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On Exploiting User Equipment Relaying Capabilities in Beyond 5G Networks: Opportunities, Challenges and Roadmap

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Abstract—*Mobile Network Operators are facing significant expenditures in deploying 5G Radio Access Network (RAN) infrastructure to achieve the level of densification required for meeting the new services demands. This will be exacerbated in Beyond 5G scenarios, which envisage the operation in high frequency bands with poor propagation. Therefore, operators need to find new and cost-efficient ways of managing and deploying their infrastructure. In this context, sustained on the technological evolution of the User Equipment (UE) and on recent standardization initiatives, this paper proposes an upgraded Beyond 5G system based on augmenting the RAN through the exploitation of UE-to-network relaying capabilities for optimizing the coverage footprint and for bringing edge computing capabilities closer to the users. The paper presents the baseline enabling technologies for realizing this concept. discusses the key architectural requirements and challenges for each one and presents a possible implementation roadmap, supported by some evaluation results, which reflect that relaying can improve the throughput in a factor 6 and reduce outage probability in around 80%.*

Keywords - *RAN augmentation, UE-to-network relaying, Beyond 5G*

Introduction

In order to realize the promise of vastly increased data rates and ultra-reliable low latency, network densification has been identified as an integral part of 5G network deployment [1]. The relevance of network densification is exacerbated as high frequency bands, e.g. millimeter wave, with poorer propagation will become more integrated [2]. Signals at these frequencies exhibit reduced diffraction and more specular propagation than their microwave counterparts, and hence they are much more susceptible to blockages [3]. Consequently, massive capital expenditure for deploying 5G infrastructure will be required to meet the insatiable appetite for mobile connectivity that consumer demand dictates.

Assessing the capacity, coverage and cost of 5G infrastructure deployment strategies is a challenge for Mobile Network Operators (MNOs) [4]. Dwindling average revenues per user, market saturation and intensifying competition stretch MNOs finances, putting pressure on deciding suitable migration paths towards 5G and beyond. Despite the expectations around 5G to unlock new sources of revenue capitalizing on emerging vertical markets, MNOs need to find not only new revenue streams but also new creative ways of managing and deploying their infrastructure towards cost-effectiveness. In this respect, leveraging User Equipment (UE) for Radio Access Network (RAN) augmentation was proposed in [5]. The paper envisions the idea of UEs actively complementing the RAN infrastructure by offering relaying capabilities to other UEs. In this way, the RAN is empowered with additional flexibility, by e.g., enhancing the performance in mitigating objects' obstructions, augmenting capacity in high-density areas or providing coverage extension in outdoor/indoor areas.

The growing interest of relays in Beyond 5G is also backed by ongoing standardization. For instance, [6] focuses on vehicle-mounted relays and identifies potential architecture and 5G system level enhancements Similarly, [7] studies the extension of the 5G Integrated Access and Backhaul (IAB) relaying technology to incorporate relay mobility. In turn, [8] studied applicability use cases of UE-to-network relaying, leading to a specific connectivity model in [9].

More recently, relays have been proposed to bring the edge computing paradigm deeper into the RAN to offload part of bandwidth-hungry extended reality applications [10]. Similarly, recent industry views [11] acknowledge that 5G topology expansions are essential to reach new levels of performance and efficiency to fully deliver the original multi-scenario 5G vision and identify the relevance of device-to-device (D2D) communications in this topology expansion. This will further extend the connected intelligent edge that encompasses wireless connectivity, efficient computing and distributed Artificial Intelligence, enabling the connectivity of more devices closer to

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the end-users. This is expected to benefit many use cases, such as automotive communication, Internet of Things, public safety, etc.

Within this framework, the value proposition and novelty of this paper is to embrace Relay UEs (RUEs) in RAN augmentation, with particular emphasis in exploiting RUEs as a powerful tool for RAN optimization. Specifically, the contributions of the paper include:

- An analysis of the technologies to implement UE-to-network relaying and their architectural requirements.
- Discussion on the key challenges to materialize the smooth integration of RUEs as additional RAN elements.
- Elaboration of a possible implementation roadmap with the different stages to realize the RAN augmentation concept, sustained on some evaluations to assess potential achievable benefits.

The paper is structured as follows. First, the enabling technologies for relaying are analysed, discussing their architectural requirements and challenges. Then, the implementation roadmap is presented and finally concluding remarks and future work are summarized.

Enabling Technologies, Architectural Requirements and Challenges

This section elaborates on candidate technologies for realizing the RAN augmentation concept through UE-to-network relaying, detailing their architectural requirements and associated challenges. The general architecture of the proposed system encompasses the 5G core (5GC) network and the augmented RAN, which includes both the base stations, e.g. the gNodeBs (gNB) in the 5G system, and the RUEs that provide connectivity to other UEs referred to as Remote UEs. These components are represented as the big boxes in Figures 1 to 3. The management functionalities of the system reside at the service management and orchestration (SMO), which is typically hosted at central MNO's premises and encompasses functions such as fault, configuration or performance management of the network.

