Dynamic Mobile Base Stations in 5G Networks – The Moving Network Paradigm

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Abstract The evolution of current wireless access networks towards 5G and beyond is characterized, among others, by the provisioning of high-bandwidth services and by the capability of serving traffic of a large number of heterogeneous devices. Among the key approaches for provisioning high capacity in such networks, a prominent role is played by network densification. However, dense deployments of many small cell base stations imply huge investments, increasing both CAPEX and OPEX for the mobile network. Additionally, densification increases the amount of over-provisioned network resources, due to variability in traffic demand over space and time. One of the most promising approaches to address these issues is the *moving network paradigm*, which exploits vehicle-mounted small cell moving base stations. This allows taking advantage of the correlation between spatio-temporal patterns of users and of vehicles, in order to create a network that flexibly and naturally densifies whenever and wherever needed by "following" users, hence reducing the need for dense deployments of static base stations. In this chapter, we review the main motivations and drivers for integrating moving base stations into future cellular access networks, and we outline the overall network architecture resulting from such integration. Furthermore, we characterize some of the main open research issues which stand in the way of the practical feasibility of the moving network paradigm. Among these are questions such as how to efficiently manage network resources in a dynamic fashion, accounting for the dynamics of service demand as well as of the moving network infrastructure; how to mitigate interference effects; how to implement mechanisms for reliable wireless mobile backhaul, for the interconnection of moving base stations to the core of the network; and how to efficiently provision Multi-access Edge Computing (MEC) services in the moving network paradigm.

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1 Introduction

Some of the main technical and economic challenges which cellular networks will have to address in the near future originate from the ever increasing amount of users and of traffic demand, particularly in urban environments. This is accompanied by an increasing dynamicity and heterogeneity of traffic demand, due to an ever changing landscape of dominant applications and services. It is estimated that by 2020 the number of mobile terminals will be three times the number of humans, generating an overall traffic of 2.3 ZB [1]. Two thirds of this traffic will terminate in wireless devices, and about half of the wireless traffic (one third of the total) in smartphones. The 5G Infrastructure Public Private Partnership (in short, 5G-PPP) established by the European Commission, together with companies and research institutions of the field, shares those extreme visions [2]. These issues are getting more acute with the transition to 5G, due to tighter requirements in terms of capacity per user (up to 1 Gbit/s for broadband users [3]) and Quality of Service (QoS) (such as the support of Ultra Reliable Low Latency Communications (URLLC) in the Tactile Internet [4]). Another key challenge for 5G is represented by the ever increasing number of users served, such as the connection of over 7 trillion wireless devices serving over 7 billion people [3], and by the service of extremely crowded environments, such as a stadium. An important contribution to such increase in traffic comes from the progressive deployment of Internet of Things (IoT) devices in urban environments, fostered by the realization of the Smart City paradigm. These paradigms rely heavily on the pervasive deployment of a large amounts of sensing, computing, and communication devices [5].

A possible way to increase the available capacity in 5G Radio Access Networks (RANs), while at the same time improving its energy efficiency, is to increase the density of Base Stations (BS), hence decreasing the mean distance of users and devices from the serving antennas. Such *network densification* is considered one of the most promising approaches to enable RANs to cope with the foreseen explosive increase in mobile data traffic of the coming years, and with the extremely dense user scenarios forecasted [6]. RAN densification requires the deployment of large numbers of small cells in those areas where the number of users, and the traffic they generate, is very high, at least for some significant portion of time. As a result of the expected growth in traffic demand, and of traffic with tight QoS requirements such as URLLC, the required BS densities that are today being forecasted in the 5G vision documents are extreme, up to hundreds per km^2 [2]. This entails large investments for BS installation and operation (consider that the cost for the installation of a urban base station is typically in the order of one hundred thousand Euro, if we include civil infrastructures [7], [8]). A big share of such operation costs would be represented by energy costs. As a consequence, a dense deployment of small cells would bring to an overall explosion of the amount of energy consumed by the wireless access network.

