Hybrid Radio Resource Management for 6G Subnetwork Crowds

Gilberto Berardinelli and Ramoni Adeogun

The authors introduce a hybrid radio resource management framework where the decision capabilities can either happen at a global agent operating on an umbrella 6G network, or locally at each subnetwork, depending on the quality of the backhaul link, the crowd density and the local spectrum sensing capabilities.

ABSTRACT

In-X subnetworks are expected to be located at the very edge of the 6G 'network of networks' and provide localized wireless connectivity for in-vehicle, in-robot, in-body communication. By nature in-X subnetworks can lead to dense crowds, calling for efficient radio resource management techniques. In this article, we introduce a hybrid radio resource management framework where the decision capabilities can either happen at a global agent operating on an umbrella 6G network, or locally at each subnetwork, depending on the quality of the backhaul link, the crowd density and the local spectrum sensing capabilities. We present a possible application of the proposed framework for the problem of radio channel selection in a dense crowd. Possible research directions leveraging the proposed framework are also described.

INTRODUCTION

The pervasiveness of wireless in everyday life is expected to take a further leap with the coming sixth generation (6G) radio technology, whose vision is currently been built by industry and academia. There is a general consensus that 6G is expected to take the form of a "network of networks," where wireless networks of different type and operational range are to be seamlessly integrated [1].

In-X subnetworks are expected to be located at the very edge of such "network of networks," supporting localized yet demanding services in terms of data rate, latency, or reliability — including life critical services [2]. For example, industrial in-X subnetworks can be installed inside a robot or a production module and replace the wired connectivity for time critical applications. In-X subnetworks can be also installed in vehicles and replace automotive Ethernet to wirelessly support engine, brake control, as well as automated assisted driving operations. In-body subnetworks can be used for control of vital functions, e.g., heartbeat control via a wireless pacemaker, glucose control for diabetic patients, but also for consumer-type of applications, e.g. streaming from a wristwatch to an Extended Reality (XR) headset.

Subnetworks are expected to be short range and low power given the very localized services. In [2], the main characteristics of these in-X subnetworks have been presented, along with their tentative requirements. It is argued how a new technology is needed as requirements may be significantly more demanding than the ones supported by current short-range technologies. Given the support of critical services, subnetworks must be able to operate autonomously, while still benefitting from communication with an external 6G network. Figure 1 depicts pictorially in-X subnetworks, and their connection with the external network. This network can take care of several operations, including the provision of a unified authorization/authentication framework [3]. Also, the umbrella network should be capable of performing management of radio resources of the subnetworks in its coverage area, aided by subnetworks themselves that must resort to local techniques when connection to the umbrella network is unavailable or discontinuous.

A fundamental characteristic of in-X subnetworks is that, by nature, their location might be uncontrolled and therefore subnetworks may spontaneously become very dense. This can be the case of subnetworks installed in humans attending crowded events or walking in a highly populated area, or vehicles in a congested road. In that respect, the concept of *deployment* as considered in wireless networks, is inappropriate for in-X subnetworks and one should rather refer to subnetwork *crowds* as situations where large agglomerates of subnetworks are dynamically created in a spontaneous manner.

Spontaneous subnetwork crowds lead to significant challenges to the support of demanding services/applications, due to possibly cumbersome and time-varying interference levels. Radio resource management can be affected by the limited environment visibility of each subnetwork, as well as the limited communication capabilities with the umbrella network. In this article, we present a novel hybrid framework for radio resource management of subnetwork crowds, where radio control capabilities are distributed between umbrella network and local subnetworks depending on the quality of the backhaul connection, battery status of the subnetworks, crowd density. The main novelty of the framework lies in the need of managing radio resources of entities — subnetworks — that can be only intermittently connected to the network, while being able to perform decisions also autonomously.

We first recall the main characteristics of in-X subnetworks, followed by a description of the hybrid resource management framework. We then present an example of application of the framework for the problem of frequency channel selection and highlight future research directions.

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The authors are with Aalborg University, Denmark.