The SMO includes a RUE activation function that decides which RUEs to activate to achieve the best performance. This function is supported by a database with the candidate RUEs, which should be dynamically updated as UEs become available or unavailable to act as RUEs. A new management interface is required between the SMO and the RUEs, e.g. for enforcing RUE activation/deactivation decisions and for notifying the availability/unavailability of a UE for acting as RUE. A RUE activation algorithmic solution should consider aspects such as the performance experienced by the RUE, the UEs in the surroundings, etc.

Beyond providing wireless connectivity to Remote UEs, a further applicability is in multi-access edge computing (MEC), where computationally-intensive tasks of certain applications at the UEs (e.g. image rendering in extended reality) are offloaded to edge servers running close to the base stations. With the RAN augmentation, certain RUEs with powerful computing capabilities could be used for offloading some of these tasks, thus further extending the edge closer to the users. This is aligned with ongoing initiatives such as the ETSI MEC 036 study item "MEC in resource constrained terminals, fixed or mobile" and would be beneficial for reducing the load at the gNBs, because part of the UE traffic would be processed locally at the RUEs. To support this, a so-called local break-out is needed at the RUE to select the traffic to be processed locally.

The specificities of three candidate technologies for UE-to-network relaying are detailed in the following. They have been selected considering different wireless communication options between the RUE and the Remote UE based on current standards and plausible future evolutions. Then, they would be applicable for different types of RUEs, such as smartphones, drones (e.g. flying base stations), telematic control units embedded in vehicles, etc.

Hotspot UE

The most straightforward method for UE-to-network relaying is to make the UE share its cellular connection via Wi-Fi by becoming a hotspot. A mobile hotspot acts like a small portable router, using 802.11a/b/n/ac/ax protocols, so any Wi-Fi enabled device can connect to it. The performance of a mobile hotspot strongly depends on the physical environment of the devices and on the used protocol, but it usually reaches connection ranges lower than 30m.

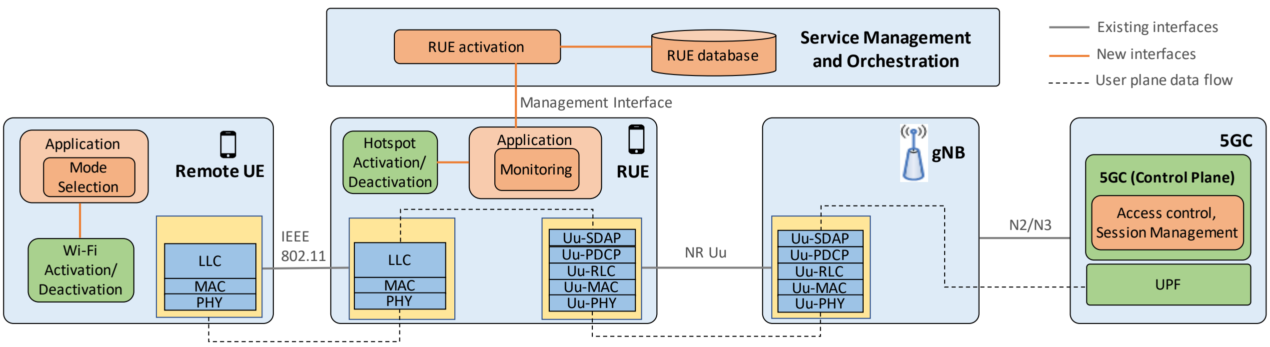

Figure 1 *Functional architecture for UE-to-network relaying based on Hotspot UE*

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Nowadays, hotspot UE capabilities are commonplace and enable useful use cases such as gaining Internet connection from a personal laptop through the user's personal handheld. However, the feasibility to exploit these capabilities to embrace an augmented RAN under the control of the MNO deserves careful consideration, as discussed in the following.

Figure 1 depicts the functional architecture for RAN augmentation using hotspot UE. Green boxes represent functionalities already standardized by 3GPP and/or included in UEs or network equipment, while orange boxes represent required functionalities not yet included in current systems or that need to be upgraded. A characteristic of the mobile hotspot capability in current smartphones is that it is activated manually by the user upon his/her own decision. However, for the purposes of an augmented RAN, an automated activation/deactivation controlled by the network should be enabled. This can be achieved through a specific application (App) running at the UE having connectivity (e.g. IP) with the RUE activation function. For a UE intending to behave as RUE, the App would control the mobile hotspot functionality and execute the decisions of the RUE activation function. The App should be installed by the UE owners upon reaching an agreement with the MNO. The agreement should specify, among others, the conditions for acting as RUE, e.g. minimum battery level, time of the day, etc. These conditions would be controlled by the monitoring function at the App.

