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Generalized Coordinated Multipoint Framework for 5G and Beyond

MUHAMMAD SOHAIB J. SOLAIJA[1], (Student Member, IEEE), HANADI SALMAN[1], (Student Member, IEEE), ABUU B. KIHERO[1], MEHMET IZZET SAĞLAM[2], AND HÜSEYIN ARSLAN[1,3], (Fellow, IEEE)

[1]Department of Electrical and Electronics Engineering, Istanbul Medipol University, 34810 Istanbul, Turkey
[2]Department of Research and Development, Turkcell Teknoloji Arastirma ve Gelistirme Anonim Sirketi, 34854 Istanbul, Turkey
[3]Department of Electrical Engineering, University of South Florida, Tampa, FL 33620, USA

Corresponding author: Muhammad Sohaib J. Solaija (solaija@ieee.org)

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ABSTRACT The characteristic feature of 5G and beyond networks is the diversity of services, which is required to support different user needs. However, the requirements for these services are often competing in nature, which impresses the necessity of a coordinated and flexible network architecture. Although coordinated multipoint (CoMP) systems were primarily proposed to improve the cell edge performance in 4G, their collaborative nature can be leveraged to support the diverse requirements and enabling technologies of 5G and beyond networks. To this end, we propose the generalization of CoMP to a proactive and efficient resource management framework capable of supporting different user requirements such as reliability, latency, throughput, and security while considering network constraints. This article elaborates on the multiple aspects, inputs, and outputs of the generalized CoMP (GCoMP) framework. Apart from user requirements, the GCoMP decision mechanism also considers the CoMP scenario and network architecture to decide upon outputs such as CoMP scheme or appropriate coordinating clusters. To enable easier understanding of the concept, a case study illustrating the effect of different combinations of GCoMP framework's outputs on varying user requirements is presented.

INDEX TERMS 5G, 6G, backhaul, clustering, coordinated multipoint (CoMP), energy efficiency, flexibility, generalized CoMP (GCoMP), multi-TRP MIMO, quality of service (QoS), radio resource management (RRM).

I. INTRODUCTION

A. MOTIVATION AND BACKGROUND

The fifth generation (5G) signaled a paradigm shift in wireless communication networks. Rather than focusing on increasing the data rates, it emphasized diversifying the supported applications and use cases. While 5G catered to the enhancement of data rates under the enhanced mobile broadband (eMBB) service, it also expanded its vision to incorporate the increasing number of wireless devices and stringent reliability and latency requirements under the massive machine type communication (mMTC) and ultra-reliable low latency communication (uRLLC) services, respectively [1]. This diversity of applications is expected to increase even further in sixth generation (6G), with more stringent requirements of throughput, latency, reliability, energy and spectral efficiency, security, and so on [2].

This diversity is evident not only in the applications and services, but also in the enabling technologies for future wireless networks. For instance, 5G tried to address the different requirements by introducing the concept of numerologies [3], [4]; the lack of available spectrum has led to research regarding spectrum sharing and utilization of higher frequency bands such as millimeter wave (mmWave) [5], visible light communication (VLC) [6] and terahertz (THz) communication [7]; furthermore, the diversity of network infrastructure itself is expected to increase with the incorporation of non-terrestrial networks [8] and reconfigurable intelligent surface (RIS)-aided smart radio environments [9]. However, a major challenge is the lack of cohesion in the development of these approaches. To achieve the envisaged goals of the human-centric future communication systems,

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TABLE 1. Summary of CoMP state-of-the-art categorized according to different 5G and beyond network requirements (CB = Coordinated Beamforming, CS = Coordinated Scheduling, DPS = Dynamic Point Selection, JD = Joint Detection, JP = Joint Processing, JT = Joint Transmission).

Requirement	Contribution/Goal	CoMP Scheme
Throughput/ Data Rates	Conduction of field trials to validate performance of CoMP.	JD [12], [13], CS, JT [12]
	Scheduling and frequency reuse schemes are extended to CoMP environment.	CS [14], JT [15]
	Comparison of different coordination schemes amongst themselves and with non-CoMP transmission.	CS [16], CB [16], [17], JT [16]–[18]
	CoMP performance in HetNets is discussed [19]–[21] and stochastic geometry-based analysis is carried out [22].	JP [19], CB [20] JT [21], [22]
Mobility Support	Soft handover using CoMP.	JT [23], [24]
	Frequent handover mitigation using CoMP.	CB, JT [25]
	Scheduling mechanisms to support mobile users.	CS [26]
	Performance comparison of different handover algorithms in a CoMP setting.	DPS [27]
	Proactive network association [28].	-
Reliability and Latency	Spatial/macrodiversity is utilized to enhance reliability of the communication.	JT [29]–[31], DPS [30], [31]
	Clustering is done considering uRLLC requirements as constraints [32].	-
	Resource allocation is done in a multi-cell network in a coordinated manner.	CS, JT [33]
Energy Efficiency	Clustering is carried out with the goal of improving energy efficiency.	JT [34], [35]
	Selective activation of TPs to reduce energy consumption.	JT [36] DPS [37], [38]
	Wireless power transfer [39] and energy harvesting [40]	JT [39] JP [40]
Security	Directional modulation against eavesdropping.	JT [41]
	Signal misalignment at the eavesdropper by leveraging multiple TPs.	JT [42]
	Beamforming to ensure signal strength/quality at legitimate user only.	CB [43]

more sophisticated networks are required that can adapt to the user and network dynamics in a synergic manner. This needs three capabilities on the network's part, namely awareness, intelligence, and flexibility [10], [11]. Awareness refers to knowledge of the radio environment including network infrastructure, device characteristics, user requirements, physical (PHY) and medium access control (MAC) layer properties of the signals; intelligence is the ability to pick the most suitable option in a given scenario; flexibility indicates the availability of different resource allocation and signal design options.

Coordinated multipoint (CoMP) was introduced in Long Term Evolution (LTE) Rel-11, where the goal was to improve the quality of service (QoS) experienced by cell edge user equipments (UEs). Since LTE focused on increasing the data rates and/or spectral efficiency of the network, CoMP was also limited to interference mitigation and throughput/capacity improvement [12]–[22]. However, the expansion of industry verticals and use cases promised by 5G has signaled renewed interest in CoMP. This is primarily due to a metamorphosis of the mentality behind CoMP, where instead of limiting it to multiplexing gains for capacity enhancement, methods are being developed to leverage diversity for reliability and other requirements [44].

The reemergence of CoMP is illustrated by multitude of works in literature targeted at addressing the diverse requirements of 5G and beyond networks such as mobility management [23]–[28], reliability and latency [29]–[33], energy efficiency [34]–[40], and security [41]–[43]. Table 1 summarizes the state-of-the-art work leveraging CoMP principles used to address the aforementioned user requirements. Inspired by these works, we propose generalization of CoMP as a potential flexibility enabler for the next generation wireless networks. The proposed generalized CoMP (GCoMP) concept is targeted towards realizing an efficient, adaptive, and optimized resource management framework which takes into account the dynamic nature of application/user requirements, network capabilities, and resource availability. Here it is important to reiterate that we are not proposing new CoMP schemes/methods. Rather, we are providing a framework that is capable of adapting to user demands and network conditions. The said framework, however, requires well-defined inputs, decision mechanisms, and outputs for its proper operation which are elaborated in the rest of this work.

B. CONTRIBUTIONS OF THIS WORK

This paper contributes the following to the literature:

- An overview of the emergence of coordination in cellular networks through the different generations is provided, highlighting the need for more evolved solutions in future wireless systems.