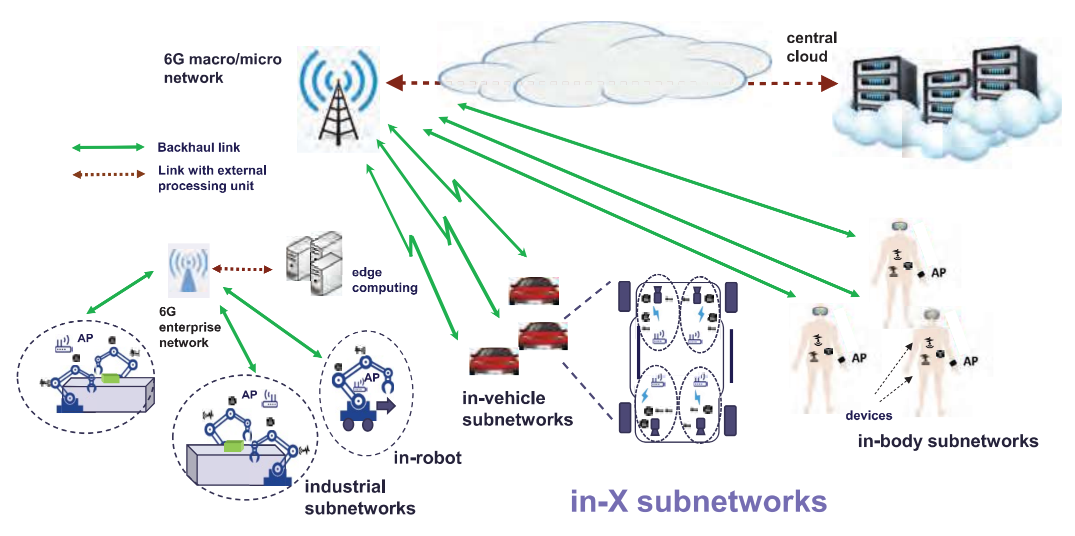

FIGURE 1. In-X subnetworks and their connection to external 6G network.

Managing radio resources in spontaneous subnetwork crowds is challenging due to their potential high density, mobility, and therefore possibly cumbersome and time-varying interference characteristics.

IN-X SUBNETWORKS

In-X subnetworks are meant to provide highly localized connectivity in specific entities where demanding services are needed (i.e., robots, production modules, vehicles, humans). A general overview of the possible in-X subnetwork scenarios, use cases and applications is given in [2]. Particularly challenging is the in-body subnetwork case, that can include both healthcare and consumer type of applications. A subnetwork is installed in a human body and consists of a set of devices such as sensors, actuators, or even XR glasses and smart watches, and an access point (AP) which controls the operations of the devices. Healthcare applications can be characterized by low data rate, non-strictly limited latencies, but extremely high reliability, while consumer applications (e.g., video streaming from a wristband to XR glasses) require high data rates.

Subnetworks may operate over diverse spectrum regions, ranging from below 10 GHz till sub-THz bands. Lower frequencies benefit from robustness to blockage but suffer from limited spectrum availability, while higher bands may suffer from increased penetration losses. We foresee the possibility of opening new license-free spectrum regions dedicated to subnetworks (with potentially new regulations for medium access), easing mobility across countries as roaming agreements are not required.

Air interface components can inherit from the broad knowledge from previous radio generation design. Orthogonal frequency division multiplexing (OFDM) is advocated as a suited waveform given its cost-efficient capability of handling multipath. Subnetworks will operate as scheduled systems where radio resources are orthogonally allocated to the served devices, to avoid intra-cell interference. High data rate services can exploit features such as link adaptation and hybrid automatic repeat request (HARQ), while low latency services should rather rely on conservative modulation and coding schemes, channel hopping combined with blind packet repetitions for avoiding delays associated to acknowledged transmissions. We refer to [2, 5] for a thorough description of the envisioned physical and medium access control features in subnetworks. Such techniques can provide a tier of protection with respect to external interference, but dedicated radio resource management actions might be needed to support challenging requirements.

HYBRID RADIO RESOURCE MANAGEMENT FRAMEWORK

Subnetworks must be able by default to manage their radio resources autonomously, given the need to support services that may not be interrupted at any time. Managing radio resources in spontaneous subnetwork crowds is challenging due to their potential high density, mobility, and therefore possibly cumbersome and time-varying interference characteristics. It is our hypothesis that, in case subnetworks are in the coverage area of a larger 6G network, the latter can be exploited for improving the quality of the radio resource management. Such network can be an enterprise, a micro or a macro cellular network depending on the specific scenario, connected to an edge computing center or central cloud with large processing capabilities.