These downsides of network densification are exacerbated by the common practice of *overprovisioning*, i.e., of worst-case dimensioning and deployment of network resources, in order to cope with traffic peaks and with the increasing variability of traffic over time. Indeed, in an urban scenario, the number of mobile users and the level of traffic they generate has been shown to exhibit remarkable spatial and temporal variations [9], [10]. Users (humans in this case) normally move from home to work in the morning of working days, and this makes business districts crowded during working hours (i.e., approximately from 9 AM to 6 PM). In this period, Mobile Network Operators (MNOs) need the capacity of the many small cells of their dense RAN in business areas. However, after 6 PM users move out of their offices, so that the RAN capacity necessary in a business district becomes much lower, and many of the installed small cells become redundant. The opposite is true for residential areas, where capacity is necessary in the evening, so that a dense RAN layout becomes necessary then, not during working hours. In addition, medium/large urban environments are characterized by massive daily commuting, typically between residential areas and business or industrial districts. These massive migrations can take a significant amount of time, thus, fostering a huge demand for data and infotainment. Therefore, network capacity needs to be provided not only in business and residential districts, but also on the move [10]. IoT traffic is expected also to follow similar spatio-temporal patterns, as a large portion of IoT services will be more active where demand (and hence users) are [11].

Indeed, demand for local computing is also typically proportional to user density. Many IoT services have a local sensing component. Events of some significance for an IoT-based system (e.g., a road accident, a sudden medical condition on a pedestrian, or the freeing up of a parking slot) are usually more frequent when and where users concentrate. In addition, the need for computing resources (e.g., the algorithm for inferring a given medical condition, for detecting the occupancy of a parking space, or for distinguishing a road accident from a normal traffic jam) correlates positively (spatially and temporally) with user mobility patterns [12]. Additionally, much of IoT sensing is devoted to either characterizing directly human patterns, or to capture conditions and events (traffic jams, aggressions) whose frequency and distribution in space are tightly related to human location patterns [12], [13]. The support of high data rates and tight latency requirements is actually a key driver of 5G and beyond networks, in order to support such applications as autonomous coordinated driving, and *Tactile Internet* services [14]. Similarly, while infotainment service demand moves with people, computing resources used to provide those services (e.g., caching) are currently statically deployed at the edge of the network (according to the MEC paradigm [15]), thus, requiring a high degree of overprovisioning in order to cope with demand fluctuations.

In order to obtain the wireless bandwidth that is necessary to meet the forecasted explosive increase of mobile traffic, it will be necessary to have a large number of Small Cells (SCs) in business districts during working hours, in residential districts during evenings, over commuting paths at the beginning and the end of working shifts, and around stadiums during special events (not to mention city squares during protest gatherings, highway portions in the event of a traffic jam, etc.). One possibility is to deploy a dense SC coverage in all areas, switching them on and off as needed. Dynamic network management can bring substantial savings in Operational Expenditures (OPEX), especially those related to energy [16]. However, it does not alleviate the issue of the huge Capital Expenditures (CAPEX) required for ultra dense 5G SC deployment, which remains to date one of the main obstacles for the transition to 5G.

One of the possible ways of decreasing the redundancy in SC deployments is to physically move SCs from business areas to residential areas and back, so as to have the capacity of those cells where and when needed. Indeed, the idea of Moving Base Stations (MoBS) is not new, and it is already exploited in several contexts. For instance, MNOs typically employ small numbers of truck-mounted BS (the so-called *cell-on-wheels* [17]) for temporary provisioning of service in areas where service would not otherwise be available, or where additional capacity is temporarily needed, such as at large outdoor events, or in areas struck by disasters such as earthquakes or floods. Several proposals suggest drones could be used to support communications in disaster areas [18]–[20] or to quickly provide connectivity in regions which are not yet served by network infrastructure. More generally, the idea of using cars as active elements of a telecommunication network is not new [21]. Several studies in the domain of vehicular networks considered the possibility of integrating a Wi-Fi Access Point (AP) in cars, and possibly also a cellular interface, so that a vehicle can provide connectivity to the surrounding cars. For instance, it has been proposed to use mobile vehicular gateways that exploit Wi-Fi for Vehicle to Vehicle (V2V) communications and LTE for Vehicle to Infrastructure (V2I) communications [22]. The study in [23] introduced the concept of *virtual APs*, which allow extending the reach of roadside access points. A Virtual AP is a vehicle that receives a message, store it, and rebroadcast it into non-covered areas. In [24]–[26], parked vehicles were exploited, in addition to roadside units, to improve the performance of video downloads and other services towards vehicles in movement.

