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Dynamic Federations for 6G Cell-Free Networking: Concepts and Terminology

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***Abstract*—Cell-Free networking is one of the prime candidates for 6G networks. Despite being capable of providing the 6G needs, practical limitations and considerations are often neglected in current research. In this work, we introduce the concept of federations to dynamically scale and select the best set of resources, e.g., antennas, computing and data resources, to serve a given application. Next to communication, 6G systems are expected to provide also wireless powering, positioning and sensing, further increasing the complexity of such systems. Therefore, each federation is self-managing and is distributed over the area in a cell-free manner. Next to the dynamic federations, new accompanying terminology is proposed to design cell-free systems taking into account practical limitations such as time synchronization and distributed processing. We conclude with an illustration with four federations, serving distinct applications, and introduce two new testbeds to study these architectures and concepts.**

I. Introduction

The work on 6G has just begun. That effort includes addressing challenges in achieving very high data rates, imperceptibly low latency, unrivalled dependability, and ultra low power consumption [1], [2]. Importantly, the above should be realized while prioritizing the reduction of full networks' carbon footprint. To support the variety of 6G applications, wireless access architectures are proposed, hosting a high number of distributed radios and computing resources. Cell-free networking [3], [4] provides an interesting concept to fully utilize the available capacity. While the theoretical potential of these novel architectures and networking paradigms have been recognized, many questions remain with respect to the feasibility of an actual deployment. How can such a great pool of resources get coordinated and allocated efficiently? How can both the infrastructure and the provided services be scalable? In this paper, we introduce the novel concept of *dynamic federations*, that provides a key to addressing the above challenges. Dynamic federations consist of constellations of antennas, edge computing units, data storage, and other resources, to serve a specific application (class). Moreover, we have identified the need to establish adequate terminology for the new distributed networking features, which we also introduce.

This paper is further organized as follows. In the next section, we explain how the 6G needs lead to the development of hyper-diverse connectivity platforms with distributed resources. In Section III-A the new concept of dynamic federations is proposed, and consequently novel terminology is introduced in Section III-B. An illustrative case study is elaborated in Section IV. Finally, Section V concludes this paper, inviting the R&D community to discuss and adopt the novel concepts and terminology, and pointing out some plans for future work.

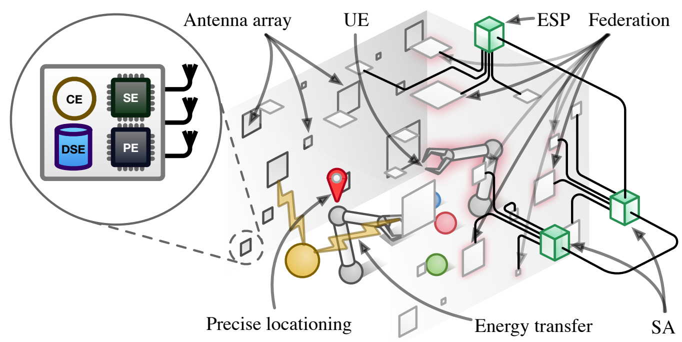

Fig. 1: Example of a cell-free system deployed in a Radioweaves setup [5]. The RadioWeaves (RW) system consists of at least one, but preferably many edge computing service points (ECSPs). This component is responsible for data aggregation and coordination of contact service points (CSPs). A CSP is the first contact point from the user equipment (UE) perspective and provides the necessary services to support user applications. A CSP can be equipped with one or several radio elements. To allow for a synchronized/coherent system, ECSP can act as a synchronization anchor to synchronize its CSPs.

II. 6G Needs and Radio Access Architectures

A. 6G needs

The 6th generation of wireless networks will need to support a plethora of services. The number of connected devices and diversity of applications to be supported is expected to further increase. Notably, this diversity leads to new requirements for 6G infrastructures that have been analyzed in recent studies [2]. These include:

1) The need to provide unprecedented capacity, better support for ultra reliability and imperceptible latency, and connecting a massive number of low power devices. This can be recognized as further raising the ambition along the three main axes considered in 5G.
2) Entirely new features to be supported by the network infrastructure. In particular, (i) many applications will rely on position information and (ii) connections to energy-neutral devices will need to be established.

In particular, novel resilient applications will rely on 'real-time' and 'real-space' interaction, whereby the physical and virtual realities share the same temporal and spatial reference frame. This necessitates a new type of radio access architecture and a paradigm shift in the wireless networking. Dense infrastructures hosting a very large number of distributed radios and computational resources bear a great potential. Such systems can offer ample diversity, solid redundancy, and proximity that can increase the link energy efficiency with orders of magnitude [6]. Distributed computation and storage can also provide nearby data processing and reduction. Many have introduced technologies that can provide the distributed infrastructure and resources, as discussed below.