From the point of view of the 6G network, the subnetwork AP can act as a user equipment (UE). This means, the 6G network may have direct visibility of the subnetwork APs, but not of their served devices, whose connection remains local. With reference to the current 5G architecture, this corresponds to the realization of Uu and PC5 interfaces introduced for device-to-device communication [6].

Radio resources to be managed can be very diverse. In [5], we have argued that the overall spectrum available for subnetworks can be divided in frequency channels, and subnetworks can select their operational channel for the sake of reducing mutual interference. Other resources can include transmit power, and medium access policy (e.g., number of channel hops/repetitions).

GLOBAL AND LOCAL AGENTS

The umbrella 6G network can take care of selecting the policy to be used by the subnetworks, or even the actions to be taken. We refer to a policy to denote the heuristic or data-driven algorithm for radio resource management, and to the action as the operation to be taken at a certain time according to a given policy selected earlier

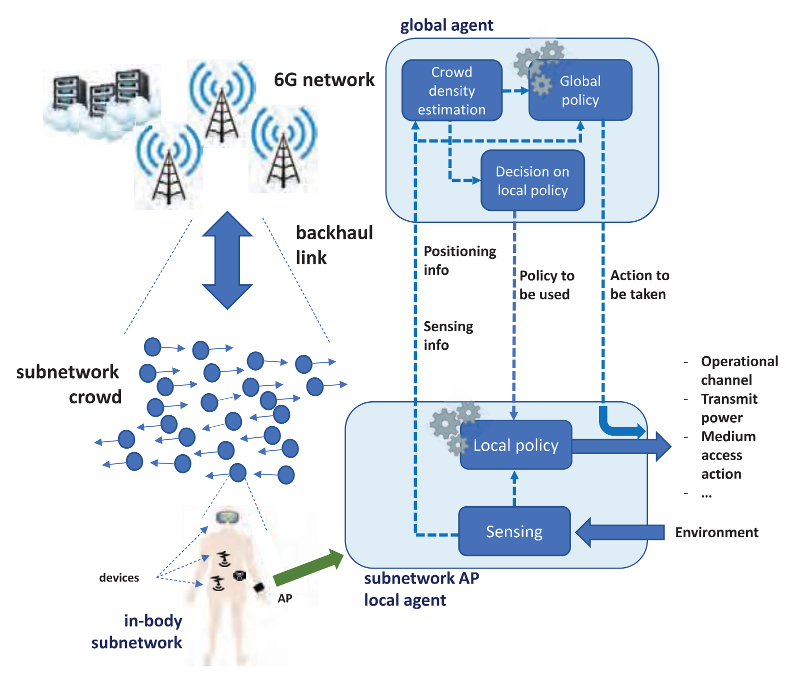

FIGURE 2. Hybrid radio resource management framework.

(e.g., switching to a new radio channel, setting a different power level, adjusting the number of packet repetitions, etc.). Policies can be local in case they can be implemented at each subnetwork AP as they only require local information, or can be global, in case they are implemented at the umbrella 6G network.

The umbrella network is then equipped with a global agent able to exploit the information obtained from the subnetworks' APs for deciding on policy and/or action, while the AP in each subnetwork is equipped with a local agent that can perform decisions locally.

This is pictorially depicted in Fig. 2. Note that the global agent can run at the gNB, in a connected edge/cloud server, or a combination of those, depending on the specific deployment. In this respect, the proposed framework can be adapted to the modern architectural solutions with distributed computation capabilities.

Subnetwork APs can communicate to the 6G network via a *backhaul* link, which we assume to be out of band, i.e., to operate over different frequencies than the ones used by subnetworks for their local communication. The 6G network can collect diverse type of information from the subnetworks via the backhaul link including:

- Positioning information; this can be in the form of GPS coordinates explicitly transmitted by the subnetwork APs, whose accuracy may be limited by the typical positioning errors, especially in indoor. In an advanced implementation, no explicit information might be transmitted by the subnetwork APs, but the network can infer the approximate positioning of the subnetworks -and/or their relative position with respect to neighbor subnetworks- by using channel charting techniques [7]. Such techniques exploit the spatial correlation of the signals transmitted in the backhaul link from APs to the network and therefore only require transmission of reference signals rather than positioning coordinates.
- Sensing information; this refers to local measurements acquired by each subnetwork AP on the perceived interference levels. For example, the AP can measure the interference level in each of the frequency channels and report those to the network. Performing spectrum sensing might be energy consuming for battery driven devices, besides requiring the insertion of measurement gaps that can reduce the transmission opportunities within the subnetwork.