More recently, research has started to focus on a completely new use case for moving BS, in which large numbers of vehicle-mounted SCs are part of a wholly new architecture for dense RAN, tightly integrating static and moving infrastructure. The moving small cell BS provide additional capacity, when and where needed, to the end users of an otherwise traditional RAN. End-user terminals can thus freely and transparently transfer their services between a normal and a vehicular BS.

Among the advantages of the *moving network paradigm* is that it is amenable to implementations with dedicated BS-carrying vehicles, such as autonomous cars or drones. These vehicles can therefore be strategically positioned, enabling an planned integration of existing infrastructure. In addition, groups of moving BS can be employed to provide local service in areas where the cellular network infrastructure is (temporarily) not operational, e.g., following some natural disaster. Finally, moving BS can effectively support delay-tolerant communications, such as those involved in smart meter reading and other IoT applications. Indeed, data transfers could be scheduled when vehicles are very close to the devices, in order to minimize the power consumed by the IoT devices for transmission. First evaluations based on realistic cellular traffic reveal that a mobile base station concept is beneficial especially in highly dense scenarios, e.g., at peak hours in vehicular traffic, to provide higher throughput than a traditional fixed base station concept [27].

2 The Moving Network Paradigm

Recently, the *moving base station* concept has been introduced in [28], [29]. In these works, the communication infrastructure on board of vehicles act as relay between User Equipment (UE) and static BS. The choice of relays instead of full fledged BS simplifies the moving communication infrastructure and the network architecture, but it strongly limits the possibility of dynamically adapting the moving infrastructure to changing conditions.

The *moving network paradigm* was initially proposed in order to serve only in-vehicle users (in trains, buses, cars) [30]. Indeed, the use of an in-vehicle access point allows improving the management of handovers (through group handovers [31]–[33]) and their impact on user perceived performance. In this respect, the use of Visible Light Communication (VLC) or mmWave for in-vehicle communications is particularly interesting, as it eliminates the issue of interference between users inside the vehicle and all the other users. However, these first proposals did not consider the moving network as a paradigm for delivering service to all users.

More recently, however, the use of 4G or 5G small cells within moving and parked cars, or on drones, has been proposed to serve both indoor and outdoor users [34], [35]. Given the high complexity of a scenario with moving BS, some existing works have considered only stationary (parked) vehicles, as this provides a more stable environment for interference and capacity provisioning. While such scenarios greatly simplify the technical issues due to dynamic interference management and to the dynamic orchestration of network resources, they greatly limit the potential contribution of the moving network paradigm to flexible densification of the network, as the density of parked cars follows different, and sometimes slower dynamics than those of vehicles in transit.

Another specific declination of the moving network paradigm, which has recently drawn a considerable amount of attention, is represented by Unmanned Aerial Vehicle (UAV)-based base stations [36], [37]. The interest in these specific installations derives from the better propagation conditions with respect to vehicular or even static installations. Indeed, for mmWave communications, transmitting from a few tens of meters above the potential users might allow avoiding those obstacles which could prevent LOS communications [34]. Hence, untethered and tethered UAVs for this purpose are been proposed, and techniques for optimizing their path as a function of various QoS metrics have been proposed [36]–[39]. All these works outline a high level network architecture, and consider some of the open technical issues posed by integrating a moving infrastructure within a classical, static network architecture. One of the main challenges emerging from such first evaluations is the fact that the part of the nomadic infrastructure whose mobility can be controlled naturally requires a dynamic and adaptive management.

These initial works show that the moving network paradigm may have a potentially enormous impact on future mobile networks, bringing to redefining the possibilities of adaptive provisioning of capacity and computing. Moreover, it provides an ideal ecosystem for a resource efficient implementation of MEC services, and hence the support of services requiring extremely low latency and/or low overhead. The moving network paradigm allows reducing drastically the redundancy in the deployed MEC infrastructure, by having computing resources follow users and demand patterns across space and time.

As regards the type of vehicles that could be good candidates to carry base stations, a special role could be played by electrical cars, either private or belonging to a car-sharing fleet, since the presence of a large energy storage in the car enables the BS operation also while the car is parked and the engine is off. In such scenarios, car sharing operators could play a role similar to that of companies that manage telecom sites and towers, providing their MoBS to MNOs under a Small Cells as a Service (SCaaS) agreement. In addition, similarly to what has been witnessed in the smart grid, where solar panels belonging to end users generate electricity that is made available for all, moving base stations owned by end users might spur the rise of a new type of prosumers, providing additional capacity to MNOs for the benefit of all network users.

