Future of Ultra-Dense Networks Beyond 5G: Harnessing Heterogeneous Moving Cells

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Abstract—For past 40 years, cellular industry has been relying on static radio access deployments with gross over-provisioning. However, to meet the exponentially growing volumes of irregular data, the very notion of a cell will have to be rethought to allow them be (re-)configured on-demand and in automated manner. This work puts forward a novel vision of moving networks to match dynamic user demand with network access supply in the beyond-5G heterogeneous cellular systems. The resulting adaptive and flexible network infrastructures will leverage intelligent capable devices (e.g., cars, drones) by employing appropriate user involvement schemes. This work is a recollection of our systematic scientific efforts in this space with the goal to contribute a holistic involvement schemes. This work is a recollection of our systematic scientific efforts in this space with the goal to contribute a holistic

I. MATCHING ACCESS SUPPLY AND USER DEMAND

Today, the use of wireless communications technology has truly become indispensable to our lives. A typical personal device is already tasked more than 1,500 times weekly, which on average translates to over three hours of daily usage. Supported by ubiquitous cellular deployments, affordable wireless connectivity has recently developed into a new commodity, on a par with water and electricity. Mobile broadband systems have thus gradually become a powerful operator asset to meet the rapid acceleration in the global traffic demand, which is about doubling every year – fueled by a dramatic increase of multimedia streaming. The proliferation of smart user devices together with the rapid adoption of mobile social networking services have effectively spawned a new generation of content acquisition habits.

The continued progress in user companion devices equipped with advanced computational intelligence and rich communication capabilities, such as smart phones, high-end wearables, connected vehicles, and (soon) autonomous drones, is forcing wireless network operators to respond promptly with decisive capacity scaling on their deployments as well as to enable the emerging computation-hungry and delay-sensitive services. Contemporary fourth generation (4G) wireless networks are already highly integrated and heterogeneous and may construct comprehensive connections across different scales, frequencies, and radio technologies [1]: cellular (3GPP LTE) macro base stations for basic coverage and system management are complemented with multiple tiers of diverse small cells and/or tightly coupled with WLAN (IEEE 802.11) solutions to improve capacity.

However, the impending advent of user applications with stringent and highly-differentiated quality-of-service (QoE) requirements, including multimedia and social networking services as well as interactive games, challenges the state-of-the-art 4G+ technologies with a massive and variable volume of traffic that nobody wants to pay for. Therefore, it is commonly expected that the new fifth generation (5G) networks will need to accommodate scenarios, which are not handled efficiently by the current 4G deployments, such as “human-intensive” urban locations that generate the lion’s share of the total data consumption. The global research on 5G radio access systems has essentially been concluded and 3GPP is in the process of ratifying a new, non-backward-compatible radio technology in centimeter- and millimeter-wave spectra to augment further LTE evolution.

With its early commercial deployments planned for 2018-2020, the 5G mobile technology promises to deliver peak data rates of 10 Gbit/s, which is over a 100x increase on top of the corresponding figures for 4G systems. This decisive improvement within a very short time frame is difficult to achieve without moving up in frequency and taming the non-conventional millimeter-wave (mmWave) bands [2]. In conjunction with the 3GPP’s “New Radio” in the mmWave spectrum [3], (beyond-)5G deployments will be able to leverage the increasingly more heterogeneous connectivity options, such as multi-radio uplink, downlink, direct device-to-device (D2D) links, as well as vehicle- and drone-assisted access. Therefore, future networks will be much more than yet another radio access standard, but rather an efficient integration of cross-domain systems to improve efficiency and provide superior user QoE.

However, we maintain that even the novel 5G technology may face severe limitations in the very near future due to highly unpredictable and non-uniform loading. Consequently, it may become insufficient to meet the QoE requirements of the end users, if supplied network capacity and demanded cell throughput do not match each other in space and time. Presently, the mainstream solution to mitigate the increasing disproportion between the irregular demand and the access supply is by deploying a higher density of heterogeneous small cells in current cellular architecture [4]. Notably, introducing an increasing number of serving stations is a gross over-provisioning at the same time leading to more complex interference management [5]. Network densification also requires massive investments from mobile network operators in the
form of higher rental fees and increased infrastructure maintenance costs, while the resulting ultra-dense deployments may be substantially under-utilized over most of their operating time [9].

