Towards Mobile Radio Access Infrastructures for Mobile Users

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***Abstract*—This paper provides a first investigation of twice-mobile networks, i.e., cellular networks where both the end users and (part of) the radio access network infrastructure are mobile. Twice-mobile networks are based on an opportunistic, dense, crowdsourced, random deployment of mobile small cell base stations carried by vehicles, and on millimetre-wave fronthaul connections between the mobile small cell base stations and the fixed network elements. Thanks to the fact that vehicles carrying mobile small cell base stations roam coherently with mobile subscribers, twice-mobile networks provide adaptive broadband wireless capacity where and when users need it, thus avoiding the cost and intrinsic inefficiency of dense deployments of fixed small cell base stations. In this paper we investigate the achievable capacity under the twice-mobile network paradigm, using real-world telecom traffic and vehicle positions in two case studies in Milan, Italy. Our results show that, thanks to positive spatial correlations between mobile network demands and road traffic, mobile small cell base stations carried by vehicles ensure performance equivalent or better to that of a traditional deployment of fixed small cells, at significantly lower cost.**

***Index Terms*—Dense radio access network; Moving base station; Small cells.**

I. INTRODUCTION

Network densification is considered one of the most promising approaches to allow radio access networks (RANs) cope with the current dramatic increase in mobile data traffic, and with the emergence of environments that exhibit extreme user (or user equipment, UE) density, such as stadiums, shopping malls and conferences. RAN densification requires the deployment of large numbers of small cells (SCs) in those areas where the presence of UEs and the traffic they generate are high for some significant portion of time. The densities of base stations (BSs) that are today forecasted in the 5G vision documents are extreme: up to hundreds or even thousands per km^2 [1]. This entails large investments for the BSs installation and operation: the CAPEX (capital expenditures) for 5G rollout in Europe is estimated at over 50 billion euros per year [2], and it shall be largely borne by telecommunication businesses.

The number of UEs and the level of traffic they generate exhibit remarkable spatial and temporal fluctuations [3], [4]. Users normally move from home to work in the morning of working days, and this makes business districts crowded during working hours. In this period, mobile network operators (MNOs) need the capacity granted by dense small cell RAN deployments to cover business areas. However, after work, users move out of their offices, so that the RAN capacity necessary in a business district suddenly drops, and many of the installed SCs become redundant. The opposite is true for residential areas, where capacity is required in the evening, but typically not during working hours. In addition, RAN densification at different locations may be necessary in presence of traffic jams emerging during commuting times.

The explosion of mobile network traffic, coupled with the mobility of users and terminals, exacerbates such a situation. For instance, the increasingly common habit of using smartphones during crowded events, such as music concerts, sports events, or large public gatherings, gives rise to time-varying hotspots where additional network capacity is required. When considered jointly, all these situations make the traditional approach of dimensioning for peak hour traffic extremely costly: dense deployment of SCs would be needed in both business and residential districts, and extremely dense coverages should be present in, e.g., stadiums, yet all such resources would be only used for a small fraction of time. Overall, this would lead to low resource utilization, hence low return on investment, for long periods of time.

In order to improve this situation, it would be very beneficial to have a large number of SCs in business districts during the day only, and in residential districts during the evening only. One possibility to achieve this is to deploy a dense SC coverage in all areas, switching them on and off as needed. This can bring savings in OPEX (operational expenditures), especially in relation to energy consumption [5], but does not alleviate the CAPEX entailed by cell deployment. Another possibility is to move SCs from business areas to residential areas and back, so as to have the capacity of those cells where and when needed. For instance, MNOs already use small numbers of truck-mounted BSs for the quick provision of service in areas where service is not otherwise available, or where additional capacity is temporarily needed [6], and several papers have proposed drones to support communications in disaster areas [7]–[9]. While these solutions may be suitable in specific use cases, they do not scale to, e.g., large metropolitan areas, where MNOs would need to run and coordinate fleets of hundreds of trucks or drones. In this paper we look at a completely new approach to implement mobile BSs that has substantial potential for scalability. Namely, we propose to use a suitably chosen set of privately-owned ground vehicles to carry (part of) the SCs that implement the dense RAN deployment and includes *mobile* small cell base station (MoBS) devices.

Our rationale is that vehicles for private ground transport have the very desirable property of moving in accordance with the mobile network subscribers. Thus, in a business district during working hours we normally have both many UEs and many vehicles. If a large enough fraction of those vehicles carries a SC, a temporary dense SC deployment is created. Quite nicely, this temporary dense SC deployment will be recreated in residential districts when drivers return home with their cars. And, situations like traffic jam areas during rush traffic hours or large events in proximity, e.g., of a stadium, will be similarly addressed in terms of network capacity provisioning.

A vehicle-based SC deployment yields multiple advantages over traditional network densification approaches that leverage fixed SCs. We summarize them as follows.

- Network densification is achieved in those areas where several connected cars are present. Given the positive correlation between the number of cars and the number of UEs in a given area, network densification moves with the peaks of data traffic demand, thus drastically increasing the efficiency of SCs. We measured such a correlation on recent real-world data, as reported in [10] and summarized later in this paper.
- Huge capacity increases are possible in dense urban areas, even with a tiny fraction of cars carrying SCs. We show that capacity gains over 100% are possible with just 1% of vehicles providing SC support.
- RAN densification is obtained very rapidly and with very limited cost for the MNO, since SCs are carried by vehicles, and are used by the MNO with a small cell as a service (SCaaS) paradigm, with no installation cost.
- Vehicles can provide, in addition to communication resources, also computing power and storage that can be exploited for the provision of extremely low latency services.
- The vehicular RAN densification solution is compatible with dedicated vehicles carrying SCs, like autonomous cars or drones that can be strategically positioned. Such vehicles would allow augmenting the deployment in a planned fashion.
- Groups of SCs can be interconnected to provide local service in areas where the cellular network infrastructure is (temporarily) not operational, e.g., following some natural disaster.
- SCs can very effectively support delay-tolerant Internet of Things (IoT) applications like smart meter reading, by downloading data while they pass by smart objects so that very little power is needed for data transfers.

Of course, the dense small cell RAN layouts resulting from vehicle-mounted SCs have quite different properties with respect to the dense small cell RANs carefully planned by network operators, and this poses a number of challenging research issues. First of all, while planners of BS deployments suitably select BS positions so as to avoid interference and maximize efficiency, drivers travel and park their vehicles without care for network planning needs. This leads to unplanned BS deployments that call for new adaptive network management solutions. In addition, the movement of SCs, coupled with that of UEs, accelerates the overall RAN topology dynamics, requiring rapid rearrangements in the network: as an example, handovers are likely to become much more frequent, and the fronthaul connectivity may rapidly change.

In this paper, we first discuss the correlation between number of vehicles and telecom traffic in a given area, by summarizing the main results in [10]. Second, we illustrate an approach for the computation of the throughput achieved with SCs on vehicles, and we show that performance gains with respect to a deployment of fixed macro BSs can be significant, comparable to the throughput gain achieved with a planned deployment of fixed SCs in equal number. We then look at the optimization of the fairness in the allocation of throughput to end users by means of a time scheduler that alternates among configurations of active SCs. In practice, we exploit an approach whose principle is analogous to the one used for counteracting inter-cell interference by means of almost blank subframes (ABS) [11], [12]. Since the computation of the maximum throughput and of the throughput that provides the optimal fairness requires the analysis of all possible configurations of active SCs, whose number is exponential in the number of SCs, we will first present an exact approach, and then a simple novel heuristic with quadratic complexity in the number of SCs. The heuristic will be shown to provide results very close to the optimum.

The rest of this paper is organized as follows. Section II illustrates in some detail the concept of twice-mobile networking, i.e., networks in which both the end users and (part of) the infrastructure are mobile. Section III overviews some related work. Section IV discusses the correlation between number of vehicles and telecom traffic in a given area. Section V presents an approach for the computation of the throughput achieved with SCs on vehicles. Section VI presents numerical results, and finally Section VII concludes the paper.

