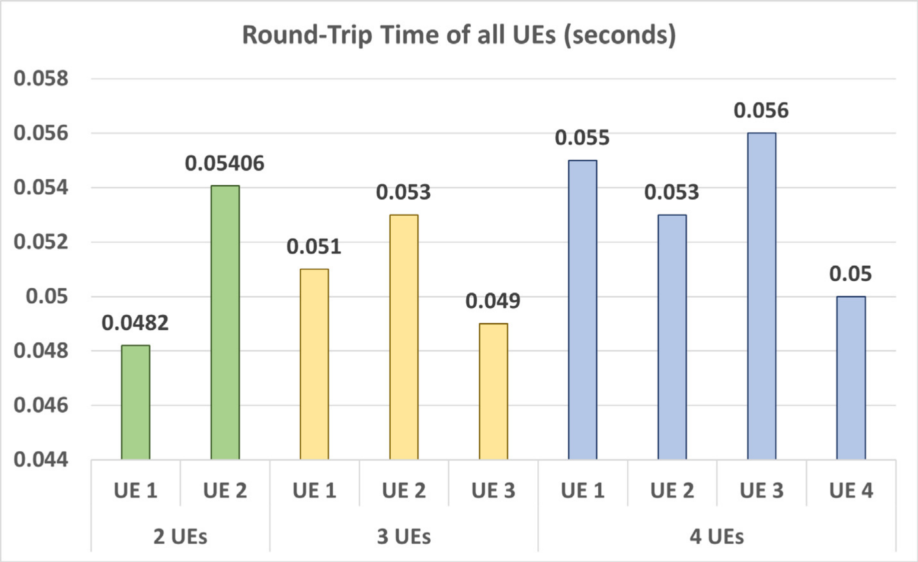

Fig. 15. Round-Trip time for different number of UEs (in seconds).

total of 18% at worst and 11% at best. But in return, more distance is achieved. Future work will explore and evaluate ways to optimize this network and improve the obtained results.

CRediT authorship contribution statement

Mohamed Khadmaoui-Bichouna: Conceptualization, Methodology, Investigation, Software, Validation, Writing. **Jose M. Alcaraz-Calero:** Conceptualization, Review & editing, Supervision. **Qi Wang:** Conceptualization, Review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Mohamed Khadmaoui-Bichouna reports financial support was provided by EU Framework Programme for Research and Innovation ICT Leadership in Enabling and Industrial Technologies.

Data availability

The data that has been used is confidential

Acknowledgment

This work is funded partly by the European Commission Horizon 2020 under the project: 6G BRAINS: Bringing Reinforcement learning Into Radio Light Network for Massive Connections [grant number H2020-ICT-2020-2/101017226]. The authors would like to thank all the partners in this project for their support.

References

[1] M. Attaran, The impact of 5G on the evolution of intelligent automation and industry digitization, J. Ambient Intell. Humaniz. Comput. (2021) http://dx.doi.org/10.1007/s12652-020-02521-x.

[2] S. Barakovic, J. Barakovic Husic, E. Cero Dinarević, IoT's tiny steps towards 5G: Telco's perspective, Symmetry 9 (2017) http://dx.doi.org/10.3390/sym9100213.

[3] M. Khadmaoui-Bichouna, G. Golcarenarenji, I. Martinez-Alpiste, J.M.A. Calero, Edge computational offloading for corrosion inspection in industry 4.0, IEEE Internet Things Mag. 5 (4) (2022) 116–120, http://dx.doi.org/10.1109/IOTM.001.2200203.

[4] I. Martinez-Alpiste, G. Golcarenarenji, Q. Wang, J.M. Alcaraz-Calero, Smartphone-based real-time object recognition architecture for portable and constrained systems, J. Real-Time Image Process. (2021).

[5] R. Triggs, What is 5G, and what can we expect from it? 2022, URL https://www.androidauthority.com/what-is-5g-explained-944868/.

[6] C. Madapatha, B. Makki, C. Fang, O. Teyeb, E. Dahlman, M.-S. Alouini, T. Svensson, On integrated access and backhaul networks: Current status and potentials, IEEE Open J. Commun. Soc. 1 (2020) 1374–1389, http://dx.doi.org/10.1109/OJCOMS.2020.3022529.

[7] 3GPP, Evolved Universal Terrestrial Radio Access (E-UTRA); Relay Architectures for E-UTRA (LTE-Advanced), Technical Specification (TS) 36.806, 3rd Generation Partnership Project (3GPP), 2015.

[8] A. Ghosh, A. Maeder, M. Baker, D. Chandramouli, 5G evolution: A view on 5G cellular technology beyond 3GPP release 15, IEEE Access 7 (2019) 127639–127651, http://dx.doi.org/10.1109/ACCESS.2019.2939938.

[9] M.N. Islam, N. Abedini, G. Hampel, S. Subramanian, J. Li, Investigation of performance in integrated access and backhaul networks, in: IEEE INFOCOM 2018 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS), 2018, pp. 597–602, http://dx.doi.org/10.1109/INFCOMW.2018.8406872.