In stark contrast to conventional thinking, we argue that the industry will not be able to leverage the full potential of the ongoing “small cell revolution” until significant changes are made to the way we approach wireless system design and content delivery. To this end, our thinking concentrates on matching irregular user demand with network access supply in beyond-5G systems. The proposed research agenda aims to build a comprehensive foundation for enabling truly dynamic and flexible network infrastructure based on leveraging moving cells (mounted on e.g., cars, drones, etc.) with lower deployment costs. Our contribution is to propose a holistic research roadmap behind heterogeneous moving networks and then offer suitable performance predictions that are grounded in reality, but permit for simple analysis of network densification limits.

II. ULTRA-DENSIFICATION WITH 5G+ MOVING CELLS

This section outlines our proposed vision of heterogeneous moving networks in beyond-5G cellular infrastructure.

A. Dynamic and Flexible Radio Access with Moving Networks

We envision that even the emerging 5G solutions may have difficulty in supporting the increasingly variable traffic demand with their rigid, fixed infrastructure without substantial over-provisioning. Indeed, over the 40 years of its history, the cellular industry has primarily relied on static radio access network (RAN) deployments that may face serious limitations in mitigating the effects of dynamic, non-uniform loading across space and time. Today, the sources of unpredictable space-time demand are spontaneous clustering of people, increasingly popular social attractors, and even the urban layout itself. While access supply (i.e., the potential cell capacity) has been well-explored in the past, the implications of user demand (i.e., the actual cell traffic) have received much less attention, especially for new bandwidth-hungry user applications and services.

In the near future, as more heterogeneous supply meets increasingly unpredictable demand, their mismatch in space and time threatens to create unprecedented levels of congestion. This is especially true for spontaneous large-scale events that require service providers to augment the capacity of their networks quickly. Therefore, we envision that future 5G systems will need appropriate methods and intelligence to adequately match supply and demand across space and time. Here, the use of moving access points (MAPs) equipped with high-rate (e.g., mmWave) radio access capabilities has the potential to offer the much needed “on-demand” capacity boost in crowded urban scenarios with extreme connectivity requirements, possibly under unreliable network coverage. Examples may include user-deployed and provisional wireless MAPs in the form of connected vehicles [7] and flying robots [8] (nicknamed drones).

The moving network infrastructure comprising car- and drone-mounted MAPs [1] indicates a promise to deliver the access supply to where the user demand actually is and thus lay the foundation for truly dynamic RAN solutions. Facilitated by these moving RAN deployments, the beyond-5G cellular systems will be able to bring the serving infrastructure closer to the content prosumer (producer-consumer). They will also enable the service providers to flexibly densify their heterogeneous networks, especially in urban areas as well as in the locations where the users are disadvantaged by excessive latency when acquiring their desired content over the conventional (static) wireless infrastructure (see Fig. 1). This capability will become crucial for beyond-5G technology since humans are particularly sensitive to perceived delay and jitter [9], whereas link latency and reliability are the key ingredients for their satisfaction.

![Fig. 1. Utilization of moving cells in 5G+ cellular.](https://example.com/fig1)

To further improve on the content acquisition performance, transparent and predictive caching of popular content at the wireless edge (i.e., small cell base stations) could be employed [10]. Given the fact that asynchronous content reuse makes a few popular files account for most of the total network traffic, proactive caching in strategic locations should allow for speeding up the content distribution as well as increasing the network resource utilization, even when the users do not request the same content simultaneously (that is, leveraging the temporal variability of network traffic). Importantly, caching at the MAPs as well as in the increasingly capable user equipment permits the shifting of traffic from peak to off-peak hours instead of straining the backhaul connections, thereby naturally mitigating load variability and reducing congestion.

Coupled with non-rigid placement of access nodes to better accommodate the varying space-time loading, in-network and in-device caching promises to quickly supply the users with their desired content as well as move it around in response to dynamic user demand. Not limited to content, moving infrastructure could also offer efficient computation offloading.