II. Twice Mobile Networking

We name our approach twice-mobile networking (or TMN for short), and we call MoBS the mobile small cell base station. We argue that the impact of the TMN approach on mobile networks can be enormous. TMN may bring a revolution in wireless network design, and can redefine the possibilities of adaptive capacity provisioning. At the same time, TMN will allow a distribution of the CAPEX for the provision of wireless capacity. Indeed, similar to what happened in smart grids where solar panels belonging to end users generate electricity that is available for all, in TMN MoBS owned by end users will provide capacity managed by the MNO for the benefit of all network end users.

A schematic picture of a portion of a TMN is shown in Fig. 1. The urban area is covered by standard cells, defined

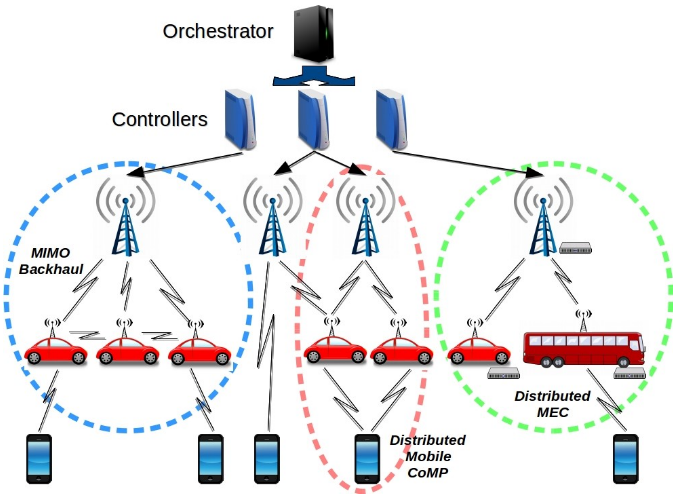


Fig. 1: The twice mobile networking concept

by the deployment of fixed macro/micro BSs, 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 the UE concentration is higher, through small cells which overlap with macro/micro cells, and provide the necessary additional capacity where needed, when needed. Each BS, whether fixed or vehicle-mounted, is connected to the core network through a fronthaul link, which can be either wired or wireless for fixed BSs, but must (obviously) be wireless for MoBS. We assume that the connection between a MoBS and the fixed network is implemented with a millimetre-wave link, so as to have sufficient capacity for the support of the traffic generated by all end users connected to the MoBS, and to avoid interference with the lower frequency channels connecting either fixed BSs or MoBS to UEs.

As shown in the picture, a millimetre-wave link is also available between MoBS. This is extremely important to allow the creation of a front/backhaul network, so that even if the direct link from a MoBS to the fixed network is not available due to obstacles, other fronthaul opportunities are possible through neighbor MoBS. In addition, the MoBS-MoBS link will permit the creation of standalone networks of MoBS when the fixed network infrastructure is not working, like for example in disaster areas.

Finally, we observe in Fig. 1 the presence of an orchestrator and several controllers, that are instrumental to the real-time management of the extremely complex TMN environment. MoBS must be switched on and off according to their utility in service provisioning, and their operation parameters (e.g., their output power) must be adapted so as to maximize the system performance. In addition to communication resources, MoBS can also provide computing power that can be exploited with the fog [13] and MEC (mobile edge computing) [14] paradigms to achieve the necessary computation with the minimum latency. Controllers and orchestrator are also charged with the management of these computing resources.

The number of critical research questions raised by the TMN vision is fairly large. Next, we briefly discuss the most obvious technical concerns and opportunities for innovation linked to TMN, although we acknowledge that our coverage is not exhaustive and many lesser aspects would also deserve investigation.

A. *Interference issues*

The random, variable layout of MoBS is very different from the carefully planned layouts of traditional cellular networks; this poses very challenging questions on the management of the interference among BSs (vehicular and fixed, unless they operate on separate frequency bands) and UEs, both in the downlink and in the uplink directions. The approach used by todays RANs tries to reduce interference as much as possible, by carefully controlling transmission power and end user associations to BSs. More innovative approaches are possible, such as the exploitation of the many MoBS for cooperative transmission approaches derived from MIMO or CoMP [15], [16]. These approaches are being studied in the context of dense small cell RANs by ARTEMIS, with their pCell (personal cell) technology [17], [18]. A different innovative approach can envision the geo-coordination of MoBS, so that they collectively “look like” a single BS for terminals, possibly exploiting CoMP [19], with the advantage of also reducing the handover rate. Interestingly, also D2D (device-to-device) communications, or MoBS-to-MoBS communications could play a crucial role in reducing the access network interference.

Since MoBS can move, they introduce inter-cell interference levels that change over time. Therefore, they exacerbate the complexity of inter-cell interference coordination mechanisms like ABS. Indeed, a static ABS approach is not suitable, and advanced stochastic ABS configurations can be leveraged instead, as the dynamic distributed scheme proposed in [20].

B. *Uplink connections*

The study of the downlink performance is simplified by the lack of contention in the access to wireless resources. When the uplink must be considered, it is necessary to account for the signalling between UEs and MoBS to acquire access to radio resources. Part of the standard procedures incorporate random access algorithms, that can become critical in the case of very large user numbers. This can be a further advantage of the TMN approach, where MoBS collect requests of medium size groups of users, alleviating contention on fixed BSs.

C. *Wireless fronthaul implementation*

The selection of the technology for the implementation of the wireless fronthaul link is possibly one of the most delicate choices for the TMN architecture, due to the high capacity requirements, and to MoBS mobility. The possibility of operating MoBS as non-transparent layer-3 relays [21]–[23], and connecting them to the corresponding macro/micro BS through the X2 and S1 interfaces [24], [25] is likely not to provide sufficient capacity. Other options, such as exploiting WiFi as a fronthaul for cars parked sufficiently close to an open access point, or even a wired fronthaul for electric vehicles connected to a recharge station, can be considered. However, the most promising solution seems to be a millimetre-wave multi-hop fronthaul connection. This approach does not generate interference with the much lower frequencies used in the wireless connections from MoBS to end user terminals, and is expected to provide capacities which are largely in excess of the sum of the data rates from MoBS to UEs. However, it must be considered that millimetre-wave links in urban environments can be problematic, due to both distance and obstacles. It is thus very important to study for what fraction of time a (possibly multihop) millimetre-wave connection from the MoBS to the fixed network can be active. This would allow computing the effective data transfer capabilities of the link, the estimation of the latency introduced due to interruptions, and the dimensioning of the storage that must be associated to MoBS to survive periods of absence of connectivity.

D. Use of SDN and NFV together with ML

The complexity of the TMN scenario is extreme, with MoBS (equipped with CPU and memory for data processing and storage) moving around the service area, over which also end users roam. This calls for a very dynamic control and adaptation of many of the network operating parameters (especially if cooperative techniques are to be implemented), that is achievable only with a careful real-time orchestration of network resources through SDN (Software Defined Networking) approaches [26]. In addition, the continuous variability of the RAN layout calls for the possibility to virtualize a number of network functions, as well as to implement services with approaches such as cloud, fog and MEC. In particular, for a number of services, NFV (Network Function Virtualization) can be exploited for the dynamical allocation of the available data storage to content caches, and SDN to route requests to the appropriate caches.

The extreme complexity of the TMN system also requires a very careful real-time management for the (de)activation of MoBS so as to optimize throughput and fairness, the control of UE associations to BSs or MoBS, the management of the millimetre-wave front/backhaul links, the control of handovers, the dispatch of autonomous vehicles to the locations where they are needed, etc. This cannot be obtained with a human in the loop, and must be completely automated. Machine learning (or artificial intelligence) algorithms become thus necessary to extract from past observations of the system, rules for the decisions about the future control of the system behaviour [27].