B. Next-Generation Radio Access Architectures

The envisioned radio access systems will need to support extreme data rates, imperceptibly low latency, dependability on par with wired networks, low-power usage, wireless energy transfer for energy neutral devices, and precise positioning [2].

Several radio access concepts to address these new requirements are proposed in literature. For instance, reflective intelligent surface (RIS), where a large two-dimensional array consisting of large number of reflective elements is used to reflect signals to a desired location. This effectively allows controlling the wireless environment. Two implementations of RIS are proposed: RIS-aided wireless communications (RAWC) [7] and RIS-based information transmission (RBIT) [8]. The former uses passive reflectors to do interference suppression and signal steering, while the latter acts as a backscatter where the signals are modulated by the RIS array. Another approach is to further extend the concept of distributed massive MIMO to the cell-free case. In cell-free (CF) massive MIMO, a set of geographically distributed antennas jointly serve a number of users. There are no cell boundaries because all access points (APs), equipped with one or multiple antennas, are connected to a central processing unit (CPU) coordinating the system. This approach is impractical to deploy in real scenarios. A special case of a cell-free system is large intelligent surface (LIS) [9], where a large set of active antennas are densely distributed throughout a three-dimensional space. Where in CF the antennas are geographically distributed, in LIS large panels of resources are encapsulating the users. The antennas are managed in a distributed and cell-free manner, i.e., all resources in the network can be used to provide a given service. Ongoing LIS research [5] is aimed at geographically constrained spaces, e.g., sports arenas or factories. However, the concept itself allows for much larger networks where users can seamlessly move around in the infrastructure, such as in a city, without requiring the hand-overs as in non-cell-free systems.

The systems described above all focus on wireless communication, however, 6G will also support, among others, precise positioning services [9] and wireless energy transfer [10], supporting energy-neutral Internet of Things (IoT) devices [11]. This is the emphasis of this work. A system architecture, having these new services in mind, is RadioWeaves [12], [13] and is further elaborated in the following section.

III. Dynamic Federations: Concepts for 6G Cell-Free Networking

A. Concepts

As discussed in Section II-A, a further evolution of current network architectures will not be able to support the anticipated requirements for 6G, therefore necessitating novel terminology and concepts. The currently studied CF systems will need to be constrained in order to allow practical deployments. For example, the notion of one central processing unit and not having cells will become impractical.

Due to the rich set of diverse services, the set of resources used, e.g., processing and radio elements, are tailored to the particular application. This means that the wireless access infrastructure needs to allocate resources to specific applications with different requirements. For instance, for wireless power transfer, charging resources located close to the intended device will yield the highest efficiency. In contrast, in XR applications the mobility of the user's body in space and the head movement, requires a high spatial diversity of the antenna resources to mitigate outage and peaks in latency. This demonstrates the need for grouping of resources in a cell-free context in a dynamic manner, i.e., in both the temporal and spatial domain. In this work, we introduce the term *federation(s)* to denote the group of resources which jointly serve a given application. In the next part, the terminology is introduced, which is required in order to design these RW systems taking practical implications and 6G needs into account.

B. Terminology

Next-generation networks are required to shift from supporting only communication to also provide sensing, positioning and wireless power transfer [13]. This entails that several additional resources need to be embedded in the core functionality of the architecture. This, next to the concept of dynamic federations, requires a specific set of terminology in order to devise such systems in practice. In this paper, we distinguish logical entities and physical elements. The latter denotes hardware elements present in the infrastructure to support, e.g., wireless charging. These hardware resources can be logically mapped to entities to form the RW infrastructure and contact points for the users. An example of such an implementation is shown in Fig. 1. The physical and logical structure, including its hierarchical components, are depicted in Fig. 2. The newly introduced terms are described as generally as possible to not impose any constraints on the implementation of these systems.

1) Logical Entities: The network consists of several logical components, elaborated in Table I. The first entity seen from the perspective of the UE is the *contact service point*. This logical service point allows to power the device wired or wirelessly, provide wireless communication or could host other elements. Several CSPs are connected to one or more ECSPs. The ECSP can have a dedicated connection to the back-haul and other ECSPs. The task of the ECSP is to provide dedicated computing resources used for collective tasks such as, e.g., coherent channel-matched beamforming. Also, this entity can host several hardware elements besides processing/memory.

As not all CSPs will contribute equally to all services, the notion of a federation is introduced. During the operation, federations will be orchestrated depending on the served UEs and their application classes, the propagation environment, and the load on the CSPs. A federation is a collection of CSPs jointly serving one or multiple UEs. A federation is typically coordinated by an ECSP acting as the federation anchor. Often, federations will consist of CSPs located closely together, but this is not mandated, nor desired in some cases.