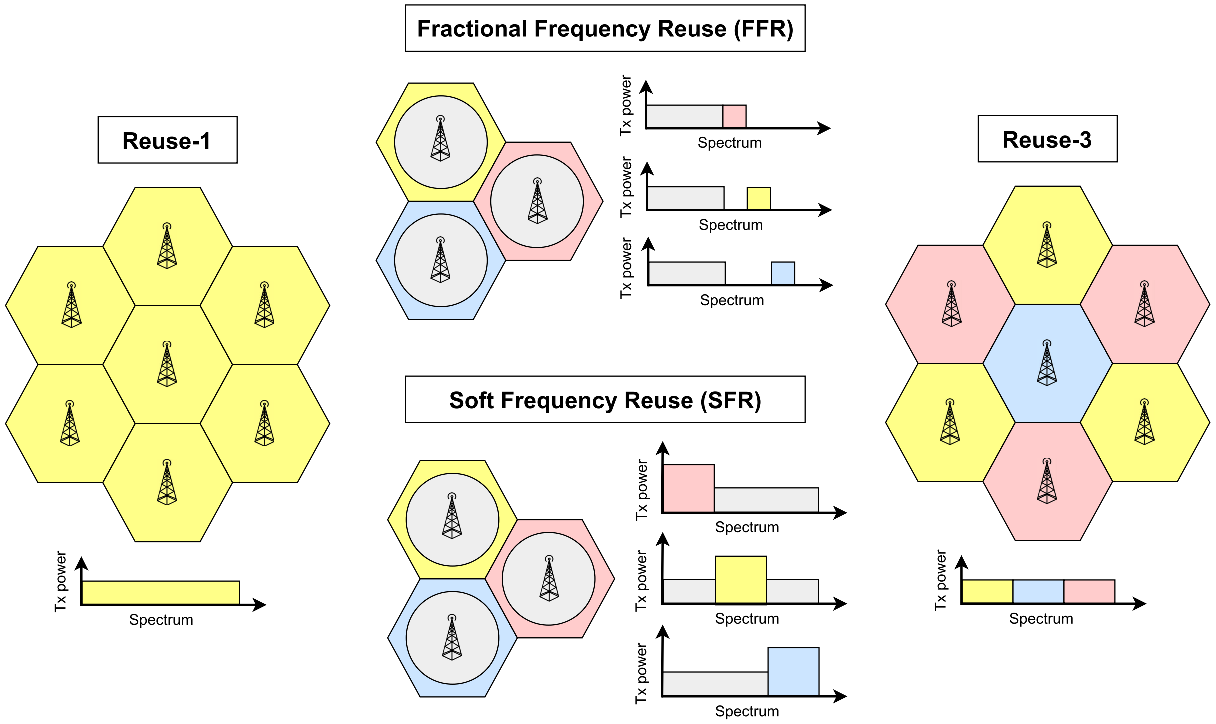


FIGURE 1. Illustration of different frequency reuse techniques for ICI avoidance. Reuse-1 scheme uses the whole spectrum in each cell, while reuse-3 splits the spectrum into three bands and different bands are used in neighboring cells. FFR and SFR split the cell into inner and outer regions, where the neighboring cells use different bands for the latter.

- A comprehensive review on the applicability of different CoMP aspects to address various requirements pertaining to the 5G and beyond networks, use-cases, and applications is presented.
- The idea of GCoMP is proposed and its associated framework is presented, which takes into account the specific user requirements, resource availability, and network constraints.
- A simple case study is provided to demonstrate the working of GCoMP, which illustrates the effect of varying user/application requirements on the performance of different clustering approaches and coordination schemes.
- Challenges and potential research directions for improving the proposed GCoMP framework, and CoMP in general, are highlighted and discussed.

C. STRUCTURE OF THE PAPER

The rest of this article is structured in the following manner. Section II highlights the need for coordination in cellular networks, its evolution through different generations, and the standardization efforts in support of CoMP for 5G networks. Next, CoMP's potential as a solution to the diverse requirements of 5G and beyond networks is highlighted in Section III. Section IV describes the proposed GCoMP framework. A simple case study to illustrate the effect of UE requirements on GCoMP outputs is provided in Section V. The various challenges that need to be faced in realizing such a framework are discussed in Section VI. Finally, Section VII concludes this work.

II. EMERGENCE AND EVOLUTION OF THE NEED FOR COORDINATION

Wireless communication systems have always been hindered by inter-cell interference (ICI), particularly at cell edges. This section describes how the ICI problem ignited the need for coordination in cellular networks leading to the emergence of techniques like inter-cell interference coordination (ICIC), enhanced ICIC (eICIC), and finally CoMP. Towards the end of this section, we highlight 5G enhancements related to CoMP or coordinated networks in general.

Earlier generations of cellular systems increased the frequency reuse distance [45] to mitigate or reduce the ICI experienced by cell edge users. Different reuse mechanisms such as integer frequency reuse (e.g. reuse-3 and reuse-7) [46], fractional frequency reuse (FFR) and soft frequency reuse (SFR) [47] are illustrated in Figure 1. In general, these mechanisms restrict the resource utilization in the spectral domain to reduce ICI. Despite their simplicity, the aforementioned mechanisms are hampered by their static and standalone nature since there is no provision for the transmission points (TPs) to coordinate with each other. This led to the emergence of the ICIC concept in 3rd Generation Partnership Project (3GPP) Rel-8, allowing the TPs to allocate transmission resources in a coordinated manner by leveraging different flags, namely relative narrowband transmission power (RNTP), high interference indicator (HII) and

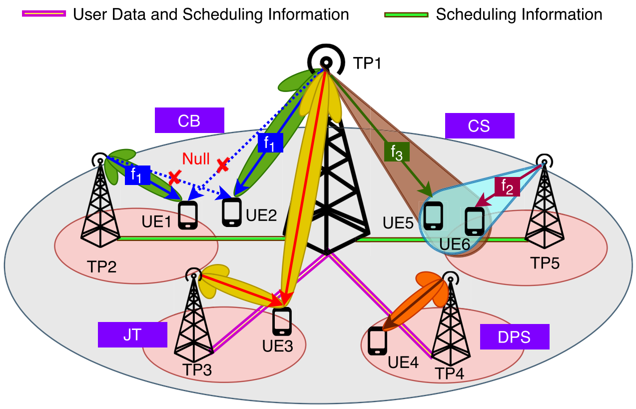


FIGURE 2. Illustration of CoMP schemes. CS/CB require exchange of channel and scheduling information amongst cooperating TPs. JT/DPS, on the other hand, also require sharing of user data to be transmitted.

overload indicator (OI) [47]. These flags indicate if the interference power on certain resource blocks (RBs) is expected (or measured) to be high, allowing neighbor TPs to schedule resources accordingly. However, even this method fails to control ICI in heterogeneous networks (HetNets) due to the power disparity of TPs. eICIC was, therefore, introduced in 3GPP Rel-10. eICIC also considers time dimension to ensure orthogonal resource allocation in the form of absolute blank subframes (ABSs), where the macro TPs are muted to allow interference-free transmission for micro/femto TPs [48].

The increase in device density, combined with elevated heterogeneity of wireless infrastructure compounded the ICI problem. This necessitated more sophisticated and dynamic coordination approaches. Consequently, CoMP was introduced in the Rel-11 of 3GPP as a mechanism to allow different TPs connected with ideal backhaul to coordinate with each other [49]. CoMP introduces spatial domain to the resource allocation problem, thereby improving spectral efficiency in addition to interference mitigation. Figure 2 illustrates the different CoMP schemes, including coordinated scheduling (CS), coordinated beamforming (CB), joint transmission (JT) and dynamic point selection (DPS). The concept was extended to multiple eNodeBs (eNBs) connected with non-ideal backhaul in Rel-12 [50]. This required the standardization of signaling over X2 interface to enable exchange of *CoMP hypothesis set* and its associated *benefit metric*, including reference signal received power (RSRP) measurements, between cooperating eNBs. The sharing of this information amongst the coordination cluster helps improve the radio resource management (RRM) [51]. 3GPP Rel-13 provided some enhancements regarding channel state information (CSI) and enhanced RNTP (eRNTP), where the latter is particularly useful for power allocation in a CoMP setting [52]. Rel-14 looked at alternatives to JT due to its stringent synchronization and CSI requirements, leading to discussion around non-coherent JT (NC-JT). The performance results indicated the suitability of NC-JT and CS/CB in low and high traffic load scenarios, respectively [53]. Rel-15 proposed monitoring X2 characteristics and the spatio-temporal traffic variation to update or manage CoMP sets under the self-organizing network (SON) umbrella.

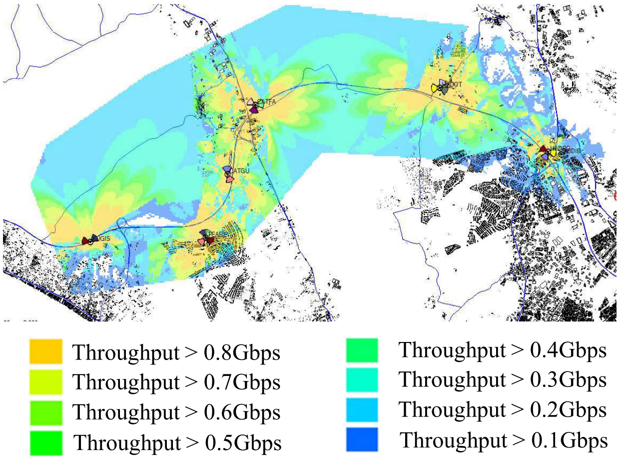


FIGURE 3. Coverage map of Istanbul Çatalca Region - Turkey for different throughput requirements obtained using Atoll radio planning tool.