For a UE intending to become a Remote UE, the App would activate the Wi-Fi connection to scan for nearby RUEs and would include a mode selection functionality for deciding whether to connect directly to the gNB or via a RUE. These decisions are implementation dependent and could be based on different criteria (e.g. activate Wi-Fi when the gNB signal level is below a threshold, choose the technology with highest signal level, prioritize cellular connection, etc.).

As seen in Figure 1, the user plane data flow between the two UEs uses the IEEE 802.11 protocol stack composed of Logical Link Control (LLC), Medium Access Control (MAC) and physical (PHY) layers. The transferred packets are delivered to the gNB through the 5G New Radio (NR) Uu interface that includes the Service Data Application Protocol (SDAP), Packet Data Convergence Protocol (PDCP), Radio Link Control (RLC), MAC and PHY layers. Finally, the gNB sends the packets to the User Plane Function (UPF) at the 5GC through the N3 interface.

As a difference from existing hotspot UE solutions in which Remote UEs are transparent to the network, an effective realization of the RAN augmentation would benefit from a better control of the Remote UEs, being registered and authenticated by the 5GC and including session management procedures. The implementation of these procedures would involve investigation of mechanisms such as encapsulating the Remote UE 5G signaling on top of the IEEE 802.11 stack or enabling the RUE to interwork with the 5GC on behalf of the Remote UE. Updates in the control plane network functions of the 5GC, e.g. Access and mobility Management Function, Authentication Server Function and Session Management Function, to handle Remote UEs connected through Wi-Fi mobile hotspots may also be needed.

A main challenge of this approach is that Wi-Fi technology does not allow guaranteeing strict Quality of Service (QoS) requirements, so this solution would not be suitable for services demanding strict delay bounds or bit rate guarantees. For this reason, the edge computing at the RUE would not be a priority with this approach, as it mainly targets low latency applications. Similarly, the encryption techniques used in Wi-Fi typically based on WPA-2, differ from those of 3GPP, which use other protocols, e.g. SNOW-3G, and involve different keys to be used at the radio interface and at the 5GC.

D2D

The support of D2D communications, in which two UEs in proximity directly communicate, was initially introduced by 3GPP under the Proximity-based Services targeting public safety-related use cases. A new PC5 interface between UEs was defined together with a radio link for direct transmissions denoted as sidelink. Later on, this concept was enhanced for a wider range of applications through the specifications for UE-to-network relaying support [9].

Figure 2 presents the RAN augmentation architecture when UE-to-network relaying is based on D2D. Both the Remote UE and the RUE should support PC5 interface, including discovery and PC5 link establishment. Two relay possibilities are defined in [9]. In the Layer-3 Relay, shown in Figure 2, the PC5 interface

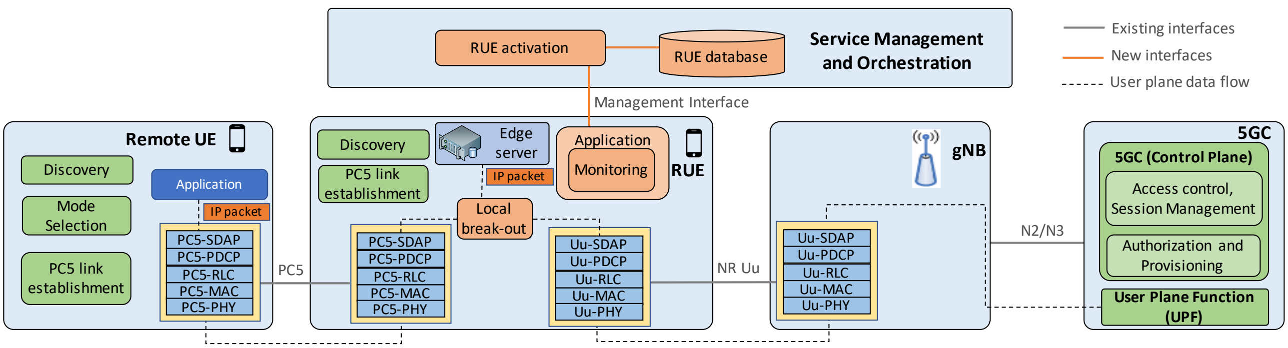

Figure 2 *Functional architecture for UE-to-network relaying based on D2D*

between the RUE and the Remote UE includes all the layers of the protocol stack. In contrast, in the Layer-2 Relay it only includes the RLC and below layers.

Like in the hotspot UE, the interworking between the RUE and the RUE activation function at the SMO can be performed through an App. When a RUE is to be activated in a gNB, the 5GC authorizes and provisions the UE to act as a Layer-2 or 3 relay. Moreover, the UE is informed about the discovery policy and parameters provided by the Policy Control Function of the 5GC. For Layer-3 relays, the RUE is also provided with the Protocol Data Unit session parameters for transferring the relayed traffic and with the mapping between the 5G QoS Indicator (5QI) and the PC5 5QI (PQI) [9].