The 6G network can use such information for estimating the crowd density, and apply a global policy deciding on the radio resource management action to be taken by each subnetwork. However, the capacity of the backhaul link can be negatively affected by poor radio conditions and radio resource congestion in case the network is covering a very dense subnetwork crowd. Since subnetworks' APs act as UEs for the 6G networks, they can easily monitor the quality of the backhaul link, and must resort to their local radio resource management policies in case its quality is deemed to be insufficient for transmitting local radio parameters or receiving timely commands from the network.

The quality of the policy -either global or local- may depend on the amount of available information in the entity taking decisions. For example, a global policy that uses the sensing information from the individual subnetworks might outperform a policy that only uses positioning information, as it is able to exploit knowledge on the mutual interference levels. On the other side, policies based on sensing information are more energy consuming, and might affect battery life of the subnetwork APs and devices. This might be particularly problematic for in-body subnetworks, which are battery-driven.

GOAL OF THE HYBRID FRAMEWORK

The goal of an intelligent hybrid radio resource management solution for subnetwork crowds, is to efficiently exploit the support of an umbrella network -when available- for performing decisions on the policy and/or actions to be taken by each subnetwork AP such that the relevant radio performance targets (e.g., data rate, reliability) are achieved and the energy consumption in the subnetwork AP and devices is minimized, while coping with the capacity limitations of the backhaul link.

In case of a high capacity backhaul link (thanks to good coverage conditions of the umbrella network over the subnetwork APs and a limited crowd density) and good battery level at the subnetwork, the AP can perform sensing over the entire operational spectrum and transmit such information to the network, which can implement an efficient global policy and take decision on the specific action to be taken by the subnetwork AP. In case subnetworks are not capable of performing spectrum sensing and transmit this information to the umbrella network, the latter can only rely on locally acquired information on the density of the subnetwork crowd, or eventually on the positioning information. In this respect, the network might not be able to apply the best performing global policy. Alternatively, the network may instruct the APs to use a specific local policy rather than pushing specific actions. This means, the contribution of the external network may be limited to the policy selection, while the actions are selected locally at each subnetwork for that given policy. Also, it is reasonable to assume that subnetwork APs can always revert to local policies even in case the commands by the 6G network are received but are deemed to be obsolete or ineffective.

Observe that, the hybrid scheme presented here refers to the actions to be taken for mitigating external interference at each subnetwork. We assume that the subnetwork AP still performs locally operations such as scheduling and link adaptation for its served devices, depending on their requirements and traffic type.

SUBNETWORKS AND HETEROGENEOUS NETWORKS

Subnetworks can be seen as a further leap of the concept of heterogeneous networks (HetNets) as they are located at very edge of the 6G "network of networks." Traditionally, radio resource management in HetNets deals with problems such as spectrum allocation (cross-tier and co-tier), user and multi-cell association, and load balancing across diverse networks (e.g., macro, micro, femtocells) [8]. Subnetworks are instead expected to operate over a different band than the umbrella network, such that there is no cross-tier interference. Also, critical communication in subnetworks is to the largest extent only local, for e.g., control applications, eliminating the need of load balancing across networks. Further, no mobility of devices from one subnetwork to another is expected, as devices are expected to be allocated to the same subnetwork for their lifetime.

Challenges of the hybrid framework here presented are instead of a different nature. Subnetworks are indeed by default independent entities, though benefitting from decision-making capabilities of the external network when available. Backhaul quality and behavior play then a pivotal role in the problem formulation and solution design. Moreover, characteristics of subnetwork crowds (potential high density, mobility) make interference management more challenging than in HetNets with lower densities and static deployments, but also offers new opportunities for exploiting the global agent capabilities. These aspects will be further discussed in Section V.

EXAMPLE OF APPLICATION OF THE PROPOSED FRAMEWORK

We highlight a simple application of the proposed framework for the problem of channel allocation in a dense subnetwork crowd. Each subnetwork AP must allocate the operational channel for communicating with its devices such that an outage data rate metric is maximized in spite of interference from neighbors. For the sake of simplicity, we restrict the analysis to channel selection only and we assume the subnetworks to operate at a fixed power, and in full buffer mode. We consider global policies implemented at the 6G network, and local policies implemented at each AP. We stick here to heuristic policies, though machine learning can play a major role in the solution space, as will be elaborated in Section V.