E. Impact of self-driving cars or drones

The diffusion of self-driving cars seems particularly attractive for car-sharing fleets, since they allow moving cars to the areas where they are most in demand. The same development may also happen for private electrical cars, as in the plans of Tesla Motors [28]. The possibility of moving cars as desired in the periods when they are not hired is an extremely interesting feature for the effective implementation of the TMN concept, since it allows the reduction of the unpredictability in the system, and opens the way to the optimization of the spatial distribution of MoBS. This adds an important degree of freedom in the management of the MoBS layout, and can yield significant performance gains. For example, autonomous cars could be programmed to drive periodically over paths with minimal traffic, in order to collect IoT data to be transferred to processing centres. Similar results can also be achieved by using drones to fill spatial and/or temporal bandwidth gaps due to occasional mismatches between traffic demand and availability of MoBS.

F. Mobility and handovers

A careful assessment of the TMN concept requires investigating the operation of the system under mobility of both MoBS and UEs. In particular, mobility implies handovers of UEs from one MoBS to another, or from a MoBS to a fixed BS, or from a fixed BS to a MoBS. In addition, it is necessary to investigate the activation/deactivation of MoBS by looking at their positions relative to other MoBS and fixed BSs, depending on the interference that is generated and the throughput that is gained. The impact of handovers can be mitigated by the simultaneous connection of UEs to multiple BSs, for example with approaches similar to CoMP.

G. Exploitation for IoT

The many emerging IoT applications are expected to either exploit specific technologies, like LORA [29], or the narrowband version of 5G [30]. However, TMN could provide a very interesting alternative to these approaches, since the loose requirements on latency of some IoT applications (such as smart meter reading) combined with the requirements of extremely low power can provide a very interesting match with MoBS passing in close proximity of meters. MoBS can opportunistically download data from smart objects, to be forwarded to the collection centre. How much power can be saved thanks to proximity, how long are the delays before a MoBS passage, how much are the storage requirements at the smart object and at the MoBS, and how to alert the meter of a MoBS in close proximity are all very relevant issues to be investigated.

H. Exploitation in disaster areas

Up to now, we have always assumed that MoBS operate in conjunction with fixed BSs. However, MoBS are also capable of direct communications with each other, and this allows them to establish a localized opportunistic cellular network providing standard cellular communication services in an area where infrastructure is not present because of digital divide issues, or because of natural or human-caused disasters (earthquake, flooding, terrorist attack, etc.).

III. Related Work

Adaptivity has traditionally been considered a very desirable feature in networking, and some classes of networks have been based on adaptivity to the environment, in particular sensor networks [31], [32], ad-hoc networks [33], delay tolerant networks [34], and networking paradigms based on opportunistic communications, such as Floating Content [35], [36] or Hovering Information [37].

The increasing softwarization of telecommunications, combined with the coming of age of artificial intelligence, are creating the conditions for extreme adaptivity of wireless (and wired) networks. It is now possible to dynamically reallocate and in some cases transfer resources so as to match users requests in terms of volume and performance. The specific case that we consider in this paper concerns adaptivity in the densification of cellular networks. The idea of adaptive cellular network densification is new, but on several occasions vehicles have already been considered as elements of a telecommunication network. Some 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 example, [38] proposed the use of mobile vehicular gateways that exploit Wi-Fi for vehicle-to-vehicle (V2V) communications and LTE for vehicle-to-infrastructure (V2I) communications. The study in [39] introduced the concept of Virtual APs, which allow extending the reach of roadside access points: vehicles that receive a message, store it, and rebroadcast it into non-covered areas. In [40]–[42], parked vehicles were exploited, in addition to roadside units, to improve the performance of video downloads and other services toward travelling cars. In [43], mobile nodes were used for the collection of data from sensors.

These approaches are different from TMN, which leverages vehicles as a support for small cell BSs of a dense RAN. TMN allows the seamless integration of MoBS with the normal macro- and micro-BSs at fixed locations, so that the MoBS 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 traditional fixed BS and a MoBS. TMN generalizes the concept of early deployments of SC BSs onboard public transport vehicles to serve passengers in ultra-dense urban environments [44]–[47], and that of using vehicle-carried SC BSs in public safety networks [48].

A concept similar to TMN has been briefly hinted at in recent works [49], [50], where the authors mention the possible use of 4G or 5G small cells within moving and parked cars, or on drones, so as to serve users both indoor and outdoor. However, no results in this direction have been published so far.

IV. Evidence of correlation between telecom and vehicular traffic

In a recent paper [10], we looked at the correlation between vehicular traffic and telecom traffic, and then estimated the average distance from UEs to MoBS in an urban area. In our analysis we used a dataset that contains values of telecom and vehicular traffic during 61 days (44 working days and 17 weekend days) for the city of Milan, Italy, organized according to a subdivision of the area into 576 squares, as shown in

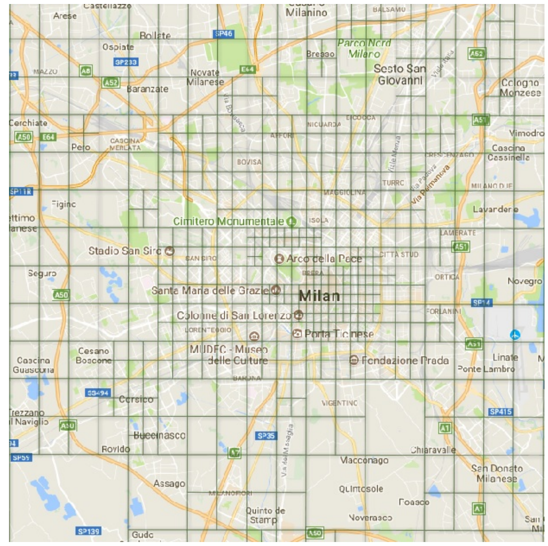


Fig. 2: The subdivision of the Milan area into 576 squares.

Figure 2. The squares (actually, rectangles) have minimum size of about 220 m by 330 m, but sides can be 2, 4, 8 times longer, as can be seen on the map. The time granularity of the dataset is 15 minutes (96 intervals per day). For each time interval, the dataset reports the total amount of mobile network data traffic (uplink and downlink voice and data, no signaling) recorded in every square by a leading Italian MNO, as well as the GPS positions of active (i.e., not parked) vehicles tracked by InfoBlu (about 4 million, on a national scale), a large Italian infomobility services provider. The total number of time intervals is 61 times 96 = 5,856. Considering the number of area squares for which data are reported separately, we have a total of 3,373,056 data points.

It is important to remark that the penetration rates of the two measurement technologies are quite different. While the telecom traffic in the dataset corresponds to more than one third of the overall MNO demand, the fraction of the monitored vehicles is less than 1%, as it mainly encompasses probe vehicles and commercial fleets monitored by InfoBlu. These percentages are consistent with the goal of our investigation: we can expect a small percentage of vehicles to act as MoBS carriers (at least in an initial phase), and would like them to cover the largest fraction possible of the total telecom traffic.

We start by showing, as an example, the average telecom and vehicular daily traffic patterns in a square covering the main train station in Milan (namely, "Milano Centrale" station). Figure 3 in plots a) and b) shows the average telecom and vehicular traffic patterns for all days of the week for the selected square (telecom traffic in the left plot and vehicular traffic in the right plot). First of all, while in telecom traffic clear behaviors exist, vehicular traffic (at our penetration level) is highly irregular. In the considered train station area, telecom traffic is very low at night, then sharply increases around 8 A.M. in working days, and remains close to its peak value from 9 A.M. to 9 P.M., then sharply decreases. The peak of telecom traffic in weekends is about one third of that in working days. Vehicular traffic is very bursty, peaking in the afternoon and evening. A qualitatively similar behaviour is observed in a square covering a business area, as shown in Figure 3, plots c) and d).

The inspection of the raw data about telecom and vehicular traffic for all squares and time slots does not provide many clues to justify correlation; rather, it reveals that telecom traffic dynamics vary widely in space and time, and vehicular traffic is generally much more bursty than telecom traffic. This latter effect is mainly due to the reduced fraction of vehicles carrying MoBS that will characterize early TMN deployments.