Once a RUE has been authorized and provisioned, the discovery procedure allows that surrounding Remote UEs connect to it. Remote UEs also need to be authorized and provisioned by the 5GC to use relaying and get information about policies and parameters for RUE discovery and PC5 communication. Two discovery models exist, namely model A, where the RUE periodically announces itself with broadcast messages, and model B, where the Remote UE sends discovery solicitation messages to find surrounding RUEs.

The mode selection at the Remote UE decides the RUE to be connected to, or to connect directly to the gNB. The selection criterion is implementation dependent and can be supported by policies received during the provisioning and by PC5 link quality measurements taken from the discovery messages. After the selection, the RUE and the Remote UE conduct a secure PC5 link establishment procedure to allow the exchange of data between them. 3GPP TS 33.503 details the security and privacy protection mechanisms at the PC5 interface. Thus, 3GPP security will hold for the end-to-end communication path from the Remote UE to the 5GC and should mitigate the threat that e.g. a malicious RUE could intercept and modify the relayed packets.

The main challenge of the D2D for UE-to-network relaying is the limited number of commercial mobile terminals with sidelink support nowadays, although this is expected to change in the near future with the appearance of new use cases for sidelink [15]. Apart from this, the UE-to-network relaying uses already standardized functionalities, so the implementation would only require the RUE activation function at the SMO and the monitoring functions at the UEs.

Regarding the support of edge computing at the RUE, with Layer-3 relays the PC5 interface allows exchanging IP packets, so the local break-out could be implemented by filtering the IP packets that have to remain local and be processed at the RUE from those to be transferred to the gNB. The 5QI/PQIs of the sessions could be used for this filtering. Moreover, to properly handle the local traffic, e.g. for charging purposes, a lightweight UPF with minimum functionality would also be needed as part of this local break-out. Here, a challenge would be the encapsulation of the N4 signaling between the 5GC and this lightweight UPF through 5G NR. Although this involves further study and possible impact on standardization, the fact that the N4 protocol stack from 3GPP TS 29.244 builds on top of generic layer 1/2 protocols would facilitate this.

IAB

This approach considers UEs with IAB capabilities. IAB is a relaying technology in which an IAB-donor, which is a base station connected with the core network, provides a 5G NR wireless backhaul to the IAB-nodes, which are seen by the UEs as normal base stations [12]. An IAB-node contains a Mobile Terminal (MT) function to keep the wireless backhaul connection with the IAB-donor, and a Distributed Unit (DU) function to provide connection to the UEs. The DU connects to the Central Unit (CU) of the IAB-donor through the F1 interface and to the UEs through the Uu interface. While current IAB assumes fixed IAB-nodes, the incorporation of IAB capabilities into UEs needs further study and standardization. In this

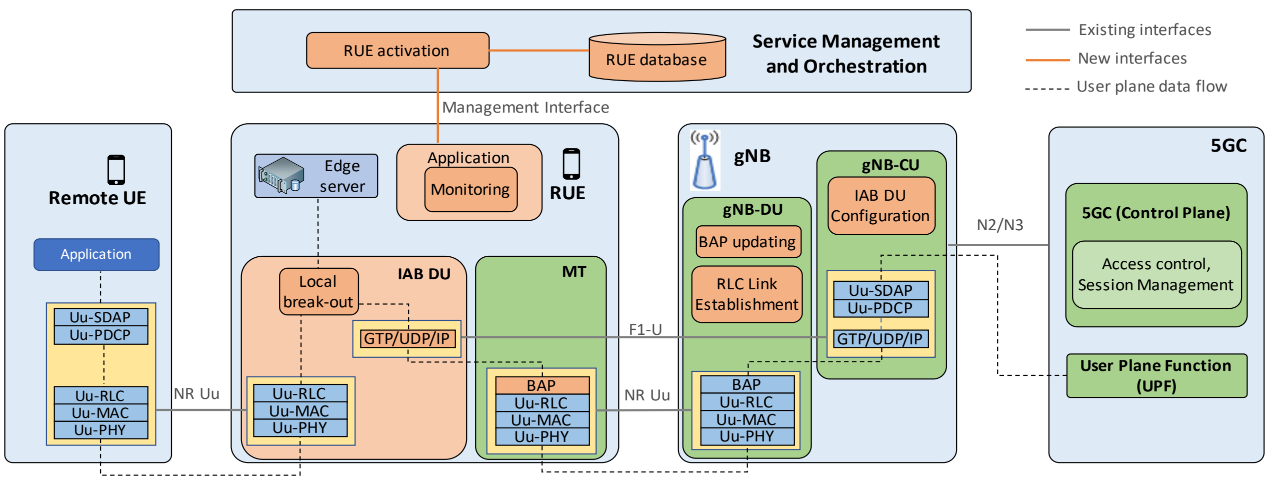

Figure 3 *Functional architecture for UE-to-network relaying based on IAB*

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direction, two related initiatives are the 3GPP work items on Mobile IAB [7] and vehicle-mounted relays [6].