SELECTED HEURISTIC POLICIES

Since the channel allocation problem is known to be NP-hard, we consider the following global policies:

- Simulated annealing. This is probabilistic technique aiming at heuristically approaching the global optimum of a given function. Similarly to [9], we apply the Metropolis algorithm starting from an initial random channel allocation and minimizing a cost function related to the average inverse signal-to-interference plus noise ratio (SINR) via iterative perturbation of the channel allocation vector. Simulated annealing requires at the 6G network information from each AP on the measured interference coupling with neighbor subnetworks.
- Graph coloring. We assume here that the 6G network is aware of the position of the subnetworks in its coverage area and can build a proximity graph where each vertex denotes a subnetwork and edges connect subnetworks to the $N - 1$ closest subnetworks, with N denoting the number of channels. Then, a greedy coloring procedure is applied for the sake of assigning a color (i.e., a channel) to each subnetwork such that none of the vertexes connected by an edge share the same channel [10]. We adopt an improper coloring correction in case a larger number of colors than the number of channels is needed to color the graph. Differently from simulated annealing, the graph coloring policy does not require subnetworks to perform spectrum sensing, but only implicit or explicit signaling of their location; it is therefore a low energy solution.

Computational complexity of simulated annealing depends on the number of iterations needed for convergence of the Metropolis algorithm, with polynomial increase with the crowd size. The greedy coloring procedure has quadratic complexity. The used local policies are the following:

- Greedy selection. The subnetwork AP measures the interference in each of the channels and select the channel with the lowest interference temperature.
- Random selection. It is the simplest policy, where the subnetwork AP selects randomly the operational channel. It is a minimum energy policy as does not require any interference sensing.

As mentioned in the previous section, the application of global policies is conditioned to the quality of the backhaul link, while the usage of a sensing-based policy (either local or global) depends on the battery conditions of the APs or devices. We can therefore exemplify the possible application of the presented policies by the hybrid framework as in Table 1.

		Backhaul quality	
		Sufficient	**Insufficient**
Battery level	**Sufficient**	Simulated annealing **Policy type:** global	Greedy selection **Policy type:** local
		Input: spectrum sensing information from subnetwork AP	
	Insufficient	Graph coloring **Policy type:** global	Random selection **Policy type:** local
		Input: explicit/implicit positioning information from subnetwork AP	**Input:** none

TABLE 1. Policies to be used in the presented example.

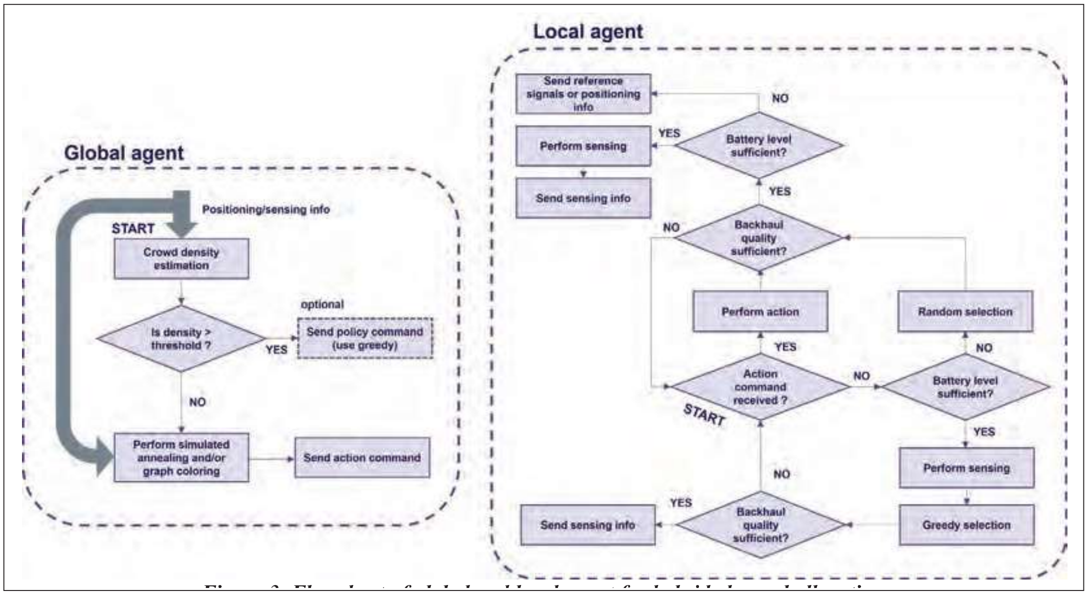

FIGURE 3. Flowchart of global and local agent for hybrid channel allocation.