Having revisited the motivation and evolution of ICIC/CoMP, we now turn our attention towards the multitude of technologies introduced to fulfill the myriad of requirements imposed by 5G and beyond networks. Here we try to identify and highlight the paradigms that are relevant to CoMP and have already been discussed in the 3GPP standardization activities:

- *Functionality split between central and distributed units:* 3GPP Rel-14 specifies eight different functionality splits between central and distributed units for 5G [54]. The functionality split has a major impact on the backhaul and can potentially relax the corresponding requirements regarding overall capacity, delay, and synchronization. This is also applicable to the concept of cloud-RAN (C-RAN) which is a potential implementation of CoMP network. However, a study showing the feasibility of lower split options illustrates the preference of standardization in this regard [55].
- *Non-uniform application coverage:* 5G introduced a variety of services with different requirements, that are expected to further diversify in succeeding generations. Given the current network infrastructure, these applications have different coverage areas. Figure 3 shows the preliminary simulation of coverage areas for different throughput requirements. For a UE at the edge of its application's coverage area, it is similar to being at a cell edge. Since CoMP was introduced to improve QoS at cell edges, the same concept can be extended to support the diverse user requirements of next generation of wireless networks.
- *mmWave and beyond:* The spectrum scarcity issue in sub-6 GHz frequencies and the envisioned extremely high data rate requirements in the future networks have led to the exploration of higher frequency bands (mmWave, THz, and VLC). However, they are susceptible to higher path loss and blockages. The exploitation

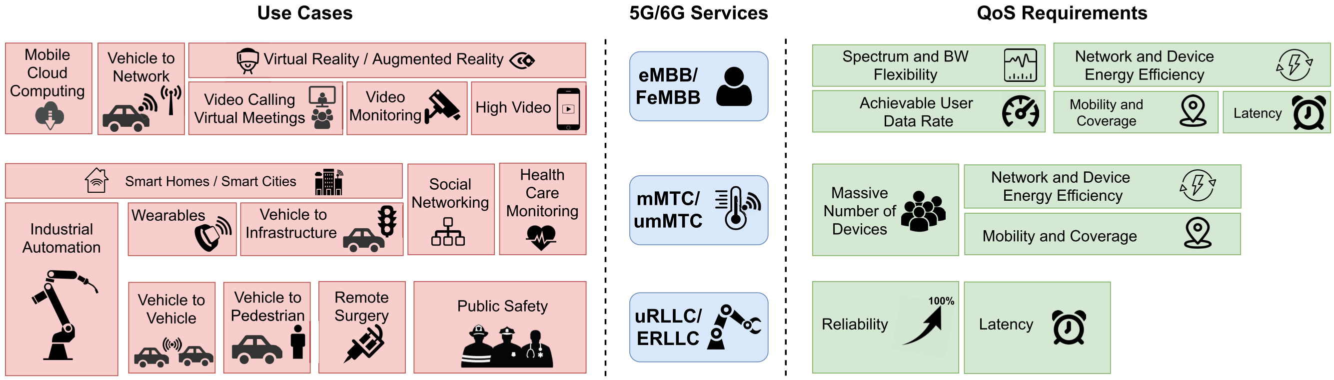


FIGURE 4. Selected 5G/6G use cases, services and requirements.

of macrodiversity offered by CoMP has been experimentally shown to provide link and capacity improvement in the 73 GHz band [56].

- *MIMO enhancements:* mmWave networks depend on technologies such as multiple-input multiple-output (MIMO) and beamforming for their reliable operation. Accordingly, 5G and 3GPP Rel-16 have offered significant MIMO enhancements over LTE, including multi-panel/transmission-reception point (TRP) operation, which is similar in essence to the CoMP concept. Furthermore, improved (type II) codebook, flexible CSI acquisition and reference signal design (including zero-power signals for interference measurement), and beam management for higher (> 6GHz) bands promise significant boost in MIMO performance [57].
- *Coexistence and convergence of wireless networks:* In a trend which is expected to continue in 6G, 5G has tried to incorporate unlicensed spectrum in its fold for improved network capacity, as evident from the presence of work item in Rel-17 [58], [59]. In fact, access traffic steering, switching and splitting (ATSSS) enables the simultaneous use of 3GPP (5G) and non-3GPP (Wi-Fi) access networks with the 3GPP-based core network [60]. Coordination between these networks can enable more efficient resource utilization in the unlicensed and/or shared spectrum.

III. CoMP FOR 5G AND BEYOND REQUIREMENTS

As mentioned earlier, fourth generation (4G) focused on achieving higher data rates and improved spectral efficiency. Consequently, CoMP was also targeted towards the same goals. However, 5G introduced diverse applications such as uRLLC and mMTC opening up CoMP to leverage its spatial diversity for various other requirements [44]. 6G aims to expand the communication paradigms envisioned by 5G even further, providing the concept of a human-centric digital society that encompasses the various aspects of human life including healthcare, transportation, immersive entertainment, education, financial transactions, agriculture, and industrial automation. Compared to 5G, 6G envisions a 50-100 times increase in data rates and about three times increase in spectral efficiency under further-enhanced mobile broadband (FeMBB), 5-10 fold decrease in latency under extremely reliable and low-latency communication (ERLLC), support of twice the mobility speeds under long-distance and high-mobility communication (LDHMC), ten times higher device connectivity under ultra-massive machine-type communication (umMTC), and 10-100 fold increase in energy efficiency under extremely low-power communication (ELPC) [2], [61]. In addition to the extension of these 5G services, 6G will also open up new paradigms of which security is arguably the most important [62]. Figure 4 illustrates the services and concerning requirements for some selected use cases discussed under 5G/6G visions. The remainder of this section describes some selected works, in addition to the state-of-the-art already summarized in Table 1, to highlight different approaches used under the context of coordinated networks for the fulfillment of these requirements.

A. MOBILITY

To ensure continuous connectivity, dual connectivity based solution was considered (though not eventually standardized) in addition to *Make-Before-Break (MBB)* handover technique [63]. CoMP or C-RAN provide a possible realization of multi-connectivity. Additionally, CoMP also reduces the number of handovers as long as the UE is within its coordinating cluster. A CoMP scheme like DPS seems particularly suitable for mobile UEs, owing to the similarity in nature of handover and DPS concepts since both revolve around the dynamic selection of best suited TP. Along the same lines, the switching aspect of ATSSS is capable of supporting smoother handovers by leveraging Multipath Transmission Control Protocol (MP-TCP) [64].

B. RELIABILITY AND LATENCY

Out of the different services of 5G and beyond networks, uRLLC or ERLLC (in 6G) presents arguably the toughest challenge owing to the targeted reliability with strict latency bounds. There are generally two approaches to address the uRLLC requirements, increasing the reliability of one-shot transmission or lowering the latency between retransmissions. CoMP, with its JT approach, can provide different versions of the transmitted signal at the receiver at the same time reducing the necessity of retransmission and addressing the latency constraint. Properly combining the received copies of the signal can improve the signal-to-interference-plus-noise ratio (SINR) performance and hence the reliability of the system. Macrodiversty is an approach to provide multiple paths for the communication of the same signal, targeted to exploit the variation of path loss and large scale fading in the different paths. An interesting idea related to this is to utilize hybrid aerial-terrestrial networks, which provide additional diversity in the wireless link owing to the different propagation characteristics of the air-to-ground channels [65]. In these networks, the aerial TPs provide a much higher probability of line of sight and reduced shadowing, resulting in improved reliability of communication. An alternative to this is the packet duplication approach supported in Rel-15 [66] which is a higher (packet data convergence protocol (PDCP)) layer complement of the PHY layer diversity techniques [67].

C. ENERGY EFFICIENCY

Energy efficient operation is imperative for future wireless networks. There are two aspects of it; firstly, the energy usage needs to be minimized for devices/sensors that are not easily accessible, medical implants being a perfect example; secondly, the overall energy consumption of the network needs to be managed so that the increasingly dense deployments are feasible. In the first case, if there are multiple communicating devices, it is possible to consider DPS with energy conservation as a goal. A similar idea in drone-based disaster recovery scenario is proposed in [68] where the uplink TP is selected from the UEs while taking into consideration their remaining battery lives. On the other hand, energy harvesting using simultaneous wireless information and power transfer (SWIPT) and TP sleeping are the two prevalent approaches for the second case. For SWIPT, coordinated beamforming can be optimized to provide both minimum SINR and required power transfer to the information and energy receivers, respectively [39]. TP sleeping, while beneficial from an energy conservation perspective, can lead to increased handovers. To cater to this situation, a simple uplink CoMP scheme is devised in [40] where the UE transmits to two cooperating nodes in a heterogeneous network. Another approach for facilitating the TP sleeping is dynamic clustering [35], since static clustering might not be able to support UEs if the network is loaded or the UE distribution is changing.

D. SECURITY

PHY layer security (PLS) has attained increasing importance in wireless networks due to its ability to secure the link/signal rather than just the data. This is particularly useful for applications such as wireless sensing. However, an overwhelming majority of PLS mechanisms rely on independent channel observations at legitimate and illegitimate nodes. This may not be realistic for mmWave bands and poor scattering environments. In such cases, the spatial diversity offered by coordinating TPs can be exploited to attain multiple/different channel and device fingerprint observations [69]. For instance, in [41] TPs transmit the signal such that data is only decodable at the intersection of their transmission beams providing location-based security against eavesdropping. CoMP has also been utilized for security in underwater communication by ensuring that the signal components sent from different TPs collide at the eavesdropper while remaining collision-free at the intended receiver. This is achieved by controlling the transmission schedule and power [42]. Power control with coordinated beamforming has also been exploited to provide service-based security [43].

Unlike eavesdropping, where the aim of the attacker is to intercept and/or interpret the legitimate communication, jamming is targeted at disrupting the communication. This is generally achieved by the transmission of noise or noise-like signals to reduce the SINR experienced by the legitimate receiver. The spatial diversity offered by the geographically separated TPs may be utilized to combat such attacks.

E. THROUGHPUT

As mentioned earlier, the spatial diversity offered by CoMP systems is exploited in various ways. JT-CoMP promises significant gains in terms of network capacity and UE throughput by combining signals from different TPs either coherently or non-coherently. Coherent JT is capable of providing higher throughput as compared to its non-coherent counterpart since it uses a joint precoding procedure while the latter focuses on improving the received signal strength [70]. Multi-TRP MIMO utilizing beamforming at mmWave bands also promises increased data rates. Furthermore, this requirement can leverage the MP-TCP and underlying ATSSS concept to split the traffic over multiple access networks, resulting in improved throughput for the user [60].