The architecture is shown in Figure 3. It is based on the expanding to the UEs the IAB-node concept standardized in [13]. The IAB-capable RUE includes the MT function and the IAB-DU function with the radio interface protocol stack to provide connectivity with the Remote UE. The IAB-DU also supports the F1 interface (F1-U and F1-C for user and control plane, respectively) with the gNB-CU. Like in the hotspot UE and D2D cases, an App at the RUE would be required to interwork with the SMO.

The IAB-capable RUE should inform the network about its IAB capabilities during the initial access procedure with its serving gNB, which becomes the IAB-donor. It also needs to be authenticated by the 5GC. When activating an IAB-capable RUE, its IAB-donor establishes one or more backhaul RLC channels between the gNB-DU and the MT following the procedure in [13]. The backhaul data delivery on top of the RLC layer uses the Backhaul Adaptation Protocol (BAP). Then, during the RUE activation procedure the gNB-DU updates the BAP sublayer with the new IAB node and the IAB-DU establishes the F1 connection with the gNB-CU. Afterwards, the IAB-based RUE can start serving Remote UEs as a conventional gNB-DU.

As illustrated in Figure 3 the packets of the Remote UE travel across the NR Uu interface between the Remote UE and the IAB-DU and across the F1-U interface between the IAB-DU and the gNB-CU. The transmission of the F1-U interface is performed on top of the NR Uu interface between the MT and the gNB-DU using the BAP sublayer.

The main architectural challenge for implementing this option is the support of the IAB-DU function at the UE. In contrast, the Remote UE does not need to incorporate any new functionality because it would see the IAB-capable RUE just as another gNB-DU, so any 5G NR commercial terminal could be a Remote UE. Another challenge is the local break-out for incorporating edge computing capabilities at the RUE. Since the protocol stack at the IAB-DU only covers up to the RLC layer, it would be more difficult to extract the IP packets for local processing. A possible solution for this could be to include the Uu PDCP/SDAP layers in the local break-out component of Figure 3 for the RLC packets of edge computing traffic. This would indeed imply the incorporation of gNB-CU User Plane functionality and associated E1 Application Protocol support for this traffic. In addition, a lightweight UPF and N4 signalling support would also be needed as in the D2D case.

Technology comparison

Table 1 summarizes the architectural requirements and main challenges for implementing the RAN augmentation with each technology. First, the functionalities to be incorporated and/or upgraded in each network element, namely RUE, Remote UE, gNB, 5GC and SMO, are given based on the previous discussions. Apart from the application at the RUE and the RUE activation function, which are needed in all three cases, in general the use of IAB demands more changes at the RUE side but has less implications for Remote UEs and for the 5G network. In contrast, the hotspot UE approach requires less changes at the UE side but needs further control of the Remote UEs at the 5G network. The table also identifies the required interfaces at the RUE, highlighting those already standardized. In this respect, a management interface with the SMO is needed for the three technologies, while the radio communication between Remote UE, RUE and gNB can be supported with standard interfaces.

Concerning security and privacy, the availability of 3GPP-based end-to-end encryption mechanisms, particularly for D2D and IAB, should mitigate the risk of attacks in the form of eavesdropping or malicious RUEs (e.g. the RUE trying to intercept and/or modify the packets of the Remote UE), while spoofing attacks in which a non-authorized RUEs identifies as a valid RUE can be mitigated through adequate authentication. The table also lists some hurdles common to all technologies, such as the way to handle the dynamics of the RUE availability or the mobility of RUEs. Battery limitations at the RUEs are also relevant. To tackle them, the RUE activation strategy should consider the battery status when deciding the RUEs to activate, e.g. by prioritizing stationary UEs connected to sockets.

The requirements to bring edge computing capabilities at the relays are also shown. These are imposed by the edge computing support in the current 5G system architecture. Ongoing standardization efforts like the ETSI MEC 036 study item and research initiatives towards the definition of future 6G architectures can contribute to solving these challenges.

Finally, the table presents the scenarios of applicability for each technology, following the discussions in next section, and summarizes some quantitative performance improvements achieved through relaying and through the incorporation of edge computing at relays.

In addition to the technologies discussed here, which are based on decode-and-forward relaying, there are alternative physical layer technologies for enhancing coverage, such as the Reconfigurable Intelligent Surfaces, which are reflectors, or the Network-Controlled Repeaters (3GPP TR 38.867), which are amplify-and-forward relays. The different nature of such technologies would limit their offered capabilities (e.g. edge computing would not be feasible). Furthermore, these technologies would be deployed as fixed infrastructures, thus resembling more to fixed relays rather than to RUEs.

Implementation Roadmap

In views of the above architectural requirements and challenges, this section elaborates a possible implementation roadmap.

Assessment of potential benefits

As a preliminary step, the benefits brought by an augmented RAN need to be qualitatively and quantitatively assessed.