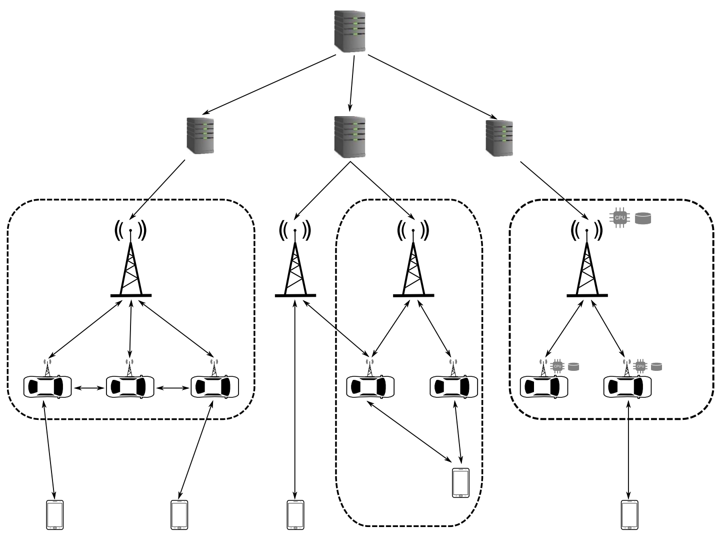

Fig. 1 Schematic description of the system architecture of a network with MoBS.

A general representation of a portion of a moving network architecture is shown in Figure 1. The urban area is covered by standard cells, defined by the deployment of fixed macro/micro BS, as we know today. In addition to this traditional coverage, vehicles carrying MoBS, either parked or driving, define a temporary dense coverage of those portions of the urban area where demand for content, connectivity and computing is higher, e.g., due to a higher concentration of broadband mobile users or of IoT devices. Such dynamic deployment of moving small cells overlaps with macro/micro cells and with static small cells in a way which is random but correlated in space and time with demand, thus helping to provide the necessary additional capacity where needed, when needed. Each BS, whether fixed or vehicle-mounted, is connected to the core network through a front/backhaul link, which can be either wired or wireless for fixed BS, but must (obviously) be wireless for MoBS. As shown in the picture, wireless backhaul links are also available between MoBS. This is extremely important to allow the creation of a wireless backhaul network, so that even if the direct link from a MoBS to the fixed network is not available (or simply overloaded), other backhaul connection opportunities are made available through neighbor MoBS. In addition, MoBS-MoBS links enable the creation of standalone networks of MoBS when the fixed network infrastructure is not working, e.g., in disaster areas, providing the basis for the provisioning of emergency communications and computing services.

3 Research Challenges

The moving network paradigm brings forward a set of research issues, which currently limit its practical feasibility and its potential benefits with respect to traditional, purely static architectures. Among these issues, we have:

- understanding to what extent the mobility of base stations is effective in bringing capacity and services where network traffic peaks;
- elaborating efficient strategies for planning and dynamic management of network resources (such as how many MoBS should be active in a given scenario and which users should be associated to each BS);
- devising techniques for interference mitigation, which minimize its deleterious effects on capacity, on service availability and connection reliability;
- designing a reliable broadband wireless mobile backhaul connecting MoBS to the core of the network; and
- elaborating mechanisms for the efficient provisioning of distributed MEC services capable of harnessing the correlation between the demand for content and computing and vehicle density.

On the one hand, the moving network paradigm is part of the general trend towards integrating ICT capabilities of vehicular systems into cellular access networks [21]. Such trend is very strong nowadays, even though concrete methodologies for effectively managing such extremely dynamic and mobile networks are currently still missing.

On the other hand, and despite the growing interest such trend is attracting, it is unclear to date to what extent and in which contexts mobile systems can actually contribute to implementing advanced connectivity and computing services with stringent QoS requirements in 5G networks and beyond. And this is mainly due to the high degree of dynamism of such a network, which is beneficial on the one hand but which also creates a number of challenging technical issues.