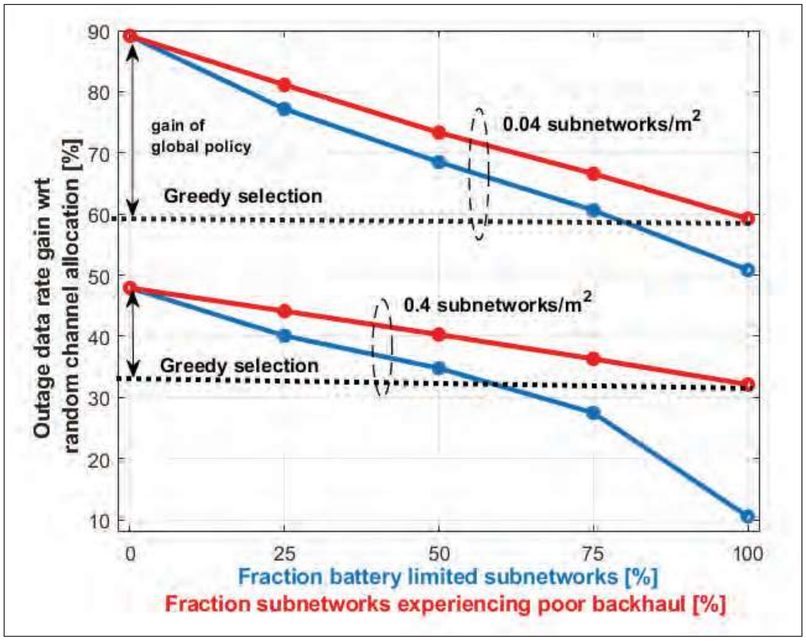

FIGURE 4. Outage data rate gain of hybrid solutions for channel allocation with respect to random allocation.

Backhaul link quality is deemed to be insufficient if the estimated delay for reporting information and receiving commands, is higher than the required response time for radio resource management. In this case, the 6G network can simply recommend the policy to be used -either greedy selection or random selection.

Note that conditions in a subnetwork crowd can be heterogeneous, and part of the subnetworks can be in good coverage of the umbrella network, while for others the backhaul link can be obstructed. Similarly, some of the subnetwork APs might have good battery level to afford performing sensing, while others do not. Battery level can be deemed insufficient if estimated not to be able to perform sensing at the same discharge profile, until the next expected charging action. Policies to be used can then be a combination of the ones presented above.

Figure 3 displays a possible flowchart for both global and local agents, considering the policies in the presented example. The global agent can easily estimate the density of subnetworks in its coverage area (thanks to the explicit positioning or the amount of received reference signals) and decide whether performing a global policy or instructing subnetworks to use a local policy by comparing it with a subnetwork density threshold whose value may depend on specific applications and scenarios. The local agent can receive the command from the network to perform a specific action or can simply use a local policy depending on its battery level.

SIMULATION ASSUMPTIONS AND RESULTS

We simulate here the effectiveness of the hybrid framework considering a subnetwork crowd deployed in a 50x50 m2 area. Each subnetwork is modeled as a circle of radius 0.5 m, where the AP is located at the center and a single device is located at a random distance between 0.3 and 0.5 m from the APs. We assume an overall bandwidth of 100 MHz centered at a carrier frequency of 6 GHz and divided in 4 channels, and a log normal shadowing with a 3 dB standard deviation, as assumed in e.g., typical outdoor environments. We focus on the downlink only assuming a 0 dBm transmit power, omnidirectional antennas, and a single served device in full buffer mode. Note that, for short range communication, the transmission direction has no major impact on the performance since balanced uplink and downlink power is expected [5].

In Fig. 4, we show performance in terms of outage data rate (calculated at the 0.001-percentile of the empirical data rate distribution) gain with respect to random channel allocation, being the simplest policy that does not require any backhaul communication neither additional energy consumption for sensing. Two different crowd densities (100 subnetworks, corresponding to a density of 0.04 subnetworks/m^2, and 1000 subnetworks, corresponding to a density of 0.4 subnetworks/m^2) are considered. Rates are estimated via Shannon mapping of the perceived SINR upon channel allocation. Results are calculated over multiple snapshots for a total of 1 million samples and are shown as a function of:

- Fraction of battery limited subnetworks, referring to those subnetworks whose battery level is insufficient for performing sensing; we assume here good backhaul conditions for all subnetworks, and we therefore refer to the first column in Table 1.
- Fraction of subnetworks experiencing insufficient backhaul quality, and therefore unable of transmitting sensing or positioning information to the 6G network; we assume here good battery level conditions for all subnetworks, and we therefore refer to the first row in Table 1.