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Previous work [5] followed a simulation-based evaluation and assessed the gains in number of base stations that can be saved in an urban scenario thanks to the contribution of RUEs for a given performance level. The relevant savings found in [5] can be a motivating factor for an MNO to further evaluate the potential benefits of the proposed paradigm change. Thus, assessing the coverage footprint improvements in practical scenarios would provide additional insight. Particularly relevant scenarios would be those in which the RUEs are stationary or with limited mobility, e.g. in indoor scenarios with coverage limitations. The UE of a person at office or the UEs of professors/students in a classroom are examples of such stationary UEs that can be acting as RUEs if necessary to enhance the provided services (e.g. augmented reality used for educational purposes).

As an illustrative example, Figure 4 shows some evaluations and measurements carried out in the Campus of UPC in Barcelona. The considered environment is a 350 m × 125 m area with 24 buildings of 3 floors. 5G NR coverage is provided by three outdoor macrocells of a public MNO in band n78 (3.3-3.8 GHz). The lower part of Figure 4 plots some simulation results in the considered area. Simulations have computed first the coverage in terms of achieved spectral efficiency with the existing macrocells and second the coverage after activating a total of 100 stationary RUEs randomly distributed across the buildings. This number is inspired on some real measurements of the space/time user distributions in the campus and corresponds to ~10% of the users during the busy hour of a working day. Computations are done in pixels of 1m representing possible locations of UEs connected to RUEs or macrocells. The UMa propagation model of 3GPP TR 38.901 at 3.7 GHz is considered for the macrocell-(R)UE links including outdoor-to-outdoor and outdoor-to-indoor losses and 2D-spatially correlated shadowing. The channel bandwidth is 100

	Hotspot UE	D2D	IAB
RUE	App for mobile hotspot activation. Monitoring function	App for RUE activation. Support of sidelink/PC5. Monitoring function.	Support of IAB-DU, F1 interface and BAP. App for IAB-DU activation. Monitoring function.
Remote UE	App for Wi-Fi activation/mode selection. Monitoring function	Support of sidelink/PC5	N/A
gNB	N/A	Support of Sidelink Relay Adaptation Protocol (SRAP) for Layer 2 relay.	Support of IAB-DU configuration, BAP and RLC link establishment with a UE.
5GC	Access control, authentication, tracking and control of Remote UEs	RUE authorization and provisioning	N/A
SMO	RUE activation function and RUE database.		
Required interfaces at RUE	IEEE 802.11, NR Uu (already standardized) Management interface: IP connectivity between App and RUE activation function at SMO.	PC5, NR Uu (already standardized) Management interface: IP connectivity between App and RUE activation function at SMO.	NR Uu (already standardized) F1-U on top of NR Uu. Management interface: IP connectivity between App and RUE activation function at SMO.
Security/ Privacy	Different security mechanisms across Wi-Fi/3GPP.	3GPP-based security/privacy protection at radio/core.	3GPP-based security/privacy protection at radio/core.
	Prevention of spoofing, eavesdropping and malicious RUEs.		
Edge computing requirements	Edge computing support not envisaged	IP-based local break-out at RUE feasible with Layer-3 relay. Lightweight UPF functionalities at RUE. N4 signalling protocol exchange on top of 5G NR and security implications.	Local break-out at IAB-DU to extract IP packets. E1 Application Protocol support. Lightweight UPF functionalities at RUE. N4 signalling protocol exchange on top of 5G NR and security implications
Main hurdles	Limited QoS support	Low availability of sidelink in commercial UEs	Support of IAB at UEs
	Handling dynamics of RUE availability and RUE mobility. User incentivization. RUE battery limitations.		
Envisaged scenarios	Only for initial assessments in small scale pilots and trials.	Feasible for large scale deployments, mainly indoor with limited mobility.	Long term vision, possibility to support high mobility.
Performance improvements of relaying	Outage probability reduction of ~80% (see Fig. 4 and [5]). Average spectral efficiency improvements of ~40% for outdoor and ~200% for indoor [5]. Throughput improves approximately in a factor 6 (see Fig. 5). Reduction of ~75% in the number of required base stations to ensure a target outage probability by engaging 20% of stationary UEs to act as RUEs [5], leading to a more cost-efficient deployment		
Performance improvements of edge computing at relays	Not envisaged	Reduction in used bandwidth at the base station: ~40-50% with respect to not using relays and ~30% with respect to using relays without edge computing [10]. Capacity improvements: number of supported users multiplies by 2 [10]. Power consumption reductions up to ~30% [10].	