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1See the recent industrial deployment examples of moving cells e.g., here https://www.ericsson.com/en/news/2016/5/wi-fi-on-wheels-drives-coverage-anywhere and here https://www.ericsson.com/en/news/2016/8/ericsson-and-china-mobile-conduct-worlds-first-5g-drone-prototype-field-trial-
where resource-constrained and energy-hungry user equipment (e.g., high-end wearables) may migrate its heavy computation tasks to (nearby) resourceful servers. As distributed caching, computing, and communication capabilities are beginning to converge within the 5G+ ecosystem, prospective network operators may setup new services promptly, which will be particularly useful in next-generation deployments during unexpected and temporary events, such as large-scale mass outdoor happenings that create unpredictable fluctuations in access demand.

**B. Private User Devices for On-Demand Service Provisioning**

In future “human-intense” urban scenarios, users will interact increasingly with the system by employing their smarter devices – from wearable and handheld gadgets to connected cars and drones – equipped with better connectivity, advanced intelligence, as well as improved caching capabilities. With the natural progress in technology, these user devices are rapidly expanding their functionality, whereas the access points are becoming smaller driven by the ongoing network densification [11]. As a result, the original functional disparity between the network and the user equipment (UE) is gradually becoming blurred, which offers excellent opportunities to utilize user devices as part of various network tasks. We thus expect the UE to take a more active role in 5G+ service provisioning and even occasionally assume the functions of the network infrastructure, especially in partial coverage situations.

Intelligent UE may therefore aid profoundly in providing wireless connectivity to relevant devices in proximity, such as offering D2D-based data relaying, proximity gaming, content distribution and caching, as well as other flavors of cooperative communications. While D2D radio technology has originally been coined in the context of public safety services, it is likely to remain at the heart of the 5G ecosystem to improve performance of future mobile applications. In fact, engaging humans with their personal devices into a plethora of collective activities is regarded as the ‘last-resort’ option for service operators, and if the energy efficiency concerns are resolved it may bring along a decisive transformation from the axiomatic network-centric to the emerging device-centric system design. However, increased cooperation between the network and the UE might e.g., lead to more frequent handovers and hence should be controlled.

Indeed, unpredictable and heterogeneous human mobility produced by a mixture of various movement patterns may jeopardize session continuity and thus compromise operator service-level agreements. Consequently, in urban environments with unrestricted mobility, providing support for seamless connectivity becomes of paramount importance to improve the availability and reliability of wireless links for users and their connected devices moving at various speeds. To achieve scalable and reliable content dissemination, the use of 5G-grade multi-connectivity in the context of truly mobile access has recently sparked renewed research interest. This calls for a careful investigation regarding the complex mixtures of mobility models and their effects on the availability and reliability metrics to guarantee superior QoE in increasingly heterogeneous future networks.

While multiple radio access technologies and multi-access networks are expected to improve connection reliability, tolerance of link failures, as well as resource utilization for mobile users, a crucial question arises on the adequate sources of motivation that would facilitate the end-user decisions to lend their personal devices for collective usage. In order to employ user-owned devices as an asset in their networks, service operators need to embrace the selfish nature of humans. The decision strategy of the customers is inherently coupled with their utility perception, and operator-driven mechanisms are strongly demanded to engage the masses of people and coin the much needed incentive-aware applications. Here, social relations and interactions between an individual human user and its proximal neighbors come into focus, among other factors.

**III. MOVING NETWORKS: HOLISTIC RESEARCH ROADMAP**

In this section, we contribute a concise summary of research challenges in moving networks (see Fig. 2) to match irregular user demand and access supply in 5G+ wireless systems.

![Fig. 2. Research challenges in beyond-5G moving networks.](image)

**Space-time multi-radio resource management:** Most past works in the field of heterogeneous networking employ formulations from stochastic geometry to characterize spatial relationships between the communicating entities. However, as small cells are becoming even smaller, more heterogeneous, and potentially mobile, this increased temporal dynamics requires a whole new perspective. Here, the knowledge from the field of queuing theory may come to aid with the goal of carefully coupling queuing theory and stochastic geometry to produce a hybrid methodology for characterizing space-time area capacity regions mindful of multiple radio access technologies (RATs). Further, the use of random shapes theory can model e.g., buildings with a random object process.
instead of a random point process. Consequently, this novel approach may be employed to perform efficient congestion control and optimize radio resource allocation in dynamic beyond-5G networks across space and time. These results will develop advanced cross-RAT load management techniques, far beyond the state-of-the-art inter-cell interference coordination mechanisms.