IV. GCoMP FRAMEWORK

Given how the CoMP principle has been utilized to address different requirements of 5G networks, we believe that the scope of CoMP should be widened from mere interference mitigation to intelligent network resource management, helping satisfy these diverse requirements. This section is dedicated to the description of the conceptual GCoMP framework, illustrated in Figure 5. The first group of elements represents the inputs to the GCoMP decision mechanism. The decision making is the intermediate stage, followed by the outputs at the end. Here, it should be noted that while most options in the inputs/outputs are well-established, we have taken the liberty of identifying some additional ones, shown in red, that are either related to beyond 5G vision or at least recent to CoMP.

A. INPUTS

The input elements include UE requirements, CoMP architecture, and scenario. The requirements are considered first since everything that follows revolves around them. Section III

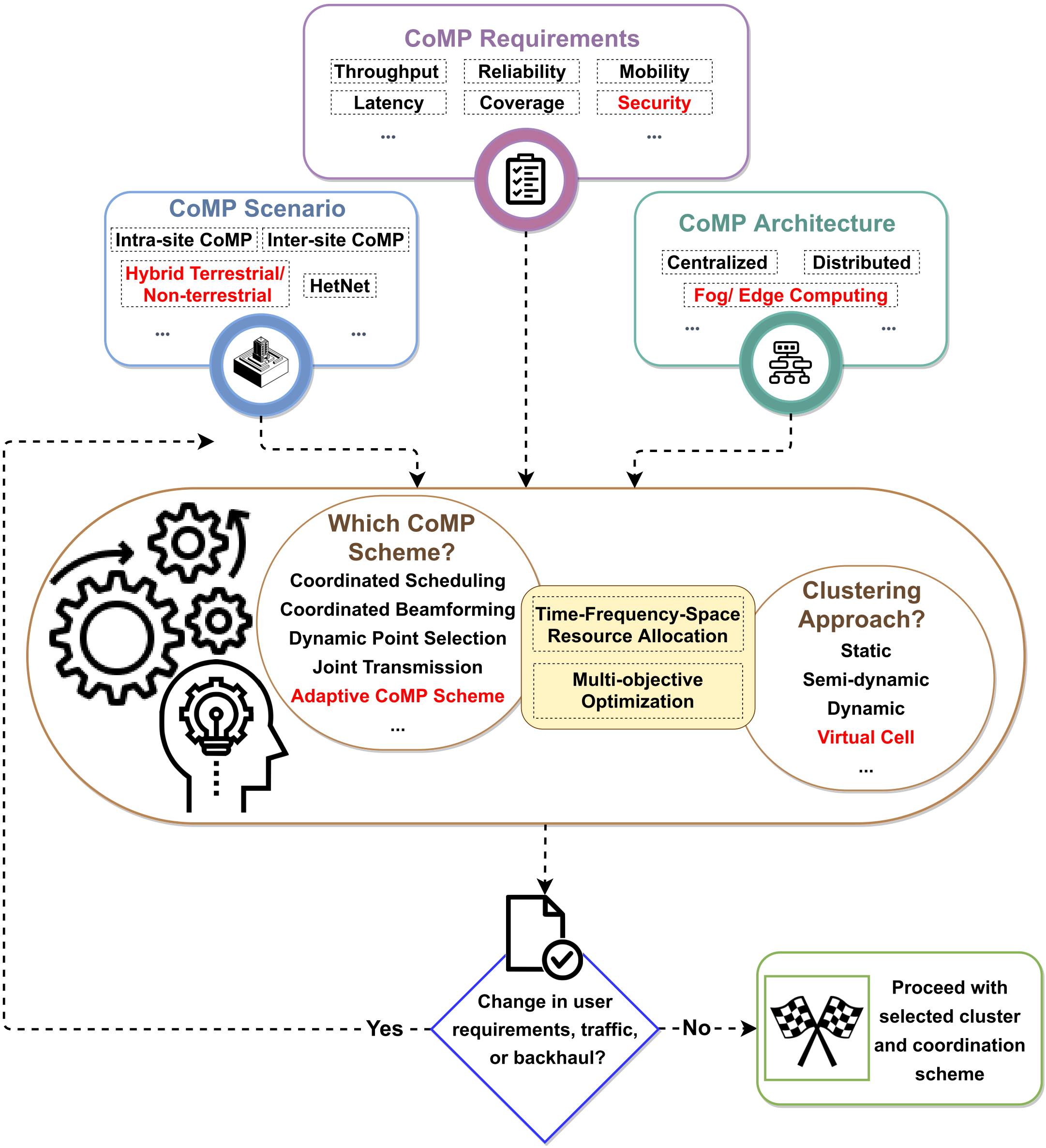


FIGURE 5. GCoMP conceptual framework. UE requirements, CoMP architecture, and scenario serve as inputs to the decision mechanism. The outputs of this mechanism include (but are not limited to) selection of CoMP scheme and coordinating cluster.

has extensively discussed the usage of CoMP for different requirements such as throughput, security, reliability, mobility, and energy efficiency. Following requirements, the second input considered is the architecture. The conventional categories include centralized or distributed coordination. In the former, all administrative tasks are controlled through a central unit, while in the latter, one of the cooperating TPs acts as a master cell and performs all resource management and communication tasks. Here it is pertinent to mention the concept of centralized or C-RAN, which has gained significant traction with operators due to its promise of reduced capital and operating expenditures. Despite its promise, one major challenge for C-RAN is to balance the tradeoff between easier network management offered by centralized control and the increasingly strict backhaul bandwidth and latency requirements. This might be critical for use cases like vehicle-to-everything (V2X) communication. In light of this, recent works have proposed the utilization of fog/edge computing to provide intelligence to components of the network close to the UE [71], [72].

The third input element is CoMP scenarios. 3GPP proposed three different CoMP scenarios for both homogeneous and HetNets [49]. The first scenario is homogeneous intra-site CoMP, in which the coordination takes place between different TPs (sectors). Due to the colocation, there is no additional load on the backhaul. The second scenario is inter-site CoMP which is also implemented on a homogeneous network. It uses high power remote radio heads (RRHs) to expand the coverage. The third scenario is implemented on HetNets and utilizes low power RRHs. Inter-site CoMP and HetNet scenarios require high-speed backhaul links, like fiber, to make the connection between the macrocells and their respective RRHs. In line with HetNets, another scenario that may be of interest is hybrid aerial-terrestrial networks. The wireless propagation channel characteristics of the air-to-ground channel are fairly different as compared to the conventional terrestrial channel, providing a better QoS to the UEs [65]. This can be extended to incorporate the non-terrestrial network or satellite communication scenarios, aimed at improving network coverage [73]. The logical next step to exploiting the variation in the propagation environment is the capability of modifying the environment itself to improve the coverage and user experience. RIS is a technology that promises exactly that by selectively modifying the incident signal's properties, such as phase, amplitude, and polarization [74].

Here it is important to categorize the nature of the above-mentioned inputs in terms of their dynamicity. While the architecture is primarily static, the scenario might change due to paradigms like TP sleeping and dynamic deployment of non-terrestrial network entities. UE requirements (unless a device is specialized for a particular application) are expected to change on an even finer timescale, depending on the particular application/service being used.

B. DECISION MAKING

The GCoMP decision making evaluates the above-mentioned input elements, network constraints, and channel conditions to make informed decisions regarding the appropriate resource allocation, namely, selection of the best suited CoMP scheme and coordination cluster. Figure 6 illustrates an exemplary decision making process [75], which starts by identification of the goal/utility function and corresponding constraints. Common examples of utility functions include fairness [76], throughput [77], or combination of the two [78], [79]. Generally, in a network comprising of N TPs the goal is to maximize this function over all TPs, which takes the form $F(B_1, B_2, \ldots, B_N)$, where B_k refers to the k-th TP. This function is commonly assumed to have properties such as, i) F is additive for the coordinating TPs, i.e. $F(B_1, \ldots, B_N) = \sum_{k=1}^{N} F(B_k)$ and ii) if the TP does not serve any UEs, $F(B_k) = 0$ [80]. The typical constraints, on the other hand, include transmission power [81], available spectral resources [82], and the provisioned backhaul bandwidth [83].

Here, it should be highlighted that there are cases such as uRLLC, where the goals (reliability, latency, throughput) are often competing. As illustrated in Figure 7, it is possible to optimize any two of the requirements at the cost of the third [84]. This is visible for point A where reliability and latency are optimized, but throughput is compromised. Point B, on the other hand, provides the opposite. In such scenarios, a single optimum solution is not possible. Rather, there is a set of (possibly infinite) Pareto-optimal solutions where improving one objective would lead to degradation in the other(s) [85].