3.1 Potential for flexible network densification

As we have mentioned, one of the most interesting properties of the moving network paradigm is its potential to enable a *natural* (i.e., unplanned, unmanaged, and automatic, at least to some degree) densification of network resources (and of BS in particular) in those locations and at those periods of the day where additional infrastructure (with respect to that which is available in period of low loads) is required, in order to cope with temporary bursts in demand for computing and communication services. For instance, Andreev et al. [34] consider scenarios in which unplanned outdoor performances bring together groups of people, who try to stream the event in VR mode in an uncoordinated fashion and on a variety of platforms. The surges in demand resulting from such scenarios are among the factors which make QoS provisioning in 5G networks and beyond a challenging issue.

Despite the importance of this property of the moving network paradigm, only few works in the literature characterize the correlation between spatio-temporal patterns of demand for connectivity and of vehicular mobility. A first study in a typical urban scenario with measurement-based vehicular traces shows that, on one side, the correlation between the density of end users and the density of vehicles is typically very limited in space (city center) and time of the day (rush hours) [40]. However, this study also shows that, despite a very low penetration rate of BS installed on vehicles (less than 1 % of the total amount of vehicles circulating in the city) the correlation is sufficient to drastically decrease the mean distance between end users and small cell BS, when these are carried by vehicles. However, it is not clear how these first results generalize to other cities and settings, and how they relate to the amount of CAPEX saving which this correlation enables.

3.2 Network planning and management

The moving network paradigm trades a lower amount of overprovisioning and lower network operating costs with an increase in complexity in the way the network is designed and managed, in terms of heterogeneity of infrastructure devices and technologies, and of the strategies required to operate it. Primarily, the moving network paradigm is part of a more general trend towards the gradual inclusion, in the network infrastructure, of elements whose configuration (e.g., location, but also amount of resource allocated, transmit power, and so on) varies by adapting to demand in a resource aware manner. This trend has developed in response to the ever increasing CAPEX and OPEX (e.g., energy) costs which MNOs have to face while assisting to a gradual commoditization of the services provided. Indeed, the presence in the network of dynamic elements calls for techniques for real time orchestration of network resources, possibly based on proactive and anticipatory mechanisms for resource allocation, acting at different time scales (from a few seconds up to several days).

Specifically, among the key features of the moving network which call for dynamic real-time orchestration, we have:

- **Stochasticity in resource distribution**. The moving network is based, at least in part, on unplanned infrastructure deployments, induced by the mobility of the vehicles. While this feature holds the potential to naturally densify the network, it also introduces an element of stochasticity on resource availability. Such randomness requires proactive strategies for ensuring that the resources required to deliver a given QoS to users are available, and possibly for deactivating redundant infrastructure in order to decrease its operational costs.
- **Changes in network configuration**. The very complexity of the network configurations arising from the moving network make it difficult to configure it statically, as the effects of changes in configurations due to movements of base stations are hard to model and account for during planning phase. Moreover, the consequences of the stochasticity in the deployments resulting from the moving network paradigm require flexibility and real-time adaptation also in the static infrastructure, in order to cope with issues related to coverage holes, locally insufficient capacity, or suboptimal load distribution across BS.
- **The presence of moving elements**, whose mobility patterns can be configured or at least influenced to some degree. Examples are UAVs, but also regular vehicles whose drivers are provided with incentives for responding to specific needs of the network by modifying their routes. Such moving elements, whose position can be configured, offer a powerful instrument to mitigate the consequences of the randomness in the deployments of MoBS.

Such an evolution of the way the network is planned and managed is facilitated by the adoption of the Software Defined Networking (SDN) [41] and Network Functions Virtualization (NFV) [42] technologies, which provide the network with the flexibility required to implement a dynamic control and adaptation of the network operating parameters. In particular, the continuous variability of the RAN layout and of the demand calls for techniques which enable an effective and rapid instantiation and adaptation of network functions in a way which takes advantage of the resources available locally in an opportunistic fashion, while minimizing the impact of variability on service availability and on performance perceived by users.

In order to design a dynamic management strategy for a moving network, a number of relevant scenarios in terms of relative density of static and moving small cells, of mobility patterns, and of service demand composition (in terms of broadband/IoT users, and traffic with tight requirements, such as URLLC) must be taken into account. Such resource-optimal strategies should allow choosing, at each time of the day, the operating point (e.g., whether active or sleeping, and the transmit power) of static and moving base stations. Moreover, they should determine the optimal number of MoBS required to implement the dynamic management strategies, as well as the optimal number and location of static BS, and of wireless access points for backhauling. These strategies should take into account the cost of energy, the issues of availability of nomadic nodes due to energy budget constraints, the costs of handovers, and the constraints on link availability.