**Higher directionality and overheads of mmWave:** As new mmWave RAT becomes one of the major 5G developments, carefully understanding the particularities of extremely high frequency communication gains importance rapidly. Much literature assumes that reliable mmWave connectivity is only possible in the line-of-sight (LoS) conditions, but recent results argue for the potential of non-LoS links at these frequencies. This knowledge is important in supporting future denser mmWave MAPs with higher channel dynamics as the user would need to perform more frequent handovers due to generally shorter and more directional mmWave links. There is a need to comprehensively understand the intricate interplay between feasible link length and blockage by human bodies and other obstacles, the effects of interference in ultra-dense 3D mmWave deployments and the associated scaling laws, and the required levels of control overhead with highly-dynamic cell changes at mmWave frequencies. This research direction will enable the construction of efficient control algorithms.

**Heterogeneous mobility of users and moving cells:** The need for explicit mobility modeling is becoming recognized relatively recently as a crucial research direction, and significant efforts have to be invested into alerting the community about the challenges of tackling heterogeneous mobility (produced by a mixture of dissimilar patterns) of human users and radio access nodes, such as car- and drone-cells. Going further, mobility-centric considerations will gain further prominence as a consequence of unprecedented urban dynamics during e.g., mass events and we propose to develop new mathematical tools and knowledge for explicit mobility modeling. In particular, there is a challenge to include the underlying features of various mobility patterns into performance analysis, which will go beyond the cite-specific models of urban deployments. Ultimately, the use of moving access infrastructure might in the future lead to very different dimensioning of our networks where they are no longer planned for peak loads, but instead provisioned for median loading.

**Synergy with remote caching and computing functionalities:** Recent research demonstrates non-incremental benefits from employing proactive cell-edge data caching, both in user terminals and in network equipment, as well as calls for studying the gains of remote computation offloading. However, the vast majority of past contributions only consider these important developments individually, which limits the potential synergy. In stark contrast, we believe that there is a need for tighter integration of communication, caching, and computing functionality (e.g., computing caches), potentially also employing advanced network coding techniques for improved content availability. For instance, novel methods for efficient deployment of MAP-based computing caches have to be developed that would capture e.g., the fundamental trade-off between the content acquisition latency and user mobility to optimize the placement of the computing/caching nodes in 5G+ moving networks. These results will open a new dimension in network optimization and content management.

**Multi-connectivity for improved availability and reliability:** Emergence of more advanced and mission-critical applications and services requires improved levels of wireless link availability and reliability. While significant progress has been made in enhancing individual RATs, the ultimate potential of using multi-connectivity for higher communication reliability is only being understood very recently. Latest findings are increasingly supporting this transformed thinking as it calls for exploring the gains made available with tight multi-radio integration (e.g., “coopetition” between cellular and WiFi technologies). Developing this line of research beyond mainstream, improved ‘on-the-fly’ MAP association mechanisms are demanded (i.e., flexible, decoupled, multi-connectivity association for fast moving objects), which will reveal the attainable degrees of freedom in dynamic cross-RAT load coordination. Here, any individual radio link may remain unreliable (as well as the spectrum availability itself with e.g., LSA-like frameworks), but the overall system-level reliability has to be guaranteed to satisfy the service-level agreements.

**Energy efficiency and wireless power transfer capabilities:** With the lion’s share of attention dedicated to network-side optimization, the user-centric performance is often overlooked and becomes the key concern if a human is to lend a personal device for network tasks. Together with higher throughputs, future user terminals (especially resource-limited wearables) will need mechanisms for improved energy efficiency (e.g., AR glasses), especially if they are equipped with multiple radios for better reliability. However, more RATs also means higher energy consumption, and practical techniques to optimize the energy efficiency of multi-radio devices under potentially unreliable, uncertain, and highly varying connection quality need to be developed. This is particularly essential for mmWave links, where conventional schemes are clearly insufficient. A complementary direction is equipping MAPs with dedicated wireless power transfer capabilities to extend battery lifetimes of e.g., proximate urban sensors. This research direction will supply constrained user equipment with predictable amounts of energy for its sustainable operation.