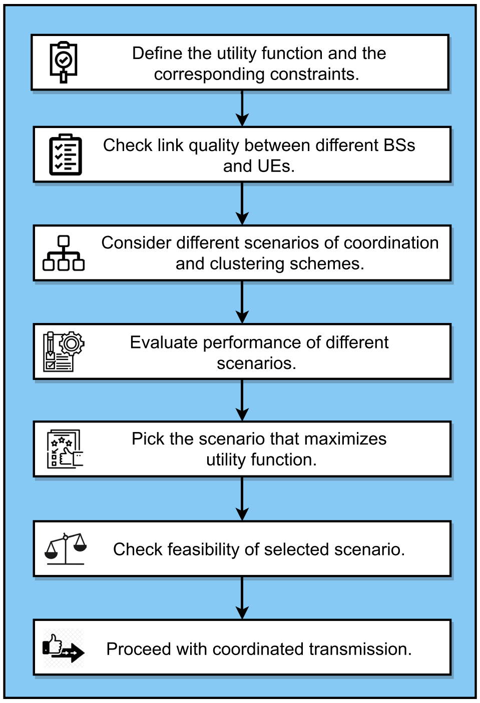


FIGURE 6. Example of a decision making flowchart for GCoMP.

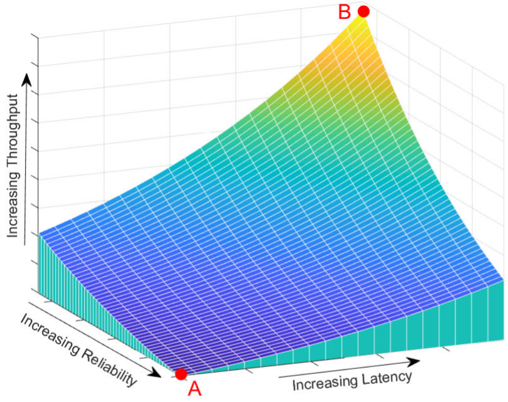


FIGURE 7. A sketch illustrating the tradeoff between latency, reliability and throughput (inspired from [84]).

Apart from the aforementioned utility functions and constraints, another factor that needs to be considered is the priority of the users. In the case of wireless standards, priority levels are defined to ensure the necessary QoS for different applications. For instance, in 5G these levels are indicated by 5G QoS identifier (5QI) [86]; and in the case of Wi-Fi, user priority (UP) or access category (AC) fields serve a similar purpose [87]. The examples of link quality metrics include SINR, RSRP, received signal strength indicator (RSSI), distance etc. The link quality helps identify coordination clusters which are used to evaluate the performance of different coordination schemes. The combination of clustering mechanism and coordination scheme which maximizes the utility function is then assessed by

$$H^{*} = \underset{H_i \in \{H_1,\ldots,H_x\}}{\arg\max} \sum_{k=1}^{N} F(B_k)|_{H_i}, \tag{1}$$

where H^{*} and H_i refer to the optimum and i-th hypotheses, respectively. As long as the constraints mentioned earlier are fulfilled, H^{*} is chosen and the coordinated transmission can be carried out.

In general, the approaches for the decision making process are categorized into *user-centric*, *network-centric*, or *hybrid*. The user-centric approach makes decisions on a per-user basis, targeted at fulfilling that particular UE's requirements. The network-centric decision making, on the other hand, places more emphasis on simplifying the implementation from the network perspective, including the architecture and overhead while trying to optimize the performance of all connected UEs. The overhead includes information (data and CSI) sharing between the nodes and processing of the information necessary for the said decision making. The hybrid approach provides a tradeoff between both the above-mentioned methods by optimizing the decisions for a group of UEs while keeping the network overhead bearable. The decision to pick any of these approaches itself presents a challenge. One way to address this is to consider the historical user behavior and preferences in a given network. For networks with more consistent user behavior and application requirements, a network-centric approach is more appropriate. In the case of significantly varying user preferences, user-centric decisions have to be used despite their considerable overhead. In the case that users have similar requirements and preferences, they are grouped and facilitated under the hybrid approach. Moreover, since these decisions are dependent upon variable parameters such as UE requirements and spatio-temporal traffic patterns, they need dynamic updates. These updates can either be *periodic* or *triggered*. As the name suggests, the former analyzes the network situation repeatedly after a fixed interval and revisits its earlier decisions, making it suitable for scenarios where the circumstances are expected to change constantly. The triggered updates, on the other hand, are set off by certain conditions. This approach is, therefore, suitable for cases where sporadic variation in the backhaul availability or traffic patterns is expected.

C. OUTPUTS

The first output of the framework is the selection of the appropriate CoMP scheme, which are illustrated in Figure 2. CS reduces interference by ensuring instantaneous exchange of channel information between coordinating TPs. In the following section, we consider a special case of CS (CS with muting), where apart from the serving TP, all other TPs are muted on the corresponding allocated RBs for a scheduled user. CB allows the edge UEs to use the same frequency resources as long as the beam patterns for different UEs do not interfere with each other. Due to the significant use of beamforming in 5G networks, CB has attained increased importance. JT, arguably the most interesting CoMP technique, constitutes of UE data being transmitted from different TPs, potentially providing macrodiversity against path loss, shadowing, and blockage. Since coherent JT (C-JT) performs joint beamforming, it requires backhaul links with high capacity and low latency as well as strict synchronization among coordinated TPs. NC-JT, on the other hand, provides a complexity-performance tradeoff by removing the burden of joint precoding and strict synchronization while still providing significant gains as compared to other schemes [53]. DPS is a special case of JT, where even though the UE data is available at different TPs, it is only transmitted from one TP at any given time [70]. All these schemes have different backhaul requirements and provide varying benefits. Therefore, the GCoMP decision needs to consider both, UE's requirements and the available backhaul bandwidth before making a decision. An interesting approach pertaining to the latter consideration is presented in [88], where the system adaptively switches between the CS/CB and JT CoMP schemes depending on the backhaul availability.

The second output identified for this framework is the decision about the coordination cluster, which comprises of the TPs that are supposed to coordinate with each other. In literature, there are three main types of clustering. *Static* clustering, which is primarily based on topology and does not vary according to the nodes or UEs, thereby providing limited performance gains. *Semi-dynamic* clustering - an enhanced version of the former - where more than one static clustering patterns are set up and UEs can select the most suitable cluster, leads to an increase in both complexity and performance. *Dynamic* clustering responds to network and UE mobility changes and reduces inter-cluster interference by updating the clusters dynamically [89]. To identify the coordinated TPs per cluster, a set of solutions is proposed in [90] taking into account real operating conditions such as connectivity and network layout. One of the solutions is to adapt the coordination areas (CAs) depending on the spatial distribution of the UEs in order to avoid concentrations of UEs on inter-CA borders. Another solution is the use of layered CAs where the borders between adjacent CAs are covered by an overlaying CA. Indeed, a coordinated TP can be part of different CAs and partitioning of scheduler resources between the CAs is needed which might cause some peak UE throughput limitations. Therefore, CA layers should be activated only when needed. In addition to the clustering approach, there is the concept of virtual cell [71], where each virtual cell is occupied by a single UE. This UE is served by multiple cooperating TPs leveraging different logical slices of the network.

V. CASE STUDY

A simple case study is presented in this section to illustrate the GCoMP concept, and highlight how it takes into account the user requirements, network resource availability, and backhaul or energy constraints. The diverse user requirements are represented by different applications [86]. The variation of available network resources is represented by the number of RBs considered in each scenario, and the significance of GCoMP itself is shown by comparing the performance of the different combinations of coordination schemes and clustering approaches.

A. SYSTEM MODEL AND ASSUMPTIONS

We consider an urban micro environment where the TPs and UEs follow Poisson point process (PPP) distribution with densities λ_B and λ_U, respectively [91], [92]. Total transmit power per TP, P_b^{Tx} (for b-th TP), is taken to be constant and equally distributed over all RBs. The power received at u-th UE for a transmission from b-th TP, $P_{b,u}$, is given by [93]

$$P_{b,u} = P_b^{Tx} - (36.7\log_{10}(d_{b,u}) + 26\log_{10}(f_c) + 22.7 + \sigma), \tag{2}$$

where $d_{b,u}$ represents the distance between b-th TP and u-th UE, f_c is the carrier frequency, and σ is the standard deviation of the zero-mean log-normal shadowing distribution.

Since the primary goal of GCoMP is to decide upon the clustering and coordination scheme, we look at the performance of their various combinations. In the case of clustering, we consider the possibility of using both static and dynamic clusters in each scenario. For the static case, conventional methods include determining the clusters which reduce outage, maximize the mean SINR, or minimize the average interference [94], [95]. Since the interference, outage or SINR inherently depend upon the distance between TPs, we have leveraged simple clustering methods from the domain of pattern recognition where the physically closest C_{max} TPs are grouped together, with C_{max} representing the maximum cluster size. This has the added advantage of simplifying the implementation. For the dynamic case, clusters are formed on a per-user basis, where the b-th TP is considered to be part of the u-th UE's cluster depending on the fulfillment of the following criteria [91]

$$P_{b,u} \geqslant P_{min}, \tag{3}$$

and

$$P_{ser,u} - P_{b,u} \leqslant P_{diff}, \tag{4}$$

where P_{min} is a predefined threshold for including a TP in the cluster and P_{diff} is the maximum difference between received power from the serving TP, $P_{ser,u}$, and the candidate TP. Another parameter regarding the clustering is the (maximum) size of the cluster itself. A larger cluster size generally improves the coordination performance at the cost of additional information exchange overhead [89].