Table 1 *Requirements and challenges for each technology and expected performance improvements*

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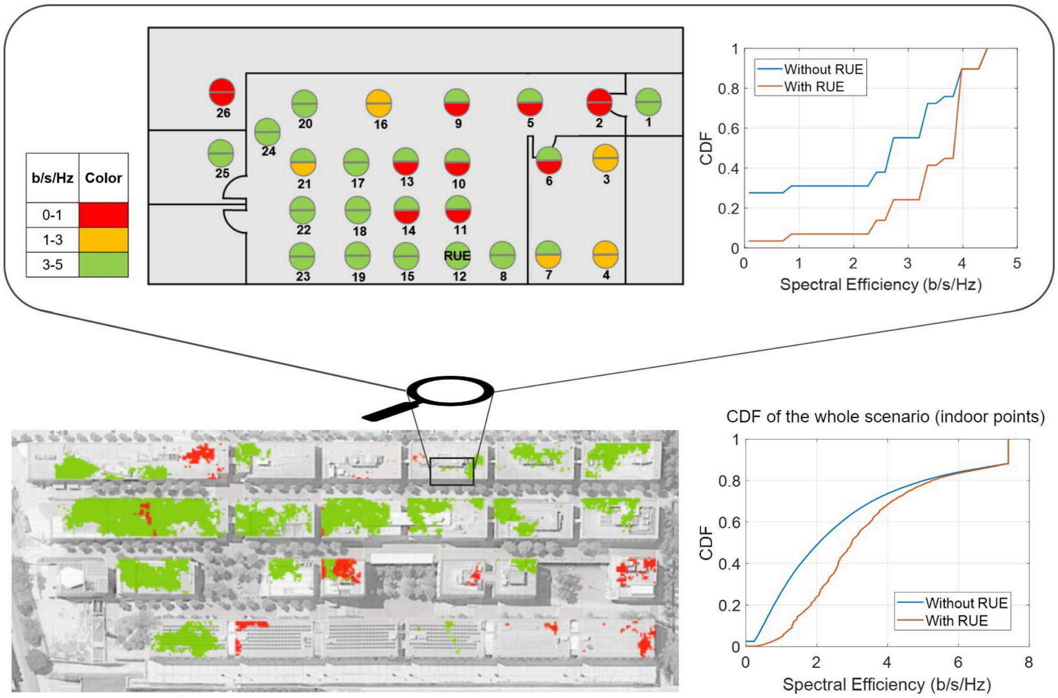

Figure 4 *Illustrative results of performance improvements achieved in a University Campus*

MHz and the equivalent isotropic radiated power (EIRP) is 48 dBm. For the RUE-UE links the same propagation model of [5] is used with EIRP=-10 dBm at 3.5 GHz.

The map plots in green the positions of the first floor of all the buildings that were in outage with the macrocells (i.e. spectral efficiency below 1 b/s/Hz) and that are no longer in outage after activating the RUEs. This result shows that the RUEs improve the outage in a large area, while only a few positions (plot in red) remain in outage. To quantify this improvement, Figure 4 also depicts the Cumulative Distribution Function (CDF) of the spectral efficiency in the indoor points of the scenario with and without RUEs, reflecting a substantial improvement, particularly in the low spectral efficiency ranges. For example, without RUEs 26% of the locations have spectral efficiency below 1 b/s/Hz, while this reduces down to 4.5% with RUEs (i.e. 82% reduction).

To complement these results, some experimental measurements have been performed in the first floor of an illustrative building. The floor's plant, with several classrooms, is shown in the upper part of Figure 4. First, QualiPoc monitoring software has been used to measure the spectral efficiency of a terminal when connected to the macrocells of the MNO at different positions. The upper part of Figure 4 plots each measured position as a circle and the color of the lower semicircle represents the spectral efficiency. With the actual 5G deployment, a total of 9 points (in red) are out of coverage. Then, following the proposed concept, an Amarisoft Callbox Classic transmitting at 3475.2 MHz with maximum power of -6 dBm has been used to emulate a RUE at position 12, where the cellular coverage was good enough (i.e. spectral efficiency of 3.9 b/s/Hz). The upper semicircle of each measured position shows the spectral efficiency when the UE connects to the RUE (i.e. the minimum between the spectral efficiency in the links UE-RUE and RUE-macrocell). Results reveal that the emulated RUE offers connectivity to most of the locations that were previously out of coverage, including position 6 at a different room. In statistical terms, the comparison of the CDFs of the measured spectral efficiency with and without RUE is also shown, reflecting a decrease in outage probability from 34.6% to 7.7%.

Development of user acceptance mechanisms

The RAN augmentation concept embraces a radical paradigm shift as the MNO involves its customers' UEs as part of the service provisioning chain. Therefore, the success of such value proposition strongly depends on users' acceptance and willingness to enable that their devices are managed by the MNO.

At this stage, MNO's marketing department should elaborate proper incentivizing mechanisms. Diverse ways of incentivizing users are described in [14]. Incentives can be monetary-based (e.g. RUEs get discounts or get paid with a virtual currency), reputation-based (e.g. reputation level of users improves when they help relaying data), social relationship-based (e.g. users are more willing to help other users with close social ties), bandwidth exchange-based (e.g. RUE obtains additional bandwidth from the network), or energy harvesting-

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based (e.g. RUE harvests energy from the base station transmissions). Moreover, users can also find the RAN augmentation concept appealing if being sensitive to common good principles (i.e., my UE can be helpful to others), so that promotion of values such as sustainability and solidarity can become an important tool to engage users. Anyway, the selection of one or another mechanism will depend on each user's interests and concerns, so it is likely that a user can choose his/her preference among different options provided by the MNO. Moreover, the conditions under which the users grant permission for their terminals to act as RUE (e.g., battery level above certain threshold, enable usage as RUE only during certain timeframes) should be carefully analyzed and clearly defined. Availability of efficient security and privacy mechanisms would be essential in order to avoid users' concerns in this respect.