**Pragmatic incentivization and business mechanisms:** Today, despite all the progress in network-side intelligence, user terminals are still relatively ‘dumb’ in their radio decisions. We envision that engaging the increasingly capable user-owned equipment (e.g., connected cars) into collective use will soon become the ‘last-resort’ option for network operators to provide on-demand capacity, content, and coverage. This is when the appropriate pragmatic (e.g., monetary) user incentivization mechanisms will be in prompt need. This direction should contribute the much needed practical user involvement tools as well as help integrate them into the operator-side business strategies. One interesting development along these lines is the taming of mmWave frequencies, with lower price for spectrum, which promises the rapid proliferation of new players, but so far with very uncertain business models. Demystifying the intricate mechanics of this emerging market may be among the goals of this research direction.
Social factors for user adoption and security constraints: Complementing the operator-driven incentives for tighter user involvement, user-side incentives should also be considered. Sociology suggests that human contacts are naturally very clustered and we believe that this social structure could be leveraged to reach the critical mass of user-provisioned applications and services in tomorrow’s networks. To this aim, convenient automated methods should be offered for direct D2D-based connectivity and content dissemination among matching proximate people with minimal user involvement, especially in partial coverage situations. However, to facilitate this vision, the very real security, privacy, and trust concerns need to be resolved comprehensively. Example questions include: “can I trust a friend of my friend?” and “to what extent the trust is transitive?” Recent research made progress in this direction and demonstrated that the role of centrally-controlled security management may in principle be extended to the out-of-coverage situations. We are confident that other remaining challenges may also be resolved satisfactorily.

IV. UNDERSTANDING CAPACITY SCALING WITH MAPS

In this section, we conduct a case study to evaluate the extent of improvements made available with MAPs across both user- and network-centric performance indicators.

A. Characteristic Urban Setup and Deployment Parameters

Considered area of interest: In this work, we address a typical urban deployment. As a characteristic example, the area around the Times Square, New York City, USA is adopted – from 5th to 8th Avenue and from 42nd to 50th Street. This location is around 0.5 km\(^2\) large and is sufficiently representative; it features wide avenues and small streets as well as includes large pedestrian zones and narrow sidewalks.

Buildings are modeled as boxes of appropriate height, whereas smaller objects, such as lampposts and kiosks, are disregarded for simplicity. Altogether, there are about 1,800 driving vehicles \([12]\) in our considered scenario. A share of those acting as MAPs – named here the MAP involvement factor – varies from 0% (no involvement, baseline scenario) to 100% (full involvement, extreme case). In addition to vehicles, over 19,000 pedestrians are positioned randomly.

Attractors and mobility modeling: The vehicles as well as the pedestrians are assumed to move at constant speeds and follow the Manhattan mobility pattern: at every intersection, a vehicle/human selects its new direction randomly, except for the direction that it is coming from. One of the available new directions is chosen with equal probability. The speed of vehicles and pedestrians equals 20 km/h (dense traffic) and 3 km/h, respectively.

To capture spatially correlated events, street performances are modeled, which attract attention of the pedestrians. A new event begins in a random location and at an arbitrary moment of time (on average, 10 events per hour). The duration of each performance is set to around 5 minutes\(^3\). The start of every performance makes some of the pedestrians within view (i.e., inside 50 m range) alter their mobility patterns temporarily to reside within a 20 m-circle around the event for its entire duration. With a certain probability, any pedestrian traversing the area of interest pauses and joins the crowd until the end of the event. All of the spectators resume their mobility patterns once the performance is over.

Network supply and user demand: We assess a beyond-5G scenario where a notable fraction of humans actively employ augmented reality (AR) glasses. In our setup, we assume the AR penetration to be 10%, hence translating to nearly 2,000 connected AR gadgets in use. Upload of the multimedia capture from the event is considered as the main application. Given the progress in built-in cameras, we model 2K video with 30 fps, thus resulting in approximately 16 Mbps of bitrate\(^4\). The AR users are allowed to initiate their uplink sessions randomly, at the average rate of 5 sessions per hour. The mean length of each session is 5 min, similar to the duration of an event.