In addition to clustering, coordination scheme selection is the other significant output of the GCoMP framework. For the performance analysis in this section, we have considered two coordination schemes, namely CS with muting [80] and JT [91]. While the latter work only considers a dynamic clustering approach, we have also used the same JT mechanism for static clustering in our simulations. Furthermore, we have also considered the case of hybrid/adaptive coordination, where both of these schemes are simultaneously used in the network. For this purpose we adapt the method proposed in [96] to use a heuristic RSSI threshold in line with [97]'s approach to select between CS and JT schemes. The general expression for the SINR experienced by the u-th UE can be described as

TABLE 2. **Simulation parameters.**

Parameter	Value
Simulation environment	Urban mirco
Carrier frequency (f_c)	5 GHz
RB bandwidth	180 kHz
Number of RBs/TP	20, 50, 75, 100
System bandwidth (B_T)	5, 10, 15, 20 MHz
Shadow fading standard deviation (σ)	4 dB
Total transmit power/TP (P^{Tx})	41 dBm
Noise power density (N_0)	-174 dBm/Hz
Max. cluster size (C_{max})	3
Min. received power to include in cluster (P_{min})	-110 dBm
Max. received power difference from serving TP (P_{diff})	20 dB
TP transmission mode threshold (P_{th})	10 dB
TP density (λ_B)	80 TP/km^2
UE density (λ_U)	800 UE/km^2
Simulation area radius	0.5 km

$$SINR_u = \frac{\sum\limits_{t \in \mathcal{T}_u} P_{t,u}}{\sum\limits_{b \in \mathcal{B}, b \notin \mathcal{T}_u, \mathcal{M}_u} P_{b,u} + N_0 B_T}, \tag{5}$$

where $\mathcal{B}$ is the set of all TPs in the coverage area, $\mathcal{T}_u$ and $\mathcal{M}_u$ are the sets of transmitting and muted TPs in u-th UE's cluster, respectively, N_0 is the noise power spectral density and B_T represents the total system bandwidth. Here it should be noted that in the case of CS with muting, $\mathcal{T}_u$ consists of a single TP while $\mathcal{M}_u$ comprises of all other TPs in the cluster. This means that each UE is served by a single TP and the corresponding RBs of all other TPs in the cluster are muted. In case of JT, $\mathcal{T}_u$ comprises of all coordinating TPs while $\mathcal{M}_u$ is an empty set, where the same RBs of all the coordinating TPs are used to serve the particular UE using zero-forcing (ZF) precoding [91], [92]. In the adaptive scheme, the decision whether a TP transmits to particular UE or not depends on the received power(s). For instance, b-th TP can be included in u-th UE's $\mathcal{T}_u$ if it satisfies the condition

$$P_{ser,u} - P_{b,u} \leqslant P_{th}, \tag{6}$$

where P_{th} is the received power threshold for adding a coordinating TP to the $\mathcal{T}_u$. As such, depending on the $P_{b,u}$ values the adaptive scheme can assume any configuration from CS to JT.

Given the SINR expression in Eq. 5, the throughput of u-th UE from one RB can be obtained using the Shannon's capacity formula, given as

$$R_u = B_{RB}\log_2(1 + SINR_u), \tag{7}$$

where B_{RB} is the bandwidth of one RB. For a given required throughput of the u-th UE, $R_{req,u}$, the number of required RBs

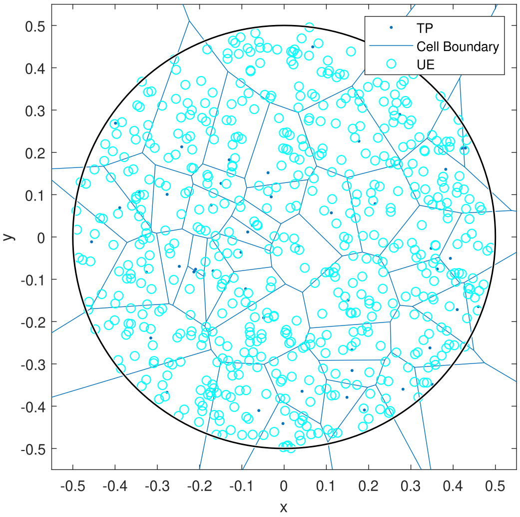


FIGURE 8. An example of the generated network layout, cell boundaries following Voronoi tessellation.

is given by

$$RB_u = \frac{R_{req,u}}{R_u \mid \mathcal{T}_u \mid}, \tag{8}$$

where | . | represents cardinality of a set. These RBs are allocated to the UE as long as they do not overload the TP, i.e., the number of allocated RBs does not exceed the available RBs. This is ensured by keeping the load of b-th TP, given by the following equation, less than or equal to one

$$l_b = \frac{\sum_{u \in \mathcal{A}_b} RB_u}{RB_{\circ,b}}, \tag{9}$$

where $RB_{\circ,b}$ and $\mathcal{A}_b$ represent the number of provided RBs and associated UEs of the b-th TP. The formulas for energy efficiency and required average backhaul bandwidth per TP are given by Eqs. 10 and 11 below:

$$EE = \frac{\sum\limits_{u \in \mathcal{A}} R_u}{\sum\limits_{u \in \mathcal{A}} \sum\limits_{b \in \mathcal{T}_u} \frac{RB_u P_b^{Tx}}{RB_{\circ,b}}}, \tag{10}$$

and

$$BH = \frac{1}{\mid \mathcal{B} \mid} \sum_{u \in \mathcal{A}} \sum_{b \in \mathcal{T}_u} R_{req,u}, \tag{11}$$

respectively, where $\mathcal{A}$ is the set of connected UEs in the network. As evident from the above expressions, energy efficiency is calculated as a function of the transmitted power. Other sources of power consumption such as precoding computation are NOT taken into account here. Similarly, backhaul requirements are also computed only considering the data sharing between the TPs for coordinated transmissions.

TABLE 3. User/application priorities and requirements.

Service/ Application	Resource Type	Priority Level	Throughput Requirements
V2X Messages	Delay-critical GBR	18	5.4 kbps
Conversational Voice	GBR	20	40 kbps
Conversational Video	GBR	40	2.5 Mbps
Buffered Video	Non-GBR	60	2 Mbps

B. PROBLEM FORMULATION AND RESULTS

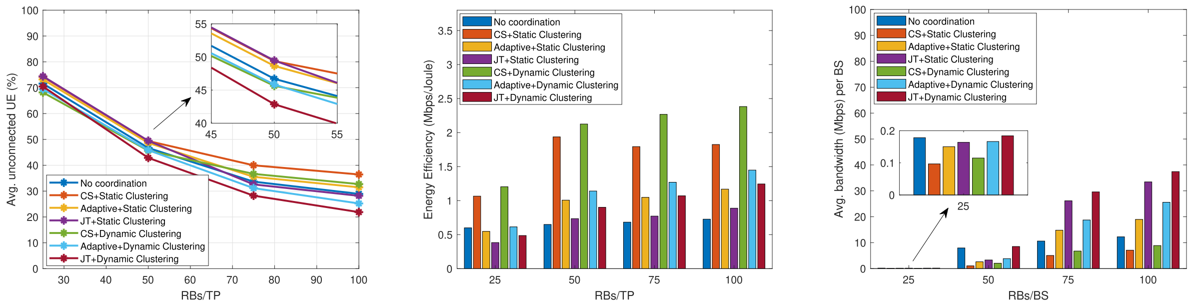
Our goal in this work is to pick the clustering and coordination scheme combination that maximizes (minimizes) the number of connected (unconnected) users, considering the energy efficiency and backhaul bandwidth constraints. Here it should be noted that the users are connected only if the network is capable of fulfilling their throughput requirements. The overall problem can be mathematically formulated as

$$\begin{aligned} H^* = & \underset{H_i \in \{H_1,\ldots,H_7\}}{\arg\max} \left.\frac{\mid \mathcal{A} \mid}{\mid \mathcal{U} \mid}\right|_{H_i} && \text{(12a)} \\ = & \underset{H_i \in \{H_1,\ldots,H_7\}}{\arg\min} \left(1 - \left.\frac{\mid \mathcal{A} \mid}{\mid \mathcal{U} \mid}\right|_{H_i}\right) && \text{(12b)} \\ & \text{subject to } EE \geq EE_\circ, && \text{(12c)} \\ & BH \leq BH_\circ, && \text{(12d)} \end{aligned}$$

where $\mathcal{U}$ is the set of all users in the coverage area, $EE_\circ$ and $BH_\circ$ represent energy efficiency and backhaul constraints, respectively, and H^* is the optimum choice out of the following CoMP hypotheses:

