# Mobile Small Cells for Adaptive RAN Densification: Preliminary Throughput Results

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***Abstract*—In this paper, we study the capacity (i.e., the maximum achievable throughput) of radio access networks that exploit mobile small cell base stations carried by vehicles for adaptive densification in urban areas. While traditional approaches for radio access network densification with fixed small cell base stations are proving ineffective and extremely costly, mobile small cell base stations carried by vehicles can provide adaptive densification while achieving higher efficiency and lower cost. As a matter of fact, the existence of correlations between the number of mobile network subscribers and the number of vehicles in a given area allows for the spontaneous creation of temporary dense small cell deployments where and when needed. Ultimately, this approach to Radio Access Network densification increases efficiency, hence reducing costs for the operator. In this context, we first present an approach for the computation of the maximum throughput that can be obtained in an area served by traditional fixed base stations and mobile small cell base stations. We then provide initial estimates for the throughput improvements with respect to traditional deployments that rely on fixed base stations only. Evaluations in the realistic case study of the main railway station area in Milan, Italy, reveal that the use of mobile base stations achieves throughout gains up to 120% over legacy fixed access infrastructures, while granting higher fairness among subscribers.**

***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) to cope with the forecasted explosive increase in mobile data traffic of the coming years, and with the extremely crowded environments that are becoming increasingly common, such as stadiums, shopping malls and conferences. RAN densification requires the deployment of large numbers of small cell base stations (SCBSs) in those areas where the number of users, and the traffic they generate, is very high – at least for some significant portion of time. The densities of SCBSs that are today forecasted in the 5G vision documents are extreme: up to hundreds or even thousands per square km [1]. This entails large investments for the SCBSs installation and operation: the CAPEX cost of the 5G rollout in Europe is estimated [2] at over 50 billion euros per year, and it should be largely borne by telecommunication businesses.

The number of mobile users and the level of traffic they generate exhibit remarkable spatial and temporal variations [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 of the many SCBSs of their dense RAN in business areas. However, after work, users move out of their offices, so that the RAN capacity necessary in a business district becomes much lower, and many of the installed SCBSs become redundant. The opposite is true for residential areas, where capacity is necessary in the evening, so that a dense RAN layout becomes necessary then, not during working hours. In addition, if a traffic jam occurs at commuting times, densification becomes necessary in the traffic jam location.

This problem is related to the management of radio resources following usage patterns, so that precious bandwidth is not wasted in low traffic areas. However, moving wireless bandwidth alone does not reduce the infrastructure CAPEX, and SCBSs that in extreme cases can remain inactive for days, because they serve areas that only become crowded during special events (for example a stadium), increase cost. The explosion of traffic, coupled with the mobility of users and terminals, has made the situation much worse, and the increasingly common habit of using smartphones during crowded events, such as a rock concert or a football match, makes the problem even harder.

The traditional approach of dimensioning a dense RAN for peak traffic is extremely costly, requiring the dense deployment of SCBSs in both business and residential districts, and extremely dense coverages of stadiums, and leads to low resource utilization (hence low return on investment) for long periods of time. In order to improve this situation, it would be extremely beneficial to have, for instance, a large number of SCBSs in business districts during the day only, and in residential districts during the evening only. One possibility is to deploy a dense SCBS coverage in all areas, switching them on and off as needed. This can bring savings in OPEX, especially those related to energy [5], but does not alleviate the CAPEX due to cell deployment.

Another possibility is to move SCBSs from business areas to residential areas and back, so as to have the capacity of those cells where and when needed. MNOs use small numbers of truck-mounted base stations (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 communication in disaster areas [7]–[9]. However, in this paper we look at a

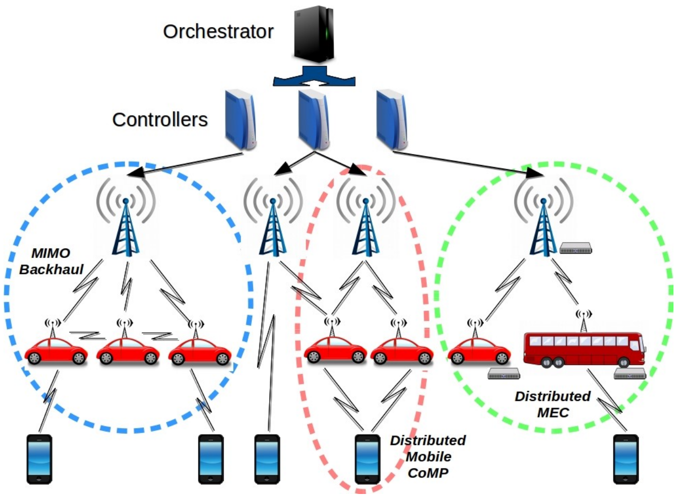


Fig. 1: The twice mobile networking (2MN) concept and its potential applications in the next generation of dynamically controlled radio access networks

completely new use for mobile SCBSs, studying the impact of large numbers of randomly positioned vehicle-mounted SCBSs on the implementation of dense RANs.