We specifically capture spatial bursts in traffic demand by assuming that each of the spectators wearing AR glasses decides to transmit multimedia stream from the street performance. For simplicity, we do not model the background traffic coming from connected vehicles or any downlink traffic. With such massive loading, 5G mmWave cellular is the only viable choice of an access network. Following the current 3GPP guidelines, mmWave access points are deployed on the walls of buildings at 10 m height as a hexagonal grid with the inter-site distance of 200 m \([13]\). We focus on the currently ratified 5G technology having the carrier frequency of 28 GHz with 1 GHz of bandwidth. The remaining deployment parameters are collected in Table I.

B. Summary of Conducted System-Level Evaluations

Modeling mmWave radio channels: The radio links between all of the users are modeled based on the UMi – Street canyon path loss model \([13]\), where LoS and non-LoS conditions are differentiated subject to the relative positions of the nodes as well as the buildings between them. The LoS condition may be further susceptible to random blockage that occurs whenever a link between the nodes is occluded by a vehicle or a human. We assume each blockage to cause about 20 dB of degradation in the received signal strength \([14]\). The current 3GPP considerations regarding the beamsteering, modulation and coding schemes, as well as initial connection establishment are employed to mimic the mmWave overheads arising from every active session.

Any mmWave access point (including the car-deployed MAPs) accepts a new session only if it has sufficient radio resources to handle it, while MAPs also ensure that their backhaul capacity is sufficient. Access and backhaul connections of MAPs coexist in the spatial and frequency domains,

\(^2\)Estimated by using Google Street View as approximately one vehicle per 5 m of the road (most of the roads in the area have more than one lane).

\(^3\)Estimated by using Google Street View as approximately two pedestrians per 1 m of the sidewalk.

\(^4\)Corresponds to the shortest realistic value: roughly one song/scene plus the initial attraction and the closing in the end.

https://support.google.com/youtube/answer/1722171?hl=en
such that the radio resources of a vehicular access point are shared dynamically between them. Whenever a new session arrives, the initiating user selects the access point with the highest signal power conditioning on the fact that it has adequate radio resources to handle this session. During its multimedia streaming, the user continuously monitors other potential access points in proximity. Should one with better signal strength and sufficient resources become available, the ongoing user session is seamlessly migrated to it by leveraging multi-connectivity capabilities [15].

**Developed simulation framework:** To characterize the described scenario and obtain the first-order performance results, an in-house system-level simulation framework was employed. It is fully implemented in Python and effectively operates in a time-driven fashion. More specifically, the target area of interest is processed to produce two path graphs: one for vehicles and another one for pedestrians. For the sake of better accuracy in the output results, all of the collected intermediate data are averaged over 300 replications. Each of such replications corresponds to one hour of real-time operation. To further make our output results unbiased, all of the vehicles, pedestrians, and street events are redeploed uniformly along the streets at the beginning of every replication.

**C. Representative Numerical Findings**

**Moving cells boost network capacity:** First, Fig. 3 reports on the number of supported AR sessions per an access point as a function of the MAP involvement factor. Clearly, the utilization of MAPs quickly augments the network capacity and much outperforms the baseline system operation for sufficiently high involvement factors. The reason behind is that in dense environments, such as the considered NYC downtown case, the centers of streets where the vehicular MAPs move are featured by reduced path loss as well as demonstrate much lower chances of blockage by other objects.

![Fig. 3. Network capacity scaling with MAPs.](image)

In contrast, the pedestrian users on the sidewalks often suffer from non-LoS conditions and frequent blockage by the dense crowd around them. Hence, it is exceptionally beneficial to offload some of the AR sessions from the conventional connections onto the MAP segment. However, the capacity scaling with MAPs is bounded primarily by two major considerations, access- and backhaul-related. Therefore, we compare our results against two extreme setups: (i) idealistic access that assumes infinite-capacity links between the MAP and any user in range, and (ii) idealistic backhaul that models a perfect link between the MAP and the nearest static access point.