Small-scale pilot

Once the MNO has a clear idea on how to present the service to its customers, an acceptance testing and a small-scale performance pilot could be conducted. Since the focus would be on exploring users' acceptance, trials should embrace the simplest possible technological choices. For example, the hotspot UE solution could suffice for testing purposes. Thus, MNOs should exploit incentivizing mechanisms to persuade users to install the App and understand that they can establish the conditions under which they grant permission for their terminals to act as RUEs. The main efforts at this stage would be in developing the App, while simple ad-hoc solutions could be implemented for the management functions at the SMO.

Recalling the results of Figure 4, a university campus could be a suitable scenario for the small-scale pilot, as students use to be early adopters. The MNO could get important feedback about users' experience to guide the development of the underlying business model for potential large-scale adoption. To illustrate the potential benefit perceived by the users, an experimental assessment of throughput improvements has been assessed in the Campus scenario and is presented in Figure 5. A RUE making use of Wi-Fi hotspot technology is located at position 12 of Figure 4. Figure 5 compares the CDF of the obtained throughput when a QualiPoc terminal performs different file uploads at different locations of the building connecting directly to the macrocell or connecting through the RUE. The average throughput increases from around 1.2 Mb/s to 7.1 Mb/s when using the RUE.

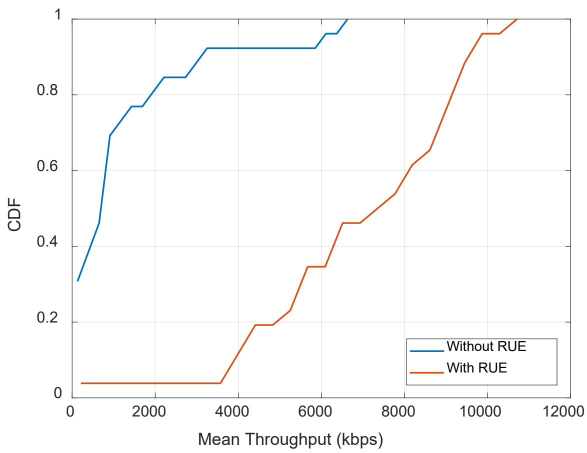

Figure 5 *Experimental uplink throughput improvements*

Preparation for service launch

If good user acceptance and promising coverage/capacity improvements are observed in the small-scale pilot, the maturing of the various technological building blocks should be triggered. On the one hand, this embraces the evolution towards higher performance and QoS-capable architectural solutions such as D2D. That is, wide adoption of D2D-capable UEs would be required, pulling the UEs manufacturers to introduce such capabilities into the market. On the other hand, the perspective of a future service launch would require the development and implementation of a solid SMO layer beyond the minimum capabilities required for the pilot. A key component would be the RUE database and associated procedures, to be designed in views of wide-scale deployment.

On the long run, consolidation of advances currently under standardization such as mobile IAB [7] or moving relays [6] would enable expansion from indoor coverage (likely the primary use case to be exploited) towards more challenging scenarios embracing mobility, which introduces additional challenges like the RUE-gNB link variations or the handovers of RUEs and Remote UEs. In this evolution, the coexistence of RUEs operating with IAB or with D2D could be possible depending on how these capabilities are progressively introduced in the market. Furthermore, future scenarios where the value chain is expanded and MNOs rely on third party solutions (e.g., provisioning rApps/xApps in O-RAN context) are envisaged, with potential Artificial Intelligence-based algorithms to efficiently tackle the service and network management.

Concluding remarks

Following recent standardization initiatives and the unprecedented technological evolution leading to User Equipment with powerful communication and computational capabilities, this paper has presented the RAN augmentation concept that exploits UE-to-network relaying to optimize the coverage footprints in a beyond 5G RAN. The architectural requirements of three enabling technologies, namely hotspot UE, D2D and IAB, have been analyzed and a possible implementation roadmap has been elaborated. This envisages a progressive introduction of these technologies as the RAN augmentation approach becomes more widely adopted. The discussion has been supported by both experimental and simulation-based results revealing that outage probability reductions of around 80% can be achieved. Future research directions include the development algorithmic solutions for detecting candidate RUEs, e.g. based on behavioral patterns, and incentivization strategies. Moreover, the design of complete and robust solutions involves addressing the identified challenges related with e.g. local break-out in edge computing, Wi-Fi/5G interworking or security.

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