The results about correlation from a spatial perspective are summarized by the scatterplots in Figure 4. The abscissa refers to the telecom traffic value, and the ordinate reports the vehicular traffic value. Each dot corresponds to one square in the Milano area (thus 576 dots), and traffic values are averaged over all time intervals of working days (Monday through Friday; 44 x 96 instances left plot) and weekends (Saturday and Sunday; 17 x 96 instances right plot). The Figure outlines correlations emerging across the geographical area. Plots also show the least square linear regression line.

The results above yield the following conclusions: i) there exists a general positive correlation between vehicular and telecom traffic, but ii) the correlation is low, due to high variability. A sensible question is then whether some hours and geographical areas show especially strong correlations, and are thus suitable periods and locations for MNOs to take advantage of the TMN paradigm. We first investigated which are the periods during the day when correlation is higher. Figure 5 (left plot) shows the curves of the Pearson correlation coefficient versus time for the average working day and for the average weekend day. We observed that correlation is low overnight in working days and in the early morning of weekends. On the contrary, the correlation coefficient values are higher in the range from 0.3 to 0.5 during high-demand periods, i.e., in working periods and evening hours. These are good news, since the correlation is low in the night periods, when the demand for mobile services is typically low, and network densification is not necessary. Instead, TMN is most effective exactly when densification is needed, that is, in presence of mobile network traffic demand peaks.

Concerning the geographical dispersion of correlation, Figure 5 (right plot) shows a heatmap where the color of each square corresponds to the Pearson correlation coefficient computed over an average day (dark blue means low correlation values, while red means high correlation values). We can clearly see that correlation is stronger in the city center. On the one hand, this is expected, since both vehicular and telecom traffic are higher in those squares, hence they follow more predictable patterns. On the other hand, and more importantly, those are also the squares where the demand for radio access network capacity is higher, hence densification is needed the most. We conclude that, in our reference scenario, TMN proves to be mainly exploitable not only when, but also where network densification is needed the most.

The next question concerns the distance between MoBS and the UEs that can use the MoBS to transmit and receive mobile network traffic. Since our dataset reports exact vehicle positions within each square, but only the origin square (and not the exact end user terminal location) for telecom connections, we randomly place end user terminals within the area covered by each square. The average distance between the end user terminal and the closest MoBS (the one to which the end user terminal normally associates) is a metric of great interest for TMN, since it is a proxy for the connection data rate.

The heatmap in Figure 6 (left plot) shows for all 576 squares that cover Milan the average distance between MoBS and user terminals (dark blue means long distances, while red means short distances). The shortest average daily distances are found in the city center and are around 120 m, while the longest average daily distances are observed in peripheral squares and grow up to around 200 m. MoBS are hardly usable under such distances. However, when looking in more detail at what happens in the city center, the conclusion is different. Results in Figure 6 (right plot) show the evolution of the average distance over time between end user terminals and the closest MoBS, in the 158 squares in the center of Milan averaged over all 61 days. Between 9 A.M. and 8 P.M. average distances are around 50 m, so that in this portion of the city we can expect a large fraction of terminals to be within reach of a MoBS. These values nicely complement the correlation results, and confirm that TMNs have the potential to represent a suitable network paradigm to enable the adaptive densification of radio access envisioned for next-generation 5G systems, at least in the highly urbanized areas where mobile network capacity will be needed the most.

V. Throughput Calculation and Optimization

In this section, we summarize the results presented in [51] for the performance evaluation of systems with BSs that can be muted with ABS on a millisecond timescale and relay groups. That work is relevant to us since it studies how to orchestrate dynamic groups of users by avoiding interference. Specifically, we can see a MoBS as a relay station in the model described in [51], while UEs that connect to MoBS are end users in that work. Therefore, we present the results in a TMN scenario and use the TMN terminology previously defined in this article rather then the one presented in [51].

Results from [51] are here applied to the TMN case to evaluate analytically the downlink throughput performance achieved when MoBS are in place. Such throughput characterization allows us to assess the gain enabled by MoBS, and to present an optimization that copes with the classical interference problem observed in dense scenarios. Here, we use the model to unveil how to select, at each given time, which MoBS should be allowed to transmit (active MoBS) and which ones should be muted instead, so to control interference. We start by computing the average number of bits per symbol transmitted to a specific UE by the serving BS, i.e., the so-called transmission efficiency (Sec.V-A). Afterwards, we compute the downlink throughput obtained by a UE (Sec.V-B)

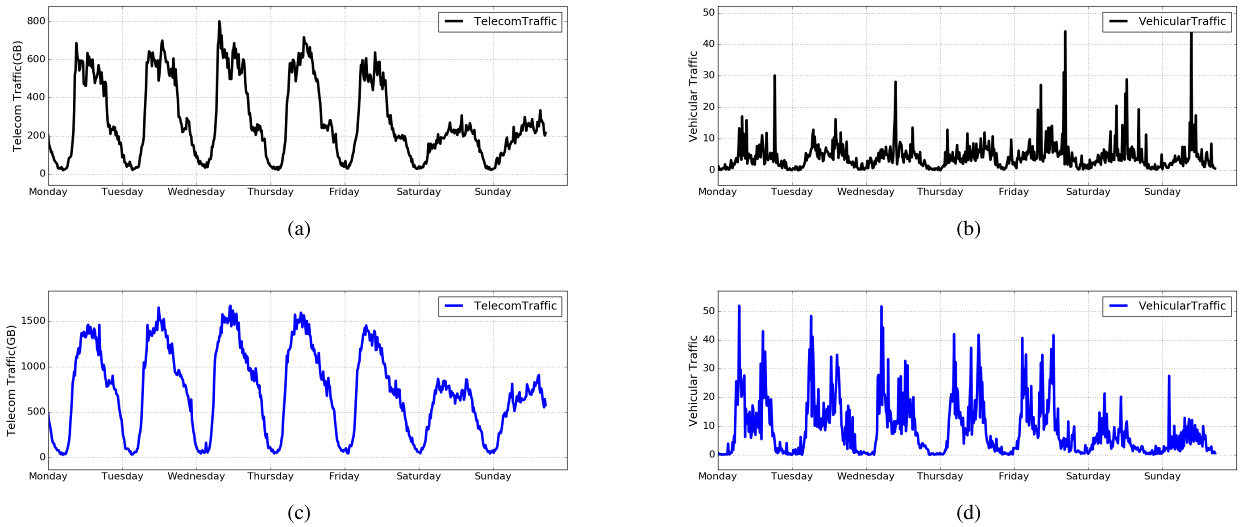


Fig. 3: Average telecom and vehicular traffic (left and right, respectively) for all days of the week in selected square areas. Plots (a) and (b) refer to a train station, plots (c) and (d) to a business area.

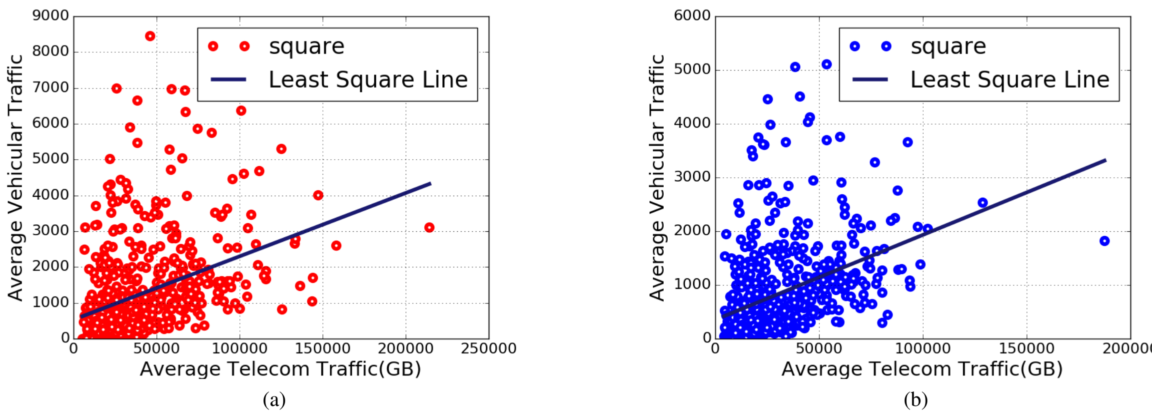


Fig. 4: Correlation between average telecom and average vehicular traffic. Plot (a) refers to 44 working days and plot (b) to 17 weekend days.

and, based on this result, we design an optimization that selects active MoBS with the aim of maximizing overall throughput or user fairness (Sec.V-C). Finally, given the complexity of the introduced optimization, we present for the first time an easy-to-deploy heuristic that can be used also when the number of MoBs is large (Sec.V-D).