If the MAP involvement factors remain low, there may be too few MAPs in the streets to reliably handle the AR sessions, especially from the crowd surrounding a public event. The access link is also susceptible to significant blockage by human bodies since the height of the MAP radio module is lower than that in conventional cellular. In contrast, with the MAP involvement factors of about 0.8 and higher, the moving network has enough capacity to accommodate the AR sessions reliably: the performance results for realistic and idealistic

| TABLE I  |
| --- |
| **MAI CASE-STUDY PARAMETERS.** |

| Deployment | Area of interest |
| --- | --- |
| Location: New York City, NY, USA | Area: 5th to 8th Avenue and 42nd to 50th Street |
| Size: \( \approx 0.5 \text{ km}^2 \) | Buildings: From real map with actual heights |

| Vehicles | Number: 1,800 per area |
| --- | --- |
| Model: Parallelepiped \( 4.8 \text{ m} \times 1.8 \text{ m} \times 1.4 \text{ m} \) | Speed: 20 km/h (constant) |
| Mobility: Manhattan pattern on the roads |

| Pedestrians | Number: Over 19,000 per area |
| --- | --- |
| Model: Cylinder \( 1.7 \text{ m} \) height, \( 0.5 \text{ m} \) width | Speed: \( 3 \text{ km/h} \) (constant) |
| Mobility: Manhattan pattern on the sidewalks |

| Street events | Start location: Uniforms within the area |
| --- | --- |
| Attracted pedestrians: 50% within 50 m (viewshed) | Frequency: \( \approx 10 \) per hour |
| Duration: 5 min (one performance) |

| User terminals | Devices |
| --- | --- |
| Category: AR glasses | Number: Almost 2,000 in the area (10% of people) |

| User traffic | Service: Uplink multimedia streaming to the cloud |
| --- | --- |
| Video quality: \( 2K \) with 30 fps | Stream duration: Exponential with 5 min mean |
| Rate of streams: \( \approx 5 \) streams per hour |

| Mobile network | mmWave radio |
| --- | --- |
| Frequency: 28 GHz | Bandwidth: 1 GHz |
| Propagation model: 3GPP UMi – Street canyon | Effect of buildings: LoS \( \rightarrow \) non-LoS |
| Effect of humans/vehicles: Non-blocked \( \rightarrow \) blocked | Signal degradation with blockage: 20 dB |

| Static access points | Deployment: Hexagonally arranged cell sites |
| --- | --- |
| Inter-site distance (ISD): 200 m | Sectorization: 3 sectors per site |
| Downtilting: 102 degrees | Transmit power: 35 dBm |
| Height: 10 m |

| Moving access points (MAPs) | Deployment: Random, uniformly on the roads |
| --- | --- |
| Transmit power: 30 dBm | Height: \( 1.4 \text{ m} \) (vehicle’s roof) |

| User terminals (AR glasses) | Deployment: Random, uniformly on the sidewalks |
| --- | --- |
| Transmit power: 20 dBm | Height: 1.65 m |

Fig. 3. Network capacity scaling with MAPs.
cases become closer. Interestingly, at the involvement factors of around 0.6 the MAP segment enters the backhaul-limited regime, where the static access point that relay traffic from MAPs become nearly saturated and do not have resources to accept additional sessions. Therefore, both access- and backhaul-related limitations have to be carefully taken into consideration prior to deploying the moving cellular infrastructure.

Moving cells improve link reliability: Further, the deployment of MAPs significantly improves the session continuity, as confirmed by Fig. 4. Here, we clearly observe that the maximum network loading, when the system may reject new AR sessions, is pushed much further up at higher MAP involvement levels. This brings considerable benefits to both the network operators (as they can serve more sessions per MAP and thus increase their revenue) as well as the prospective users (since the chances that a session is accepted and runs without interruption grow dramatically).

Another important effect is observed in Fig. 4 low and medium ranges of the MAP involvement factor (specifically, up to 0.6) do improve the probability of admitting new sessions, but these may be dropped later on if the associated MAP moves away and there are no other MAPs to assist, whereas the conventional link to static cellular still remains poor. However, at larger MAP involvement factors the system behavior becomes more predictable and far better than with static access points. The reason behind is that with higher penetration of MAPs, most of the AR sessions are served by the moving network where the best MAP-based connection is significantly more efficient than the link to a static cell.