2) Physical Elements: The logical components consist of several physical elements. As in a RW infrastructure the network provides not only communication but also positioning and power transfer, the service points consist of more than only radio elements. All physical components are summarized in Table I. An example of the (optional) physical components hosted on a CSP is shown in Fig. 2.

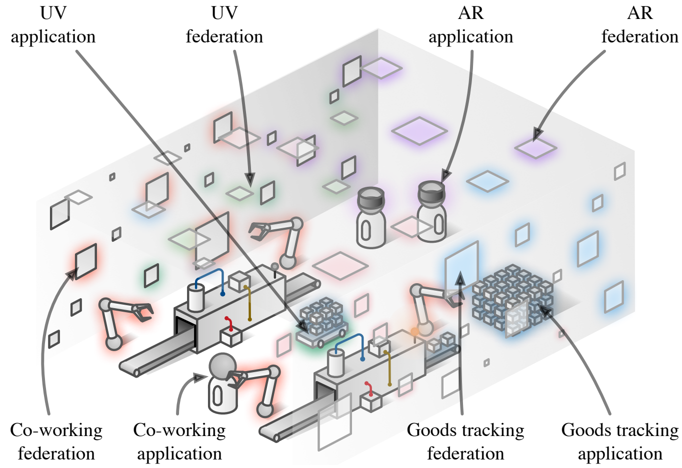

Fig. 3: An example RW deployment in a smart factory, with federations and their served devices color coded. The four applications are augmented reality (AR) for professional applications (purple), tracking of robots and unmanned vehicles (UVs) (green), tracking of goods and real-time inventory (blue), and human-robot co-working (red).

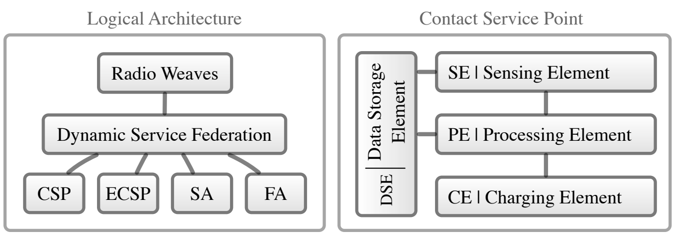

Fig. 2: Physical and logical architecture of the RW setup. The physical architecture depicts an example implementation of a CSP including data storage, sensing, processing, charging and radio elements.

IV. Illustration

Fig. 3 shows an example deployment of RadioWeaves in a smart factory, with four federations, shown in different colors. RadioWeaves CSPs are deployed throughout the production hall on the walls and ceiling, and are dynamically assigned to federations to serve the devices and their running applications that are present at any given time. The constellation of CSPs assigned to each federation is tailored to the particular application's requirements.

In Fig. 3, there are currently four different applications running, taken from the use cases presented in [1]. These are AR for professional applications (shown in purple), tracking of robots and UVs (green), tracking of goods and real-time inventory (blue), and human-robot co-working (red). Each application is served by a federation, with its CSPs shown in the same color as the application.

For the AR for professional applications use case, human workers wear energy-neutral AR goggles, which display digital information overlaid on the physical area in which they are working. As described in [1], using energy-neutral devices allows the goggles to be extremely light and thus comfortable to wear, but it increases the requirements on the infrastructure, which must transmit uncompressed video to the goggles as they lack the processing capability to decode a compressed video stream. This means that this application requires an extremely high data rate (potentially up to $3\,\mathrm{Gbps}$ [1]), as well as very low latency to prevent motion sickness. The goggle also need to be powered via wireless power transfer from the serving federation. To meet these requirements, the federation thus consists of a cluster of CSPs located on the wall and ceiling close to the user devices. The close proximity of the CSPs gives a good link budget both for communication and wireless power transfer, and the short distances between CSPs keeps the latency low.

Meanwhile, for the UV tracking use case, one of the biggest challenges is mobility. Tracking of the UV also requires low latency, high reliability, and a relatively high data rate. To serve this application, we again show a cluster of nearby CSPs, but in order to account for the UVs mobility, the federation is adapted as the UV moves. Some CSPs are not currently serving the UV but are standing by to join the federation as it is predicted the UV will move in their direction. This dynamic adaptation of the federation as it "follows" the robot around the factory floor ensures a consistently good channel even as the robot passes objects that may cause shadowing, while also allowing the federation's panels to be physically close to each other to provide low latency communications.