3.3 Mitigation of interference and handovers

Interference mitigation is a well known critical issue in dynamically managed cellular networks. On one side, vehicle-based BS bring a clear advantage in terms of antenna gain and channel conditions, with respect to static BS [43]. However, modifying the position of base stations, turning them on or off, or changing their transmit power (as done for instance in sleep mode techniques for energy efficiency [16]) alter interference patterns in ways which are difficult to predict and to account for in the network management strategies themselves. The fact that MoBS are generally not deployed in space according to predefined layouts, but they follow the mobility patterns of the vehicles on which they are installed (except, of course, for drones), contributes to making the problem of interference management more difficult to cope with. Furthermore, the use of wireless technologies for MoBS backhauling implies that interference is an potential issue also in the backhaul. Traditional approaches such as frequency reuse or carefully controlling transmit power and end user association to BS become more complex to implement in such a dynamic setting. One way to tackle this issue is to resort to collaborative approaches such as Coordinated Multi Point (CoMP) [44], in which a sets of base stations coordinate transmissions in a way which minimizes the impact of interference. A possible approach is based on Time-domain Inter-Cell Interference Coordination (ICIC) recently proposed to mitigate the impact of inter-BS interference in ultra-dense network deployments. With this respect, [27], [45] proposed an approach based on Almost Blank Subframe (ABS), an ICIC technique by which BS are partitioned into groups, and take turns in transmitting. Vitale et al. [45] propose a scheme which combines ABS with outband D2D, in order to maximize the spectral efficiency. However, the design of optimal dynamic scheduling schemes is particularly challenging, given the large amount of possible configurations.

Another key issue, stemming from the high dynamicity of MoBS, is the high frequency of handovers. The movement of MoBS, in conjunction with the small size of the cells, and with the traditional user association strategy based on the strongest received signal, can easily lead to very frequent handovers. As a result, network services are likely to experience heavy degradation of their availability, and a general increase in latency, making it very challenging to support communication services with tight QoS requirements, such as URLLC. In this respect, the use of techniques based on BS coordination such as ICIC can also mitigate the impact of handovers, as they imply that each user is either served by several base stations at the same time, or that the serving base stations changes continually. In this last case, it is the CoMP scheme which takes care of managing the effects of user mobility, by dynamically and gradually changing the group of BS which coordinate to serve the user.

3.4 Highly reliable dynamic wireless backhauling

A highly reliable, low latency wireless backhaul connectivity is key to adequately support traffic with stringent QoS requirements in 5G networks. Additionally, the use of dynamic techniques for interference management calls for a backhaul architecture that is capable of enabling tight coordination between moving and static BS. Such coordination is achievable through some form of synchronization between nodes. This requires very low delay and highly reliable connections between MoBS in a pool of BS which coordinate in order to minimize interference. Synchronization demands are particularly challenging when considering to exploit distributed receiver diversity on the physical layer in such mobile networks. How to satisfy all these tight QoS and availability requirements with the currently available technologies in a network that integrates MoBS and static BS is still an open challenge.

A possible approach could be based on the combined application of heterogeneous networking, dynamic load balancing, and proactive resource management. The main idea of the heterogeneous networking approach is to share the load in the backhaul between two or more wireless communication technologies in a way which takes into account the level of availability of the connection in each technology. Indeed, exploiting diversity in space and frequency (e.g., sub-6GHz, mmWave, and even VLC) holds the potential to increase the availability of each link, and of the whole connection between the source MoBS and the wireless backhauling AP. The main challenge is to maintain link quality measures such as Channel State Information (CSI) for each channel. Secondly, techniques for QoS and availability-aware load balancing between different wireless technologies, and between MoBS and static BS, need to be integrated. Relying on approximated CSI, heuristics to switch to the most adequate communication technology for each transmission can be integrated. Thirdly, a proactive approach based on short-term prediction of mobility information helps to establish one (or more, and possibly multi-hop) routes between a MoBS serving UEs and the backhaul AP. This approach should also exploit short term predictions on channel quality in the various wireless technologies and in all the possible links, and adapt in real time the route to changes in topology, in propagation conditions, and in load variations at each MoBS.