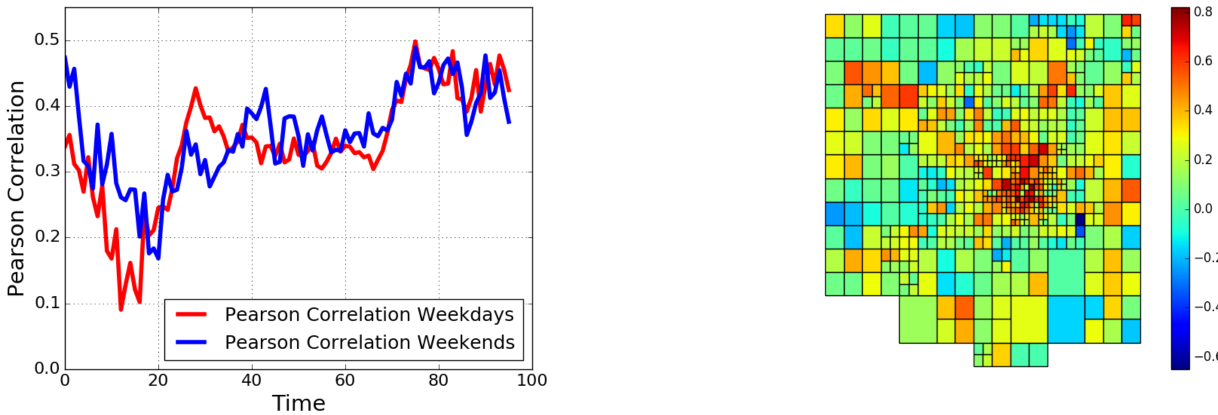
A. Transmission efficiency

We consider a cellular access network with a set $\mathcal{B}$ of interfering BSs. A BS belonging to $\mathcal{B}$ is either a standard fixed BS or a MoBS. In the following, we consider short time slots where the location of UEs and MoBS can be considered as fixed. Furthermore, we assume that users attach to BSs (either fixed ones or MoBS) according to the strongest signal received. Transmission efficiency, though, not only depends on the location of BSs and UEs, but also on the mapping between Signal to Interference and Noise Ratio (SINR) and Modulation Coding Schemes (MCSs) (we refer the reader to [52] for further details on MCS mapping examples). Considering time slot t, where UEs and MoBS locations can be considered as fixed, the transmission efficiency $\zeta_i(t)$ of UE i can be then computed as:

$$\zeta_i(t) = \sum_{k \in \mathcal{M}} b_k \left[F^t_{\text{SINR}}(T^{\max}_k) - F^t_{\text{SINR}}(T^{\min}_k) \right], \quad (1)$$

where $\mathcal{M}$ is the set of MCSs, b_k is the number of bits per symbols for MCS k, $(T^{\min}_k, T^{\max}_k]$ is the interval of the SINR for MCS k, and F^t_{SINR} is the Cumulative Density Function (CDF) of the SINR at time t. In practice, (1) evaluates the probability of UE i to use a specific MCS in time slot t, given the experienced SINR distribution.

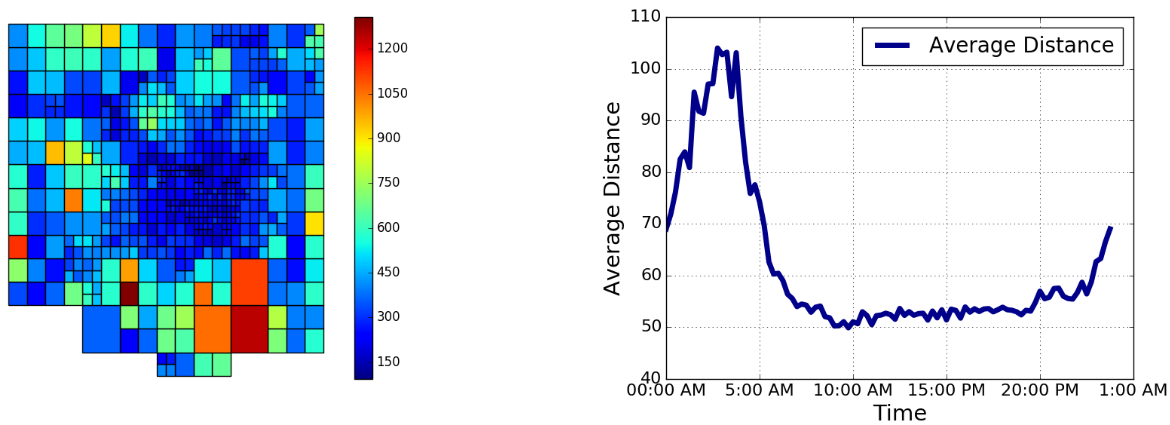
The CDF of the SINR depends on the radio propagation between the BSs and the UE. As pointed out in [53], in urban environments, UEs are most likely to experience Rayleigh fading. For this reason, we assume that the power received by



(a)

(b)

Fig. 5: Pearson correlation coefficient versus time between average telecom and vehicular traffic over all squares and over 44 working days and 17 weekend days in left plot; Pearson correlation coefficient heatmap between telecom and vehicular traffic for each Milano square, averaged over 61 days in right plot.



(a)

(b)

Fig. 6: Average distance between vehicles and origins of telecom traffic for all square areas over one day (March 2, 2015) in left plot; average distance between vehicles and origins of telecom traffic versus time of day for 158 squares in the center of Milan averaged over 61 days in right plot.

a UE both from the attached and the interfering BSs follows a negative exponential distribution.

Proposition 1. *The CDF $F_{SINR}(x)$, resulting from an exponential useful signal with average power $1/\lambda_S$, J independent exponentially distributed interfering signals with average power $1/\lambda_{I_j}$ and constant noise power N, is, $\forall x \geq 0$:*

$$F_{SINR}(x) = 1 - e^{-\lambda_S N x} \prod_{j=1}^{k} \frac{\lambda_{I_j}}{\lambda_{I_j} + x\lambda_S}. \qquad (2)$$

Proof. The proof can be easily obtained from the following expression, in which $f(\cdot)$ is an exponential pdf:

$$F_{\text{SINR}}(x) = \Pr\left\{ \frac{S}{N + \sum_{j=1}^{J} I_j} \leq x \right\} =$$

$$= \int_0^\infty \int_0^\infty \dots \int_0^\infty \Pr\left\{ S \leq x \left(N + \sum_{j=1}^{J} I_j \middle| I_j = y_j \right) \right\}$$

$$\cdot \prod_{j=1}^{J} f_{I_j}(y_j)\, dy_j$$

$\square$

The average received power levels can be computed with standard distance-based path loss models [54].

B. User throughput

We are now able to compute the average throughput of UE i in time slot t, $\Gamma_i(t)$, by multiplying $\zeta_i(t)$ obtained with (1) times the average number of symbols per second D_i available for i at the attached BS.

$$\Gamma_i(t) = D_i \zeta_i(t). \tag{3}$$

D_i mainly depends on the scheduler used by the BS. Like in [51], we assume that the Equal Time Scheduler (ETS) is in force, so that each UE receives on average the same amount of symbols, which yields:

$$D_i = \frac{K}{N_i}, \tag{4}$$

where K is the number of symbols per second available for data transmission, and N_i is the number of UEs attached to the BS serving UE i.