The gains achieved with the local greedy selection policy are also shown as a reference. For the simulated annealing policy, 500 iterations are needed for convergence in case of 100 subnetworks, and 2000 iterations for 1000 subnetworks. The achievable outage rates with random allocation are in the order of 30 Mb/s and 13 Mb/s for 100 and 1000 subnetworks, respectively.

In the case of 0 percent battery limited subnetworks, the global policy is applied to all subnetworks, and offers an outage data rate gain of around 90 percent with respect to local random selection, and a relative gain of 30 percent with respect to local greedy selection in the case of a low-density crowd. For the higher density crowd, these gains are reduced to around 47 percent and 15 percent, respectively, due to larger likelihood of having closer interferers operating in the same channel.

For larger fractions of battery limited subnetworks (blue curves), the global policy exploits a combination of graph coloring for those subnetworks for which no sensing measurements are obtained, and simulated annealing for the subnetworks for which sensing information is obtained. As expected, gains are decreasing. The 100 percent fraction corresponds to the case where distance-based graph coloring is applied for all subnetworks, and relative gains are lower than the ones with greedy selection due to the lack of sensing information. This suggests that, in case sensing information cannot be sent to the 6G network, subnetworks with good battery level should use local policies rather than relying on a global policy with limited information.

In case of good battery level for all subnetworks and fraction of subnetworks experiencing poor backhaul larger than 0 percent (red curves), the global agent performs simulated annealing allocation for those subnetworks for which it can retrieve the interference sensing information, while the other subnetworks performs a local greedy policy. The case of 100 percent fraction of poor backhaul subnetworks obviously corresponds to the case in which all subnetworks perform greedy allocation. The relative losses with respect to the ideal conditions (high capacity backhaul and high battery level for all subnetworks) are then reduced compared to the case of large fraction of battery limited subnetworks, suggesting that the capability of performing local sensing can be more important than the presence of a high capacity backhaul link.

It is worth to mention that the absolute gains obtained in this example may vary with more complex policies and different radio resource management problems, but the identified trends are expected to hold. In general, results show that performance gains tend to decrease with high density crowds. Note that high density crowds are more likely to experience poor quality of the backhaul link due to radio resource congestion for measurement reports. Also, complexity of the global policy increases significantly with the number of subnetworks. In this respect, a ~15 percent gain of a global policy may not justify its application, and the global agent may instruct to use local policies (e.g., greedy) for a sufficiently high crowd density. In practice, the 6G network should be able to estimate the tradeoff between capacity of the backhaul link, computational cost of the global policy, and expected performance for a given crowd before opting for a global policy or simply recommending a local one.

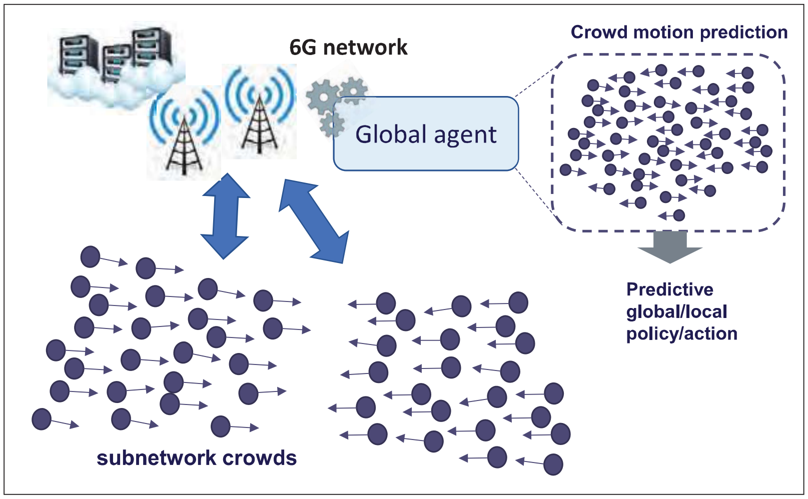

FIGURE 5. Global agent learning motion pattern of subnetwork crowds and performing predictive policies/actions.