From a more technical perspective, and as a fundamental basis, status information about each node and its connectivity to other nodes needs to be collected. In dense scenarios, such as those which are foreseen in urban environments, the exchange of such information easily leads to congested wireless channels. As already shown in [46], the joint use of novel neighbor table maintenance algorithms and of probabilistic data structures help nodes to gather status information about other nodes in their vicinity in a communication efficient manner. The main research issues related to this approach consist in *(a)* determining how to take advantage of neighbor information in order to achieve efficient routing of large data in a highly mobile network, and *(b)* how such a strategy can be extended to heterogeneous networking scenarios.

3.5 Distributed MEC on vehicles

Similarly to what happens to connectivity services, a densification of the MEC infrastructure is required to provide MEC services in next generation wireless access networks. Modern cars are typically endowed with a variety of ICT resources that can be used in such cases [21], [47]. The main distinction between traditional multi-access edge computing approaches found in the literature and the one which has to be implemented in a moving network scenario is that in the former, all resources are centrally managed in a 5G system, while in the latter only a partial view on available communication and computation resources is available, and dynamic resource management schemes have to cope with much higher dynamics. To this end, a key issue is how to design MEC services based on a combination of static BS and MoBS, which are able to exploit the flexible densification of computing infrastructure enabled by the moving infrastructure while overcoming its shortcomings due to the heterogeneity, dynamics, and volatility of the moving resources.

In order to address this issue, resource optimal algorithms for dynamically mapping computing tasks to a heterogeneous sets of computing resources, distributed over a mix of static and moving BS need to be elaborated. Specifically, such sets might include more than one MEC server (if the computation task is complex and it can be split in sub-tasks), and they may vary in composition over time, e.g., due to churn, failing nodes, or connectivity problems. A challenging aspect is represented by the fact that the resulting scheduling problem which the mapping algorithm employs needs to be solved on rather small time scales and with sparse topology information due to the limited approximation of mobility pattern of the vehicles. The optimization problem which the scheduling has to solve is complex, as many aspects have to be taken into account in allocating a task, such as current and predicted load of each MEC resource, predicted completion time of each resource, delay constraints, and the nature of the task itself. Thus, predictive techniques need to be explored, which proactively adjust load distribution among resources over time.

Moreover, in MoBS-enabled MEC, new computational offloading strategies have to be designed, which take into account the composition and structure of the available computational resources as well as their dynamics. Indeed, some computing tasks are a better fit for offloading to such a moving MEC than others. For instance, computing tasks such as those resulting from speech recognition applications are characterized by a large task-input file, and by a relatively small sized outcome. Such tasks are a good fit for moving MEC servers, which may take advantage of the proximity to the user to upload large input files with very small latency.

Scheduling algorithms for computational offloading are considered to be NP-hard [48], [49], thus, approximation algorithms need to be employed to allow fast and energy-aware scheduling decisions. Further, our multi-access edge cloud in combination with the moving network paradigm is not static, which therefore adds an additional dimension of complexity to the scheduling problem. The main challenge is to find strategies to allow the MoBS to exchange scheduling information, e.g., available resources and deployed subtasks in very short time scales which depend on the mobility of the vehicles and their link quality.

Of course, information about the mobility and link quality cannot be known in advance and estimates will suffer from uncertainties. Strategies and algorithms that allow to deal with those uncertainties help to perform computational offloading without sacrificing the scheduling performance too much. For a number of services provided by the MEC, ideas from the domain of NFV can be exploited for dynamic allocation of the available data storage to content caches, as well as SDN to route requests to the appropriate caches combined with approaches from the field of cloud and fog computing.

4 Concluding Remarks

In this chapter, we explored the novel moving network paradigm and how dynamic mobile base stations on vehicles can help supporting the necessary densification of upcoming 5G networks. The idea of using mobile small cell base stations is not new as such, however, there is no coherent approach available to kind of crowd sourcing the cellular infrastructure in a dynamic way, which automatically follows the users of 5G networks. The observation that resources are usually needed in places, where users also use or park their cars, combined with the ever improving ICT capabilities of modern cars, suggests that these cars can help forming a dynamic mobile infrastructure both in the fronthaul as well as interconnecting themselves in the backhaul. We identified a number of research challenges that need to be solved to make this idea reality. Most importantly, we outlined issues on flexible network densification, requirements on network planning and management, interference mitigation on front and backhaul, dynamic backhaul management, and multi-access mobile edge computing. We hope the research community takes on these important research issues to pave the road towards a widely available and resource-rich 5G deployment.

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