C. Throughput optimization

We now exploit the fact that muting and reactivating transmissions at a BS is today possible at millisecond timescale with ABS, as discussed in [52], therefore causing no handovers. Thus, by alternating subsets of BSs $B \subseteq \mathcal{B}$ to transmit, we can control the interference in the system and the SINR distributions without having to continuously deal with BS attachment procedures. Hence, selecting the right subsets of BSs allowed to transmit, and the frequency at which subsets are muted, we can optimize the average user fairness or throughput in a way that is transparent to UEs.

We assign to each subset B of $\mathcal{B}$ a portion P_B of transmission resources, where only BSs and MoBS in B are allowed to transmit, while all other MoBS are muted. For instance, groups of MoBS can be scheduled sequentially so that B be active for a fraction P_B of the system time. The throughput of each user i when B is active, i.e., $\Gamma_i^B(t)$, can be easily obtained considering as interfering BSs in Eq.3 only the ones included in B:

$$\Gamma_i(t) = \sum_{B \subseteq \mathcal{B}} P_B \Gamma_i^B(t). \tag{5}$$

Obviously, if the BS b to which i is attached is not included in B, then $\Gamma_i^B(t) = 0$.

In order to maximize the average user fairness, as well as the overall system throughput, it is then sufficient to optimize over P_B. Specifically, we present a convex optimization which maximizes proportional fairness, namely, the *proportional fair muting* (PFM) problem. Analogous optimization problems can be easily obtained for other fairness metrics.

Problem PFM :

At time t, with N_t UEs in the area, select $P_B, \forall B \in \mathcal{B}$, so to:

$$\begin{aligned}
\text{maximize} \quad & \frac{1}{N_t} \sum_i \log \left(\sum_{B \subseteq \mathcal{B}} P_B \Gamma_i^B(t) \right); \\
\text{subject to:} \quad & \sum_{B \subseteq \mathcal{B}} P_B = 1, \\
& P_B \in [0,1], \quad \forall\ B \in \mathcal{B}.
\end{aligned} \tag{6}$$

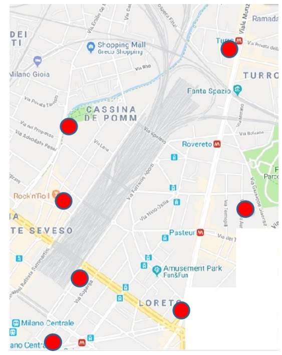


Fig. 7: The area of the central railway station in Milan with 7 fixed macro BSs

ABS muting patterns are generally fixed and can be updated every second (roughly). Problem PFM can be therefore computed on the same time scale, so as to update $\Gamma_i^B(t)$ according to the positions of MoBS and users.

D. Heuristic solution of the PFM problem

Problem PFM can be solved with standard optimization tools (we used the MATLAB optimization toolbox), provided the number of subsets B of $\mathcal{B}$ is not too large. When the number of MoBS to be scheduled is equal to n, the cardinality of the number of subsets B is equal to 2^n, so that the solution of problem PFM becomes rapidly problematic.

However, by examining the optimal solutions in those cases that can be handled with the MATLAB optimization toolbox, we observed that in most cases the largest values of probabilities P_B are associated with subsets of MoBS B comprising either a large number or very few MoBS. We thus decided to implement a simple heuristic approach to optimization that only considers the subsets B comprising:

- no active MoBS (one subset)
- just one active MoBS (n subsets)
- two active MoBS ($\binom{n}{2}$ subsets)
- all but two active MoBS ($\binom{n}{2}$ subsets)
- all but one active MoBS (n subsets)
- all active MoBS (one subset)

By so doing, the heuristic does not consider the entire set of 2^n subsets B of $\mathcal{B}$. Rather, it considers $2 + 2n + 2\binom{n}{2} = n^2 + n + 2$ subsets, and can thus be solved for large values of n. Numerical results in the next section show that the difference between the optimization and the heuristic results is quite small.

VI. Numerical Results

In this section, we describe the settings in which we computed the throughput achievable in TMN scenarios, and then we present the corresponding numerical results.

Our evaluation focuses on two representative case studies. The first one is the geographical area shown in Fig. 7, which comprises the central railway station in Milan, Italy. The second is an area of smaller size covering the Politechnic University of Milan (POLIMI).

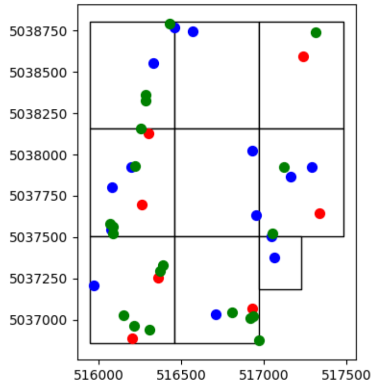


Fig. 8: The area of the central railway station in Milan with 7 macro BS (red dots) and 34 vehicle positions (blue and green dots; the 20 green dots correspond to muted MoBS) at 8 A.M. on April 15, 2015.

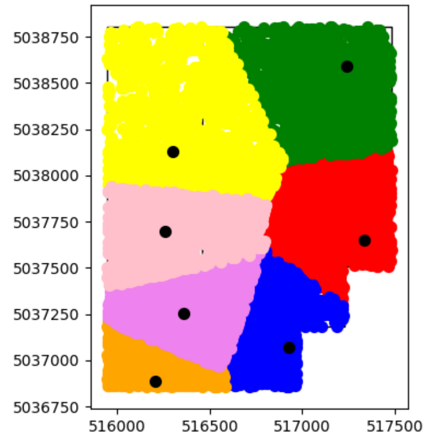


Fig. 9: UE associations to the 7 fixed macro BSs for the case of Fig. 8.

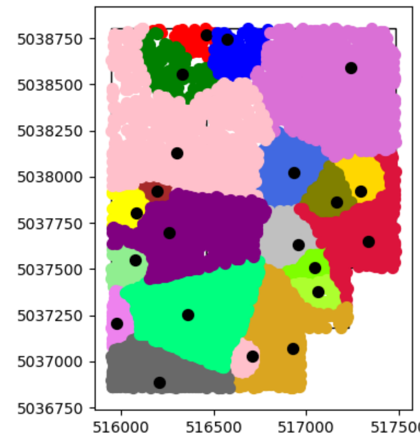


Fig. 10: UE associations to the 7 fixed macro BSs and the 14 useful MoBS for the case of Fig. 8.

A. The railway station scenario

The area in Fig. 7 is divided in nine rectangles. For each of those, we have data about the mobile network traffic and the number of probe vehicles, at 15-minute time intervals and over several days in April 2015. The mobile network traffic refers to data connections and voice calls of one of the largest Italian MNOs, hence amounts to a large fraction of the total data traffic. For the same MNO, we have the positions of fixed BSs. On the contrary, tracked vehicles are less than 1% of those in the area, since they are only those managed by an Italian fleet management operator. We assume that each of the tracked vehicles is equipped with a MoBS, which is coherent with the expected limited penetration rate of mobile small cells in the vehicle population.

For example, in the time interval from 8 A.M. to 8:15 A.M. on April 15, 2015, the reported vehicles positions are as shown in Fig. 8 as blue/green dots, together with the positions of fixed macro BSs as red dots. We clearly see that fixed BS positions are nicely spaced, while vehicles cluster along the main roads surrounding the railway station, and in some cases are very close to fixed BSs, risking to generate excessive interference with their MoBS. It is thus necessary to decide which MoBS to use, so as to obtain acceptable interference (this is a responsibility of the Orchestrator in Fig. 1). In this paper, we preselect the set of useful MoBS, that correspond to blue dots in Fig. 8, with a simple greedy heuristic algorithm. Recalling that useful BSs are always scheduled by the `PFM` optimization (otherwise attached UEs experience no throughput), our algorithm aims at filtering available BSs in order to reduce the overall interference. Assuming that the transmission power of fixed macro BSs is 30 dBm, and the one of MoBS is 20 dBm, we compute for each pair of MoBS (or each pair comprising one MoBS and one fixed BS) the average received signal at both ends, following the path loss model in [54], and we discard the MoBS with the highest value of generated interference. Since the channel model is symmetric, when the highest value of generated interference is due to a pair of MoBS, so that both generate the highest interference value, we discard the MoBS with the highest second value of pairwise generated interference. The process ends when no MoBS generates interference levels higher than -75 dBm. Discarded MoBS are denoted by green dots in Fig. 8.