RESEARCH OPPORTUNITIES

The framework here presented is to be seen as a general container of novel solutions to be designed by academia and industrial researchers working in the context of radio resource management for such subnetwork crowds.

Subnetworks — and in particular subnetwork crowds — represent a novelty also from a radio channel characterization and modelling perspective. Both the desired link and the interfering radio links deserve a dedicated characterization, as they may have a very different behavior. For example, the in-body radio link (especially for healthcare applications where a wristband AP must communicate with implants or patches) is different from the interfering link versus APs or devices in other subnetworks, which is affected by the external environment and possibly shadowing from other humans nearby. A proper design and evaluation of efficient local and global policies subsumes then a careful propagation modelling work.

As radio resource management problems such as power or channel allocation are known to be NP-hard, policies to be used -either local or global- can be heuristics such weighted minimum mean square error power allocation (global), open loop power control (local), or the ones presented in the above example for channel allocation. Also, data-driven machine learning methods are to be explored for hybrid radio resource management as they have the promise of outperforming the rule-based heuristics by making decisions tailored to the specific operational environment.

In this respect, graph neural networks are emerging as a promising framework for radio resource management, provided large datasets can be collected in the environments of interest [11]. Multi-agent reinforcement learning (MARL) has also a good match with the proposed hybrid framework. Known MARL solutions such as actor-critic are based on a centralized training phase where the central agent exploits global information on mutual interference relationship of the local agents, and the trained model is then used locally at each subnetwork during the exploitation phase [12]. This approach is compatible with the presence of a backhaul with limited capacity since the model can be transferred to the local agents and be only seldom updated. Also, global agents can aggregate models trained independently by the local agents in case those are equipped by machine learning capabilities, according to the federated learning paradigm [13]. An interesting research avenue, is the possibility of building machine learning models with full environmental knowledge, including mutual interference, while exploiting only minimum information (e.g., positioning of the subnetworks) at the global agent in the execution phase. This has the promise of improving the performance of global policies based on minimum information, while avoiding energy consuming spectrum sensing at the subnetworks during runtime operations. Also, in case only a limited fraction of subnetworks is able to perform spectrum sensing and report such information, the global agent may exploit variational interpolation techniques [14] to reconstruct the expected interference levels for those subnetworks for which only positioning information is available. This can improve performance with respect to pure positioning-based policies.

Another interesting opportunity is the possibility of learning the motion pattern of the subnetwork crowd. Movements of crowds follow self-organized patterns according to social force dynamics and depend on the specific location and density [15]. By using positioning information and/or locally inferred time varying spatial patterns of neighbor subnetworks, the global agent can predict the crowd motion and eventually perform proactive radio resource management decisions. For example, it can identify two subnetwork crowds that move towards each other and are expected to merge (Fig. 5), and perform more conservative decisions to the actions to be taken (or policies to be adopted by the subnetworks) such that they are ready to deal with increasing interference levels and prevent potential packet losses. This is particularly important for life-critical services where packet losses must be minimized.

CONCLUSIONS

In this article, we have introduced a general framework for hybrid radio resource management in dense in-X subnetwork crowds, where an umbrella 6G network can assist the decision on policy and/or actions to be used by the subnetworks in its coverage area for their local communication. Successful exploitation of hybrid radio resource management depends on the quality of the backhaul link and the capabilities of the subnetworks of performing spectrum sensing; subnetworks should rely on local policies in case backhaul link quality is insufficient for a prompt reporting of sensing or positioning information. We have presented a simple application of the framework for the problem of channel allocation in subnetwork crowds, highlighting that the capability of performing local sensing is more appealing than the disposal of a high quality backhaul link, especially for dense crowds. We believe the presented framework can inspire new research in the context of radio resource management for the 6G "network of networks."

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BIOGRAPHIES

GILBERTO BERARDINELLI (gb@es.aau.dk) received his Ph.D. degree from Aalborg University, Denmark, in 2010. He is currently an Associate Professor at Aalborg University. His research interests include physical layer, medium access control, and radio resource management design for beyond 5G systems.

RAMONI ADEOGUN (ra@es.aau.dk) received the Ph.D. degree from Victoria University of Wellington, New Zealand in 2015. He is currently an Associate Professor at Aalborg University. His research interests include channel characterization, machine learning and AI for communications, intelligent spectrum access, and interference management.