In the tracking of goods use case, the requirements on latency, data rate, and reliability are significantly relaxed, but instead positioning accuracy becomes the most important requirement as the items to be tracked move around the production hall. A key ingredient in providing high-accuracy positioning is aperture size, and so for this application the federation is assigned panels spread out over the deployment area. The spatial diversity thus provided also ensures goods can be located and the tracking devices communicated with anywhere in the production hall.

TABLE I: Logical Entities and Physical Elements

	Name	Abbreviation	Description
Logical Entities	RadioWeaves	RW	Wireless access infrastructure consisting of a fabric of distributed radio, computing, and storage resources.
	Contact service point	CSP	Integrates local computation and storage resources, and provides at least communication, sensing or charging functionality. It is the first contact point as seen from the UE and takes the role of an anchor in the context of position related applications.
	Edge computing service point	ECSP	Shared compute resources integrated in the RW that can support applications in need of substantial compute power and/or connection to the back-haul or other RW infrastructures.
	Federation	-	(Temporary) set of cooperating resources in the RW, working in unison, that could be more or less synchronized, and including at least CSPs and typically a synchronization anchor, and potentially edge processing unit(s), established to serve a cluster of devices and/or application(s).
	Synchronization anchor	SA	Logical function flexibly located attributed to a certain CSP to serve as a synchronization reference for a set of cooperating CSPs for some period.
	Federation anchor	FA	The FA is responsible to orchestrate and to coordinate a federation. This task will be primarily performed by an ECSP.
	Energy neutral device(s)	EN-device(s)	EN devices are a specific subset of UEs, housing dedicated circuitry for energy harvesting. Their main characteristic is that they are passive devices, i.e., they do not have their own power supply. All power they use for operation is harvested from incident EM fields. From a perspective of EM fields, they act as a power sink, as opposed to devices that have some internal power supply. EN devices rely on the WPT capabilities of the infrastructure for power provisioning. In contrast to conventional networks, RW inherently supports EN devices, requiring dedicated protocols and technologies to do so. This includes both energy harvesting techniques with intentional sources (i.e., WPT) and with unintentional sources (i.e., ambient energy harvesting)
Physical Elements	Sensing Element		Unit integrated in a CSP that can sense signals in the environment via radio channels or other media, e.g., a camera.
	Data Storage Element		Memory resource integrated in a CSP.
	Processing Element		Local computational resources integrated in a CSP.
	Charging Element		Functionality integrated in a CSP that can efficiently charge devices in the environment, e.g., electromagnetic via antennas or inductive through coils.
	Radio Element		Transmit/receive units, most often including an antenna, that can serve to exchange data or charge devices using electromagnetic waves.
	X-haul		It interconnects CSPs locally (front-haul) and also provides access to remote network and cloud resources (back-haul). It can comprise both wired (including optical fibers connections) and wireless segments. In contrast to conventional networks, in RW, no clear distinction can be made between the front- and back-haul. The X-haul, thus, comprises a mix of the two.

Finally, for the human-robot co-working use case, we again see a dense cluster of CSPs located close to the user devices. As in the AR use case, this provided good data rates, high reliability, and low latency. This use case also does not require wireless power transfer, as it does not employ energy-neutral devices. This simplifies initial access for the devices because the devices themselves can actively contact the infrastructure, rather than needing to receive sufficient power to establish initial contact before their position can be determined. This, combined with a somewhat lower data rate compared with the AR use case, means that fewer CSPs are needed per user for the human-robot co-working federation.

V. Conclusion and future work

To support the challenging 6G use cases that are emerging, a distributed, cell-free architecture will be needed, if not universally then at least in specific application domains with dense deployments. We propose the introduction of dynamic federations, consisting of constellations of antennas, edge computing units, data storage, and other resources, to serve specific applications or application classes. Each federation can be distributed throughout the deployment area in a cell-free manner, and internally manages itself, simplifying orchestration in such a complex system. We have developed an accompanying terminology, with definitions for physical and logical entities, to describe this type of architecture and its federations. We invite the research and development community to discuss, further develop, and adopt both the federation concept and the terminology for distributed, cell-free 6G systems.

We plan to bring such an architecture, along with dynamic federation orchestration, into reality by implementing them in two testbeds, located at KU Leuven and Lund University. The KU Leuven testbed, Techtile [13], was inaugurated in October 2021 and already has the physical infrastructure in place, but work is ongoing on the software to run the testbed. Techtile consists of a room built with 140 modular panels, each of which contains software-defined radios, edge computing units, and sensors. The Lund University testbed is scheduled to become operational in mid-2023 and will consist of a number of Xilinx UltraScale Plus radio frequency system-on-chip devices, each of which contain 16 antenna elements, along with X-haul connectivity between them and co-located edge computing resources. With these two testbeds, we will be able to implement the federation concept and test its performance in real application scenarios.

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