As regards UEs, since for each rectangle in the map of Fig. 8 we know the total data traffic volume in the considered time slot, but we have no information about UE positions, we randomly place UEs in the rectangles, assuming that one UE is present for each GB of reported traffic. UE associations to fixed macro BSs or MoBS follow a maximum received power criterion. Using the transmission powers mentioned above, the resulting UE associations are as reported in Fig. 9 in the case of fixed macro BS only, and in Fig. 10 in the case when both fixed macro BSs and MoBS are active.

We compute the maximum achievable throughput and the throughput at maximum fairness for the interval between 5 A.M. and 10 P.M. on April 15, 2015, at one-hour spacing. The total number of MoBS, the number of active MoBS, and the total data traffic for each time slot are reported in Fig. 11.

B. Railway station results

By applying the procedure outlined in Section V, it is possible to compute for each time slot t the maximum downlink throughput achievable in the setting we just described, as well as the throughput that corresponds to maximum fairness. The procedure first computes the throughput for each user under each configuration of the system, that is, for each configuration of active/inactive (i.e., transmitting/muted) useful MoBS[1]. If the number of useful MoBS in the area is equal to n, the

[1]Note that we say that a MoBS is useful when it is not discarded by the orchestrator because it could generate excessive interference; useful MoBS can be active or muted in different time intervals according to the chosen time schedule.

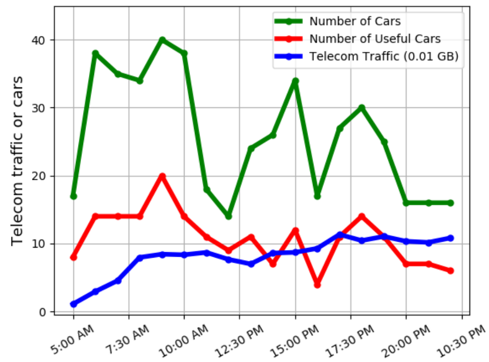


Fig. 11: Number of vehicles, number of useful MoBS and data traffic (in TB) in the area of the central railway station in Milan on April 15 from 5 A.M. to 10 P.M.

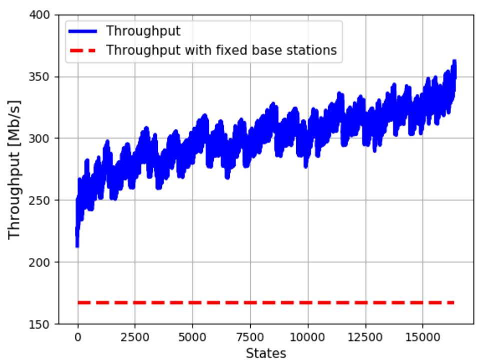


Fig. 12: Throughput of the 2^{14} MoBS configurations in the area of the central railway station in Milan on April 15 at 8 A.M.; configurations are ordered according to increasing number of active MoBS. The red dashed horizontal line refers to the case of only fixed BS, with users attached to fixed BS only.

number of configurations is 2^n. Then, by summing over all users in a given configuration, the total throughput of each configuration is obtained; the maximum over all configurations is the maximum achievable throughput in time slot t. As an example, Fig. 12 reports the total throughput of all configurations in the considered area at 8 A.M. on April 15, ordering configurations so that all cases with one active MoBS appear first, then all cases with two active MoBS, and so on, until the configuration with all active MoBS is reached. For equal number of active MoBS, configurations are ordered according to their binary representation (0 means muted and 1 means active; the all 0 configuration thus mutes all MoBS, while the all 1 configuration has all MoBS active). Since the number of possibly active MoBS is 14, the total number of configurations is $2^{14} = 16,384$. The red dashed horizontal line refers to the case of only fixed macro BS, with users attached to fixed macro BS only.

In this case, the maximum throughput is reached when all 14 MoBS are active, i.e., at the rightmost point in the graph. However, this is not always the case: at multiple times, maximum throughput configurations mute some MoBS.

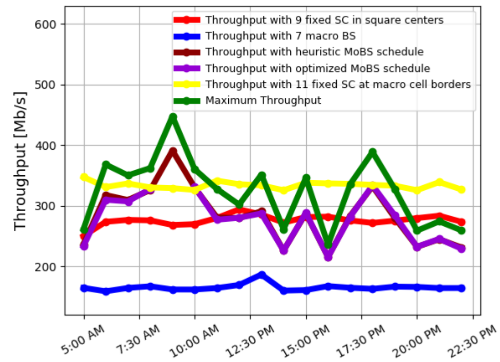


Fig. 13: Throughput with: (i) 7 fixed macro BSs and 9 fixed SCs in square centers, (ii) only 7 fixed macro BSs, (iii) the MoBS configuration yielding maximum throughput, (iv) the time schedule that optimizes fairness (computed with the optimization and the heuristic), (v) 7 fixed macro BSs and 11 fixed SCs in optimal positions, (in Mb/s), in the area of the central railway station in Milan, on April 15 from 5 A.M. to 10 P.M.

Finally, by applying a time schedule that alternates over a set of configurations chosen so that fairness is optimized, the optimized throughput is obtained by exploiting the approach of the PFM problem described above.

In Fig. 13 we report, for each time slot of April 15, five throughput values: 1) the throughput with only the 7 fixed macro BSs (and all UEs associated to just fixed macro BSs); 2) the throughput of the MoBS configuration yielding maximum throughput; 3) the throughput of the time schedule over MoBS configurations that optimizes fairness (computed using both the heuristic and the MATLAB optimization toolbox); 4) the throughput with 9 fixed SCs located in the centers of the 9 squares; 5) the throughput with 11 fixed SCs strategically positioned at the edge of the macro cell coverage. Of course, the throughput of the MoBS configuration yielding maximum throughput exhibits the highest peaks, especially when the number of useful MoBS is high. As expected, the throughput with only 7 fixed macro BSs is lowest. The throughput achieved with 9 fixed SCs in the square centers is lower than the optimum fairness throughput achieved with MoBS, except for most cases when the number of useful MoBS is less than 9 (which happens at 5 A.M., 2 P.M., 4 P.M., 8 P.M., 9 P.M., 10 P.M.).

The throughput achieved with 11 fixed SCs in strategic positions is obviously higher than with 9 fixed SCs in the square centers, and is also higher than the optimum fairness throughput achieved with MoBS, except for 9 A.M. (when the number of useful MoBS is 20) and 6 P.M. (when the number of useful MoBS is 14). This is due to the fact that the MoBS positions are not optimal, but when a large number of MoBS is present, the additional capacity makes up for the loss in

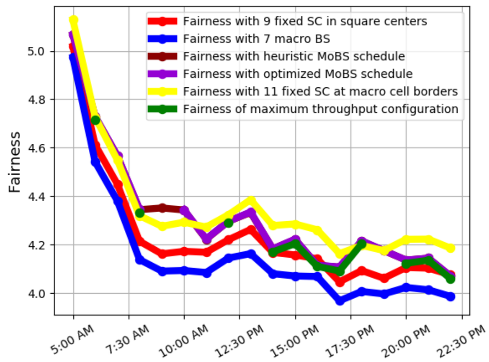


Fig. 14: Fairness per user in the cases: (i) only 7 fixed macro BSs, (ii) 7 fixed macro BSs and 9 fixed SCs in square centers, (iii) fairness of the time schedule obtained with Problem `PFM` (computed with the optimization and the heuristic), (iv) throughput with 7 fixed macro BSs and 11 fixed SCs in optimal positions, (v) fairness of the MoBS configuration yielding maximum throughput, in the area of the central railway station in Milan, on April 15 from 5 A.M. to 10 P.M.

efficiency due to suboptimal positioning.