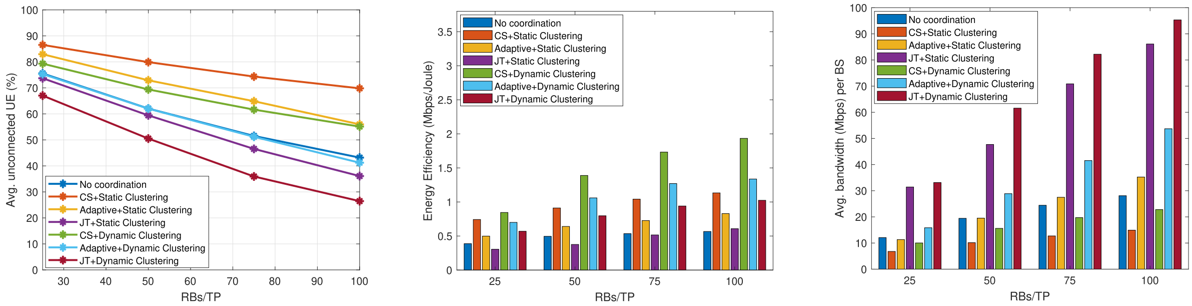
$$H = \begin{cases} H_1 & : \text{No coordination} \\ H_2 & : \text{CS scheme with static clustering} \\ H_3 & : \text{Adaptive scheme with static clustering} \\ H_4 & : \text{JT scheme with static clustering} \\ H_5 & : \text{CS scheme with dynamic clustering} \\ H_6 & : \text{Adaptive scheme with dynamic clustering} \\ H_7 & : \text{JT scheme with dynamic clustering} \end{cases} \tag{13}$$

The simulations are carried out in MATLAB® environment and the simulation parameters used are summarized in Table 2. In line with the results observed in [91] we have selected a maximum cluster size of 3, since the coordination benefit diminishes with a higher cluster size. An example snapshot of the generated network layout is shown in Figure 8. To depict realistic network traffic, we have considered applications belonging to the guaranteed bit-rate (GBR), non-GBR and delay-critical GBR categories. Table 3 lists the requirements for the particular applications selected from these categories [86]. Furthermore, we have also incorporated the effect of varying availability of network resources in terms of RBs. Figure 9 shows the results averaged over 100 network (and UE) realizations for the case where users are equally distributed amongst the four applications listed in Table 3. The percentage of unconnected users for different coordination/clustering schemes and the associated energy efficiency



(a) (b) (c)

FIGURE 9. **Performance comparison of different coordination schemes and clustering approaches when all applications (given in Table 3) are equiprobable. (a) Number of unconnected users, (b) Energy efficiency, (c) Average backhaul bandwidth required per TP.**



(a) (b) (c)

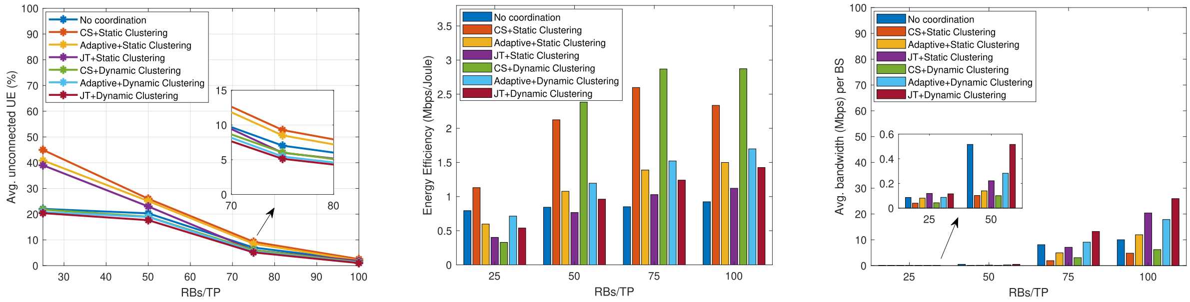
FIGURE 10. **Performance comparison of different coordination schemes and clustering approaches when 100% of the UEs use conversational video. (a) Number of unconnected users, (b) Energy efficiency, (c) Average backhaul bandwidth required per TP.**

and backhaul requirements are shown in Figs. 9(a), 9(b), and 9(c), respectively. It is observed that in terms of unconnected UEs dynamic clustering performs better than the static approach for all three coordination mechanisms; CS scheme performs the worst, JT scheme offers the best performance and the adaptive scheme provides intermediate results. ''No coordination'' bisects the two clustering approaches, providing better performance than all coordination schemes with static clustering and worse than all dynamic ones. While the performance of CS being worse than ''No coordination'' scheme might seem rather surprising, it should be kept in mind that CS and (some) adaptive cases are accompanied by muting of the other TPs in the cluster. This means that overall a smaller number of RBs is used for transmission, leading to reduced energy consumption, as shown in Figure 9(b). Since muting improves the SINR experienced by UEs, it improves the energy efficiency as compared to the ''No coordination'' case, even though a smaller number of users is entertained. This is also evident in Figure 9(c) where CS with static clustering requires the lowest backhaul bandwidth out of all approaches. It is interesting to note that the difference in performance for the various H's becomes more evident as the system bandwidth increases. In order to study this effect in more detail, we look at how the performance varies for different user/application requirements.

Figure 10 illustrates the scenario where all UEs utilize conversational video and the results seem to follow the same trend as the equiprobable application distribution case. However, it can be seen that the performance of different schemes has a more significant gap in this case (for maximum system bandwidth, B_T), with CS and static clustering leaving 70% UEs unconnected and JT with dynamic clustering leaving around 25% unconnected UEs, as compared to the equiprobable case where the former has about 40% users unconnected and the latter has 20% unconnected UEs. Accordingly, the backhaul requirements for JT are much more pronounced in this case as compared to the previous one. In the case of energy efficiency, even though CS schemes are still the best, this effect is not as pronounced as the first scenario.

Considering how the performance diverged with an increase in application demands, we can expect the opposite to happen when the requirements are lowered. This is validated in Figure 11, where all UEs are assumed to use V2X messaging which has the lowest requirements of the applications mentioned in Table 3. As expected, the performance of different coordination/clustering schemes seems to converge in this case. Though it should be noted that for 25 RBs, the ''No coordination'' and dynamic clustering approaches have significant gains as compared to static clustering. Also, the energy efficient nature of CS is more pronounced as compared to both the earlier scenarios.

The GCoMP decision making can be illustrated with the discussion provided above. First, it should be noted that the prioritization defined by 5QI is employed to sort the



(a) (b) (c)

FIGURE 11. Performance comparison of different coordination schemes and clustering approaches when 100% of the UEs use V2X messaging. (a) Number of unconnected users, (b) Energy efficiency, (c) Average backhaul bandwidth required per TP.

users and then a network-centric approach is used to maximize the number of connected UEs. Now consider the second scenario (Figure 10) where 25 RBs are available per TP. If the available backhaul, $BH_{\circ}$, is limited to 40 Mbps with energy efficiency requirement, $EE_{\circ}$, of more than 0.5 Mbps/Joule, GCoMP decision mechanism looks at the possible approaches that satisfy the given criteria. In this case, CS with both clustering approaches (H_2, H_5) and adaptive (H_6) and JT (H_7) schemes with dynamic clustering are possible candidates. Since the goal is to minimize the number of unconnected devices, JT with dynamic clustering would be chosen, i.e., $H^* = H_7$. Now consider the case where $BH_{\circ}$ is lowered to 20 Mbps with the same $EE_{\circ}$. Now the possible candidates include CS with both clustering approaches (H_2, H_5) and adaptive scheme with dynamic clustering (H_6). In this case, the latter would be chosen to minimize the number of unconnected users. In case $EE_{\circ}$ is increased to 0.75 Mbps/Joule, only CS schemes (H_2, H_5) meet both constraints with dynamic clustering being chosen by the GCoMP framework, i.e., $H^* = H_5$. Given the definite trend in performance, energy efficiency, backhaul, user requirements, and resource availability, it is possible to develop a look-up table kind of strategy that can select H^* depending on the distribution of user applications.

Here, we would like to reiterate that this case study and the accompanying simulations present a very simplistic illustration of the proposed GCoMP concept, aimed at providing elementary understanding to the readers. More thorough analysis and contributions, some of which are highlighted below, are required to practically realize such a system in future networks.

VI. CHALLENGES AND FUTURE DIRECTIONS

There are considerable challenges that need to be overcome in order to make GCoMP a reality. Some of these issues are illustrated in Figure 12 and discussed below:

- Owing to the diversity of future wireless networks both in terms of user/application requirements and device/node capabilities, optimized resource allocation is going to become even more challenging [98]. Multi-objective optimization is, therefore, going to be imperative. This also includes the need for improved network slicing capabilities which will be necessary to support future applications [99].
- The spatial diversity afforded by the geographical separation between TPs can be utilized to provide capacity, security, and reliability gains. However, all of these are competing objectives which means one can only be achieved if the others are waived. Optimizing these tradeoffs remains a challenge. This might also require multi-objective resource optimization.
- In this work, we have assumed that all the coordinating entities in the network are capable of supporting all clustering approaches and CoMP schemes. However, there might be a scenario where this is not true. Adapting the GCoMP decisions to accommodate such scenarios remains an open challenge. Moreover, here we have only focused on the backhaul bandwidth and energy considerations in terms of added data exchange between TPs. The analysis in terms of convergence of the CoMP function on an appropriate time-scale, impact on TP complexity and any impact of the network configuration still needs to be carried out [90].
- For any CoMP scheme, timely exchange of information between cooperating nodes and/or central controller is imperative which has been assumed in this work. However, achieving this can be quite challenging in practical scenarios. This issue has been studied in the context of optical networks from the perspective of coordination controller placement [100] and resource (bandwidth) allocation scheme that prioritizes signaling over data traffic [101]. The impact of this latency on GCoMP specifically, however, remains to be studied and suitable mitigation mechanisms should be developed accordingly.
- Significant efforts are being made to improve the compatibility between different wireless radio access technologies. ATSSS is one such example, which promises not only the coexistence but convergence of non-3GPP access networks (such as Wi-Fi) with 3GPP's 5G core network [64]. The upcoming amendment of the Wi-Fi standard, i.e., IEEE 802.11TGbe has introduced multi-access point (AP) coordination concept which is similar to CoMP [102]. Furthermore, coordination is also being