Moving cells impact operator profits: Finally, the benefit of MAPs for the network operator come primarily from their capability to relieve congestion on the static access nodes and/or handle additional user sessions. Consequently, the projected operator revenues grow since they are proportional to the number of the AR sessions that the network can handle. Meanwhile, the costs of the operator to maintain the MAP segment also increase with higher MAP involvement factors, and an important question arises on the appropriate balance between these two effects.

To this end, Fig. 5 offers a comparison of two alternative incentivization models that an operator can employ: “fixed price per an offloaded session” and “fixed price per a new MAP”. In order to compare them fairly, we balance the total costs at 1,000 extra sessions per hour (assuming one section corresponds to one unit). When the MAP segment is underloaded, the “fixed price per MAP” policy is not preferred, since a large number of MAPs are required to reliably accommodate even a few sessions. However, as the population of MAPs grows, each of them serves multiple concurrent streams, and the revenues grow at a much faster rate than the costs. Ultimately, when the MAP segment approaches saturation, many extra MAPs are needed to accept an additional user session, which makes the costs dominate the revenues again.

![Fig. 5. Operator costs incurred by MAP operation.](https://5g-ppp.eu/wp-content/uploads/2015/02/5G-Vision-Brochure-v1.pdf)
Our envisaged moving access infrastructures will offer the operators an opportunity to dramatically boost system capacity in their desired area of interest on demand, by dynamically engaging a sufficient number of proximate MAPs. This vision is further fueled by aggressive developments in the automotive sector, where contemporary cars are becoming equipped with high-rate wireless access capabilities. Employing this underutilized vehicular connectivity, car-deployed MAPs may constitute the first generation of practical moving cars, with more diverse and heterogeneous options following shortly after.

The performance results contributed in this work evidence that the MAP-based networks contribute the much needed capacity and session continuity gains, which surpass the performance of conventional (static) cellular access. Making a step further, our conducted evaluation elaborates on the preferred operating regimes, where a given density of static access nodes may translate into certain MAP involvement factors. This evolved thinking calls for novel business models and incentive-aware strategies, which take into account the appropriate involvement costs. Ultimately, moving networks may convert the radio access infrastructure into a liquid resource as well as lead to a proliferation of new types of virtual operators and service providers that lease their assets and scale them on demand.

B. Broader Impact of Moving Networks

Successful deployment of moving networks requires close cooperation between system operators, network infrastructure vendors, and car/drone manufacturers. This is because the hardware and software components of MAPs need to be unified across various automakers, essentially calling for dedicated standardization efforts. Furthermore, this path promises deeper cross-penetration of telecommunication and automotive sectors, which may result in notable mutual benefits. In particular, the network operators will improve their system capacity, the automakers will recover the costs of equipping vehicles with high-rate wireless connectivity, while the infrastructure vendors will supply additional equipment to support the process.

Importantly, the integration of MAPs also calls for adequate billing mechanisms, where involvement of each party is accurately, fairly, timely, and transparently converted into monetary benefits. The traditional (centralized) billing schemes may thus evolve into semi-distributed solutions, where trust in the monetization outcomes relies not on the use of specialized hardware, but on dedicated crypto primitives, such as blockchain-based tools. Since the scaling of costs is not necessarily linear and the moving networks are highly dynamic, all of the stakeholders may end up playing a ‘game’ to determine their desired reward levels. Suitable game theoretic techniques may hence be demanded to make it happen.

Finally, a possibility to utilize the user’s property (e.g., privately-owned vehicles and drones) temporarily or permanently as part of the moving network infrastructure calls for a number of additional considerations. Here, the interests of device owners have to be taken into account, so that the corresponding incentivization strategies remain applicable beyond business-to-business segment (e.g., equiping a taxi fleet with MAP capabilities), but also operate in business-to-customer settings, where service operator employs private user equipment. In addition to appropriate incentivization approaches, evolved interaction mechanisms will also be necessary and may lead to unprecedented human-to-machine interaction opportunities.

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