As a matter of fact, vehicles have the nice property of moving together with end users. Thus, in a business district during working hours we normally have both many end users and many vehicles. If a significant fraction of those vehicles carries a SCBS, a temporary dense small cell deployment is created. Quite interestingly, this temporary dense SCBS deployment will be recreated in residential districts when drivers return home with their cars, or in traffic jam areas. We demonstrated and quantified such a correlation between the number of vehicles and that of end users, hence between telecommunication traffic and potential SCBS deployments, in a recent analysis based on real-world data [10].

Of course, the dense small cell RAN layouts resulting from vehicle-mounted SCBSs have quite different properties than the dense small cell RANs carefully planned by MNOs, and this poses a number of challenging scientific issues. Among those, the foremost problem is that, while planners of BS deployments carefully select BS positions so as to avoid interference and maximize the effectiveness of BS coverage, drivers drive and park their vehicles with no awareness of network planning needs. This results in unplanned BS deployments, which call for careful adaptive network management approaches.

In this paper, we introduce the *twice-mobile networking* – or 2MN for short – paradigm, which brings together mobile users (as in legacy cellular networks) and mobile small cell base stations (MoBSSs), hence the name. We then tackle the major problem of interference management outlined above. To this end, we first present an approach for the computation of the maximum downlink throughput achievable in an area served by traditional fixed BSs and MoBSSs. Then, we develop an easy-to-deploy optimization that selects active MoBSSs with the aim of maximizing overall throughput or user fairness. Finally, we provide initial estimates for the throughput and fairness improvements provided by MoBSSs: our quantitative assessment considers a representative case study of the area around the main railway station in Milan, Italy, and relies on real data about vehicle mobility and data traffic.

The rest of this paper is organized as follows. Section II briefly describes the 2MN concept. Section III describes the approach that we used for the calculation of the achievable throughput and fairness. Section IV presents and discusses numerical results. Section V briefly overviews related work. Finally, Section VI concludes the paper.

## II. Twice Mobile Networking

A schematic picture of a portion of a 2MN is shown in Fig. 1. The urban area is covered by standard cells, defined by the planned deployment of fixed macro/micro BSs, as we know it today. In addition to this traditional coverage, vehicles carrying MoBSSs, either parked along streets or driving, define a temporary dense coverage of those portions of the urban area where the end user terminals (or User Equipments – UEs) concentration is higher, through small cells which overlap with macro/micro cells, and provide the necessary additional capacity where needed, when needed (mostly outdoor). Each BS, whether fixed or vehicle-mounted, is connected to the core network through a front/backhaul link, which can be either wired or wireless for fixed BSs, but must (obviously) be wireless for MoBSSs. We assume that the connection between a MoBS and the fixed network is implemented with a broadband wireless technology, e.g., with MIMO or millimetre wave links, so as to have sufficient capacity for the support of the traffic generated by all end users connected to the MoBS. Furthermore, we assume that such broadband links smartly avoid interference with the lower frequency channels connecting either fixed BSs or MoBSSs to UEs.

As shown in the picture, a broadband link (e.g., a low-power millimeter wave link) is also available between MoBSSs. 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 either too long or not available due to obstacles, other (possibly multi-hop) front/backhaul opportunities are possible through neighbor MoBSSs.

In addition to what mentioned above, the adoption of 2MN with MoBSSs can also be used to provide coordinated multi-point (CoMP) transmissions toward end users (although using a dynamic infrastructure rather than a legacy static topology of base stations), as well as distributed MEC (i.e., mobile edge computing, or multi-access edge computing) resources. The novel functionalities enabled by 2MN in the radio access network require, as shown in the topmost part of Fig. 1, the introduction of network controllers coordinated by a resource orchestrator, which is however compatible with current SDN/NFV trends [11]. Although all these aspects are important for the practical deployment of 2MN and its market applications, we leave them out of the scope of the paper, in which we instead shed light on the basic potential of 2MN.

## III. Throughput Calculation and Optimization

In this section, we summarize the results presented in [12] for the performance evaluation of systems with BSs that can be muted on a millisecond timescale, and relay groups. Such results are here applied to the 2MN case to evaluate analytically the maximum downlink throughput performance achievable when MoBSs are in place. This capacity characterization allows the assessment of the gain enabled by MoBSs, and the formalization of an optimization problem that copes with the classical issue of interference observed in dense scenarios. The result unveils how to select, at each given time, which MoBS should be allowed to transmit and which ones should be muted instead, so to control interference. Note that the approach we describe is used to just mute MoBS, not fixed BS, but it can also handle the muting of fixed BS.