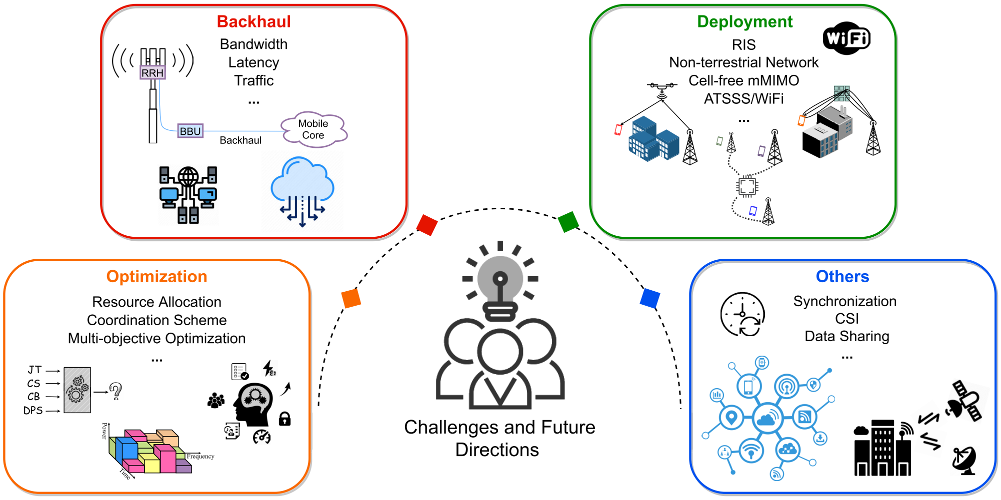


FIGURE 12. **Challenges and future directions.**

considered for the purpose of sensing in 802.11's sensing task group, TGbf [103]. This illustrates the need for developing more efficient coordination mechanisms not only for communications but other aspects of wireless networks as well.

- Even though the discussion around 6G is still in its early stages, it is evident that the next-generation wireless networks demand novel paradigms such as RIS-enabled smart radio environments [62] and cell-free massive MIMO systems [104], [105]. It might be interesting to consider incorporation of RISs in a CoMP setting. Not only does the use of multiple RISs provide an opportunity for ICI mitigation at cell edges [106], but also coordination can help with the biggest challenge in practical RIS deployment, i.e., channel estimation [107]. Since the introduction of RIS and the associated phase shifts contributed by different elements of the surface affect the channel, it would also have an impact on the channel estimation process. The frequency of the channel estimation would depend on the number of RISs, the number of elements in each surface, and the frequency of their update. This process can be streamlined by the use of a centralized/coordinated control mechanism.
- Some of the major roadblocks towards widespread deployment of CoMP in wireless networks include insufficient backhaul, imperfect CSI, and clock synchronization [70]. The limited backhaul issue is addressed by quantizing the CSI and data signals or reducing the number of connected users, which leads to significantly diminished throughput, increased end-to-end latency, and lower user density [108]. While optical technology is extensively used for backhaul, it may not scale with the expected densification of future networks. This has led to a discussion around the usage of mmWave for integrated backhaul/fronthaul and access operation [109]. However, in this (especially self-backhauling) case, RRM becomes critical necessitating the development of flexible and adaptive resource usage methods.

VII. CONCLUSION

5G was characterized by the introduction of diverse services, applications, and user requirements. The trend of expanding wireless paradigms is set to continue with 6G, prompting the need for an intelligent and flexible network that can coordinate its resources to improve the QoS provided to the users. Driven by the realization that presently available techniques are unable to achieve this goal, we have proposed the generalization of CoMP concept. The aim is to expand the scope of CoMP from mere interference management at cell edges to enhancing the throughput, decreasing latency, increasing reliability, improving coverage, and providing seamless connectivity to UEs with varying requirements. To this end, a generalized CoMP framework has been discussed in this paper, which we believe will prove to be a stepping stone towards the realization of fully coordinated next-generation wireless networks.

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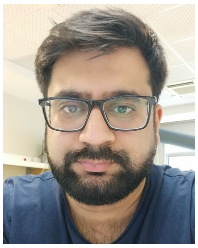
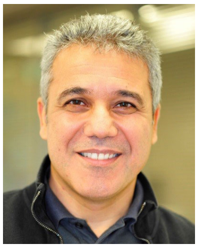


MUHAMMAD SOHAIB J. SOLAIJA (Student Member, IEEE) received the B.E. and M.Sc. degrees in electrical engineering from the National University of Science and Technology, Islamabad, Pakistan, in 2014 and 2017, respectively. He is currently pursuing the Ph.D. degree with the Communications, Signal Processing, and Networking Center (CoSiNC), Istanbul Medipol University, Turkey. He is also a member of the Communications, Signal Processing, and Networking Center (CoSiNC), Istanbul Medipol University. His research interests include interference modeling and coordinated multipoint implementation for 5G and beyond wireless systems.

HANADI SALMAN (Student Member, IEEE) received the B.S. degree in telecommunication engineering from An-Najah National University, Nablus, Palestine, in 2017. She is currently pursuing the Ph.D. degree with the Communications, Signal Processing, and Networking Center (CoSiNC), Istanbul Medipol University, Turkey. She is also a member of the Communications, Signal Processing, and Networking Center (CoSiNC), Istanbul Medipol University. Her research interests include interference mitigation, resource scheduling, and coordinated multipoint (CoMP) for 5G and beyond wireless systems.

ABUU B. KIHERO received the B.S. degree in electronics engineering from Gebze Technical University, Turkey, in 2015, and the M.S. degree in electrical, electronics and cyber systems from Istanbul Medipol University, Istanbul, Turkey, in 2018, where he is currently pursuing the Ph.D. degree in wireless communication technologies. He is also working as a Research Assistant with the Communication, Signal Processing and Networking Center (CoSiNC). His research interests include wireless channel modeling and emulation, interference modeling, and coordinated multipoint (CoMP) for 5G and beyond wireless systems.

MEHMET IZZET SAĞLAM received the B.S. degree in electrical and electronics engineering from Çukurova University, in 2001, and the M.S. and Ph.D. degrees in wireless communication from Istanbul Technical University, in 2003 and 2018, respectively, and the E.M.B.A. degree from Yıldız Technical University. He is currently a Researcher and a 3GPP RAN WG2 Delegate at Turkcell Research and Development. His current research interests include radio resource management of wireless systems and non-terrestrial networks.



HÜSEYIN ARSLAN (Fellow, IEEE) received the B.S. degree from Middle East Technical University (METU), Ankara, Turkey, in 1992, and the M.S. and Ph.D. degrees from Southern Methodist University (SMU), Dallas, TX, USA, in 1994 and 1998, respectively.

From January 1998 to August 2002, he was with the Research Group of Ericsson, where he was involved with several projects related to 2G and 3G wireless communication systems. Since August 2002, he has been with the Department of Electrical Engineering, University of South Florida, where he is currently a Professor. In December 2013, he joined Istanbul Medipol University, to found the Engineering College, where he has worked as the Dean of the School of Engineering and Natural Sciences. In addition, he has worked as a part-time Consultant for various companies and institutions, including Anritsu Company and the Scientific and Technological Research Council of Turkey. He has been collaborating extensively with key national and international industrial partners and his research has generated significant interest in companies, such as InterDigital, Anritsu, NTT DoCoMo, Raytheon, Honeywell, Keysight Technologies. Collaborations and feedback from industry partners has significantly influenced his research. In addition to his research activities, he has also contributed to wireless communication education. He has integrated the outcomes of his research into education which led him to develop a number of courses at the University of South Florida. He has developed a unique Wireless Systems Laboratory course (funded by the National Science Foundation and Keysight Technologies), where he was able to teach not only the theory but also the practical aspects of wireless communication system with the most contemporary test and measurement equipment. He conducts research in wireless systems, with emphasis on the physical and medium access layers of communications. His current research interests include 5G and beyond radio access technologies, physical layer security, interference management (avoidance, awareness, and cancellation), cognitive radio, multi-carrier wireless technologies (beyond OFDM), dynamic spectrum access, co-existence issues, non-terrestrial communications (high altitude platforms), joint radar (sensing), and communication designs.

Dr. Arslan has served as a Technical Program Committee Member, the General Chair, the Technical Program Committee Chair, a Session and Symposium Organizer, and the Workshop Chair for several IEEE conferences. He has also served as a member for the Editorial Board for the IEEE TRANSACTIONS ON COMMUNICATIONS, the IEEE TRANSACTIONS ON COGNITIVE COMMUNICATIONS AND NETWORKING (TCCN), and several other scholarly journals by Elsevier, Hindawi, and Wiley Publishing. He is a member of the Editorial Board for the IEEE COMMUNICATIONS SURVEYS AND TUTORIALS and the *Sensors* Journal.

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