The difference in the optimum fairness throughput computed using the heuristic and with the MATLAB optimization toolbox is negligible. This is very good news, since the optimal solution of the `PFM` problem becomes problematic already with 20 MoBS. This is the reason why we do not show the point of the optimum fairness throughput at 9 A.M. in Fig. 13.

It is remarkable to see that by using MoBS we can achieve gains of up to about 150% with respect to using only macro BSs, when several vehicles are available.

Fig. 14 reports the fairness values in the same five cases. We can see that the fairness achieved when MoBS are present is always higher than in the cases of only fixed BSs, both when we consider only macro BSs, and when we consider the addition of 9 SCs in the center of rectangles.

The fairness values of the MoBS configurations providing maximum throughput in some cases are not reported, because when the max throughput state (which must be used with a resource share factor $P_B = 1$ to achieve the maximum throughput configuration) is such that not all useful MoBS are active, some users receive zero throughput all the time, so that fairness takes the value $-\infty$. This proves that the use of the time scheduler is extremely important in order not to exclude some UEs from access to network resources.

C. The POLIMI scenario

The area covering the Polytechnic University of Milan comprises 6 rectangles and 5 fixed macro BSs. Fig. 15 reports, for the time interval from 8 A.M. to 8:15 A.M. on April 15, 2015, the vehicles positions as blue/green dots, together with the positions of fixed macro BSs as red dots. The total number of MoBS, the number of useful MoBS, and the total data traffic for each time slot are reported in Fig. 16. We can see that in this case the number of tracked cars and the number of useful MoBS exhibit higher variability with respect to the train station area. In particular, the number of useful MoBS varies between 22 (at 6 A.M.) and 0 (at 9 P.M.).

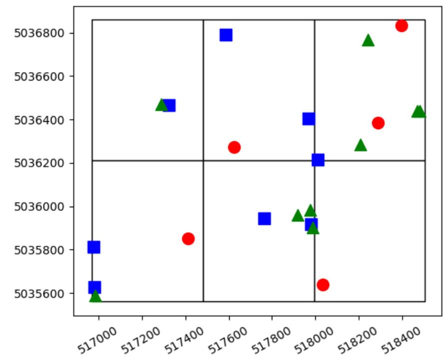


Fig. 15: The area of the Technical University of Milan with 5 macro BS (red circles) and 17 vehicle positions (blue squares and green triangles; the 9 green triangles correspond to muted MoBS) at 8 A.M. on April 15, 2015.

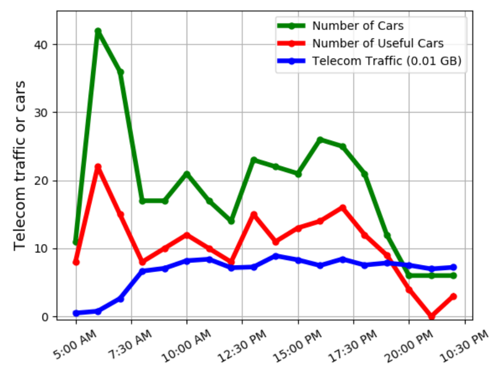


Fig. 16: Number of vehicles, number of useful MoBS and data traffic (in TB) in the area of the Polytechnic University of Milan on April 15 from 5 A.M. to 10 P.M.

D. POLIMI results

In Fig. 17 we report, for each time slot of April 15, five throughput values: 1) the throughput with only the 5 fixed macro BSs (and all UEs associated to just fixed macro BSs); 2) the throughput of the MoBS configuration yielding maximum throughput; 3) the throughput of the time schedule over MoBS configurations that optimizes fairness (computed using the heuristic); 4) the throughput with 6 fixed SCs located in the centers of the 6 squares; 5) the throughput with 7 fixed SCs optimally positioned at the edge of the macro cell coverage. Also in this case, obviously, the throughput of the MoBS configuration yielding maximum throughput exhibits the highest peaks, especially when the number of useful MoBS is high, and the throughput with only 5 fixed macro BSs is lowest.

The throughput achieved with 6 fixed SCs in the square centers is almost invariably lower than the optimum fairness

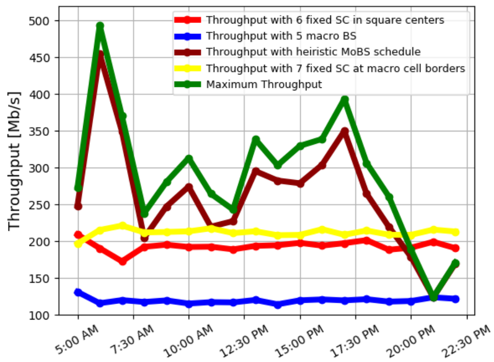


Fig. 17: Throughput in the area of the Polytechnic University of Milan, on April 15 from 5 A.M. to 10 P.M. with: (i) 5 fixed macro BSs and 6 fixed SCs in square centers, (ii) only 5 fixed macro BSs, (iii) 7 fixed macro BSs and 7 fixed SCs in optimal positions, (iv) the time schedule that optimizes fairness (computed with the heuristic),(v) the MoBS configuration yielding maximum throughput (in Mb/s),

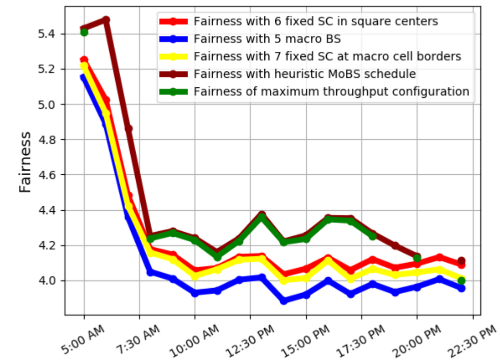


Fig. 18: Fairness per user in the cases: (i) only 5 fixed macro BSs, (ii) 5 fixed macro BSs and 6 fixed SCs in square centers, (iii) fairness of the time schedule obtained with Problem `PFM` (computed with the heuristic), (iv) throughput with 5 fixed macro BSs and 7 fixed SCs in optimal positions, (v) fairness of the MoBS configuration yielding maximum throughput, in the area of the Polytechnic University of Milan, on April 15 from 5 A.M. to 10 P.M.

throughput achieved with MoBS , except for few cases with small number of useful MoBS (in the evening at 8, 9 and 10 P.M., when the numbers of useful MoBS are 4, 0, and 3, respectively).

The throughput achieved with 7 fixed SCs in strategic positions is slightly higher than with 6 fixed SCs in the square centers (except at 5 A.M.), and in most cases significantly lower than the optimum fairness throughput achieved with MoBS, except for evening hours, when the number of useful MoBS is very low.

In general we see that, even if the MoBS positions are not optimal, the maximum throughput achievable in the area can be drastically improved by the presence of MoBS, especially in those time slots when a large number of MoBS is present. For example, at 6 A.M., with 22 useful MoBS, the throughput increases by about 300% with respect to the case of fixed macro BSs only.

The corresponding values of fairness are shown in Fig. 18. We can see that The fairness achieved with the schedule resulting from the heuristic is significantly better than with only fixed macro BSs, or with fixed macro and SC BSs.

VII. Conclusions

In this paper we looked at cellular radio access network architectures where adaptive densification is achieved with small-cell mobile base stations carried by vehicles. Considering the geographical areas around the central railway station and around the Polytechnic University in Milan, Italy, and using real data about data traffic and number of vehicles, we computed the throughput achievable with and without mobile small cell base stations, showing possible capacity increases of up to a factor 4 with respect to the case of macro base stations only, and capacity comparable to the optimal positioning of fixed small cells in the same number.

Our results prove that adaptive densification of radio access networks with small-cell mobile base stations carried by vehicles can be a high-performance and low-cost solution for the rollout of 5G and beyond.

Acknowledgments

This work was supported by the Siebel Energy Institute through the Seed Grant Award 59/2016 and by the European Commission through the H2020 projects 5G-TRANSFORMER (Project ID 761536). The work of V. Mancuso was supported by a Ramon y Cajal grant (ref: RYC-2014-16285) from the Spanish Ministry of Economy and Competitiveness.

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