[10] M. Jaber, F.J. Lopez-Martinez, M.A. Imran, A. Sutton, A. Tukmanov, R. Tafazolli, Wireless backhaul: Performance modeling and impact on user association for 5G, IEEE Trans. Wireless Commun. 17 (5) (2018) 3095–3110, http://dx.doi.org/10.1109/TWC.2018.2806456.

[11] C. Saha, M. Afshang, H.S. Dhillon, Bandwidth partitioning and downlink analysis in millimeter wave integrated access and backhaul for 5G, IEEE Trans. Wireless Commun. 17 (12) (2018) 8195–8210, http://dx.doi.org/10.1109/TWC.2018.2874655.

[12] C. Saha, H.S. Dhillon, Millimeter wave integrated access and backhaul in 5G: Performance analysis and design insights, IEEE J. Sel. Areas Commun. 37 (12) (2019) 2669–2684, http://dx.doi.org/10.1109/JSAC.2019.2947997.

[13] P. Fabian, G.Z. Papadopoulos, P. Savelli, B. Cousin, Performance evaluation of integrated access and backhaul in 5G networks, in: 2021 IEEE Conference on Standards for Communications and Networking (CSCN), 2021, pp. 88–93, http://dx.doi.org/10.1109/CSCN53733.2021.9686110.

[14] M. Pagin, T. Zugno, M. Polese, M. Zorzi, Resource management for 5G NR integrated access and backhaul: A semi-centralized approach, IEEE Trans. Wireless Commun. 21 (2) (2022) 753–767, http://dx.doi.org/10.1109/TWC.2021.3098967.

[15] B.P.S. Sahoo, S. Swain, H.-Y. Wei, M. Sarkar, Medium access strategies for integrated access and backhaul at mmWaves unlicensed spectrum, in: 2021 Wireless Telecommunications Symposium (WTS), 2021, pp. 1–6, http://dx.doi.org/10.1109/WTS51064.2021.9433686.

[16] O.P. Adare, H. Babbili, C. Madapatha, B. Makki, T. Svensson, Uplink power control in integrated access and backhaul networks, in: 2021 IEEE International Symposium on Dynamic Spectrum Access Networks (DySPAN), 2021, pp. 163–168, http://dx.doi.org/10.1109/DySPAN53946.2021.9677384.

[17] M. Polese, M. Giordani, A. Roy, S. Goyal, D. Castor, M. Zorzi, End-to-end simulation of integrated access and backhaul at mmWaves, in: 2018 IEEE 23rd International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, CAMAD, 2018, pp. 1–7, http://dx.doi.org/10.1109/CAMAD.2018.8514996.

[18] 3GPP, NR; Integrated Access and Backhaul (IAB) Electromagnetic Compatibility (EMC), Technical Specification (TS) 38.175, 3rd Generation Partnership Project (3GPP), 2020.

[19] M. Diamanti, P. Charatsaris, E.E. Tsiropoulou, S. Papavassiliou, The prospect of reconfigurable intelligent surfaces in integrated access and backhaul networks, IEEE Trans. Green Commun. Netw. 6 (2) (2022) 859–872, http://dx.doi.org/10.1109/TGCN.2021.3126784.

[20] 3GPP, NR; Backhaul Adaptation Protocol (BAP) Specification, Technical Specification (TS) 38.340, 3rd Generation Partnership Project (3GPP), 2019.

[21] 3GPP, NG-RAN; Architecture Description, Technical Specification (TS) 38.401, 3rd Generation Partnership Project (3GPP), 2022.

[22] G.R. Hiertz, D. Denteneer, S. Max, R. Taori, J. Cardona, L. Berlemann, B. Walke, IEEE 802.11s: The WLAN mesh standard, IEEE Wirel. Commun. 17 (1) (2010) 104–111, http://dx.doi.org/10.1109/MWC.2010.5416357.

[23] J. Kim, D. Kim, S. Choi, 3GPP SA2 architecture and functions for 5G mobile communication system, ICT Express 3 (1) (2017) 1–8, http://dx.doi.org/10.1016/j.icte.2017.03.007, URL https://www.sciencedirect.com/science/article/pii/S240595951730019X.

[24] 3GPP, Study on Central Unit (CU) - Distributed Unit (DU) Lower Layer Split for NR, Technical Specification (TS) 38.816, 3rd Generation Partnership Project (3GPP), 2018.

[25] OPENAIRINTERFACE, OpenAirInterface 5G Radio Access Network Project. URL https://openairinterface.org/.

[26] What is 802.11ac? 2023, https://www.cisco.com/c/en/us/products/wireless/what-is-802-11ac.html, accessed: 2023-05-16.

[27] AC1200 whole home mesh Wi-Fi system, 2023, https://www.tp-link.com/uk/home-networking/deco/deco-e4/, accessed: 2023-05-16.