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 (in Section III-A). Afterwards, we compute the downlink throughput obtained by a UE (in Section III-B) and, based on this result, we design an easy-to-deploy optimization that selects active MoBSs with the aim of maximizing overall throughput or user fairness (in Section III-C).

### 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 during which the location of UEs and MoBSs can be considered as fixed. Furthermore, we assume that UEs attach to BSs (either fixed ones or MoBSs) according to the strongest received signal.

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 [13] for further details on MCS mapping examples). Considering time slot $t$, where UEs and MoBSs locations can be considered as fixed, the transmission efficiency $\zeta_i(t)$ of UE $i$ can be then computed as:

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

where $\mathcal{M}$ is the set of MCSs, $b_k$ is the number of bits per symbol for MCS $k$, $(T_k^{\min}, T_k^{\max}]$ is the interval of the SINR for MCS $k$, and $F^t_{\text{SINR}}$ 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 [14], in urban environments, UEs are most likely to experience Rayleigh fading. For this reason, we assume that the power received by 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, $\forall x \geq 0$:*

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

*Proof.* The proof can be easily obtained from the following expression, in which $f(\cdot)$ is a negative exponential pdf used to characterize the power of the signal received under Rayleigh fading assumptions:

$$F_{\text{SINR}}(x) = \Pr\left\{ \frac{S}{N + \sum_{j=1}^{J} I_j} \leq x \right\} = \\ = \int_0^\infty \int_0^\infty \dots \int_0^\infty \Pr\left\{ S \leq x \left( N + \sum_{j=1}^{J} I_j \middle| I_j = y_j \right) \right\} \\ \cdot \prod_{j=1}^{J} f_{I_j}(y_j)\, dy_j$$

□

The average received power levels can be computed with standard distance-based path loss models [15].

### 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.

$$\Gamma_i(t) = D_i \zeta_i(t). \quad (3)$$

$D_i$ mainly depends on the scheduler used by the BS. In this paper, 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:

$$D_i = \frac{K}{N_i}, \quad (4)$$

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 time-scale (see the Almost Blank Sub-frame (ABS) tool, as an example [13]), therefore causing no user handover. 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 MoBSs in $B$ are allowed to transmit, while all other MoBSs are muted. For instance, group of MoBSs 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 base stations 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 MoBS $b$ 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:

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

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 MoBSs and users.

## IV. Numerical Results

In this section, we describe the settings of our preliminary analysis of the throughput attained in 2MN systems, and then we present the corresponding numerical results.

### *A. Case study*

Our evaluation focuses on one representative case study, i.e., the geographical area shown in Fig. 2, which comprises the central railway station in Milan, Italy. The map area 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 am to 8:15 A.M. on April 15, 2015, the reported vehicles positions are as shown in Fig. 3 as blue/green markers, together with the positions

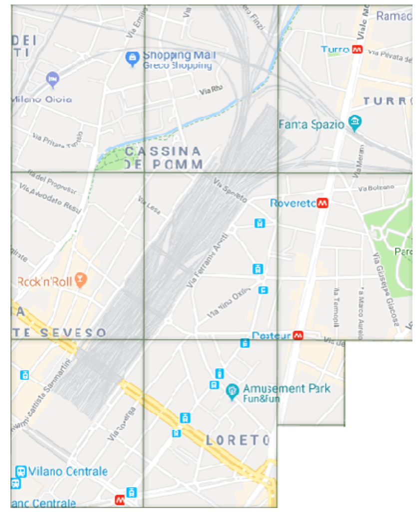

Fig. 2: The area of the central railway station in Milan

of fixed BSs as red circles. We clearly see that fixed BS positions are nicely spaced, while vehicles cluster along the main roads surrounding the railway station, and in some case are very close to fixed BSs, risking to generate excessive interference with their MoBSs. 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 MoBSs, that correspond to blue triangles in Fig. 3, with a simple greedy heuristic algorithm. Recalling that useful BSs are always scheduled by the PFM optimization (otherwise, attached users experience no throughput), our algorithm aims at filtering available MoBSs in order to reduce the overall interference. Assuming that the transmission power of fixed BSs is 30 dBm, and the one of MoBS is 20 dBm, we compute for each pair of MoBSs (or each pair comprising one MoBS and one fixed BS) the average received signal at both ends following the path loss model in [15], and we eliminate the MoBSs 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 MoBSs, so that both generate the highest interference value, we eliminate the MoBS with the highest second value of pairwise generated interference. Removed MoBSs are denoted by green squares in Fig. 3.

As regards UEs, since for each rectangle in the map of Fig. 3 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 BSs or MoBSs follow a maximum received power criterion. Using the transmission powers mentioned above, the resulting UE associations are as reported in Fig. 4 in the case of fixed BS only, and in Fig. 5 in the case when both fixed BSs and MoBSs are active.

We compute the maximum achievable throughput for the interval between 5 A.M. and 10 P.M. on April 15, 2015, at

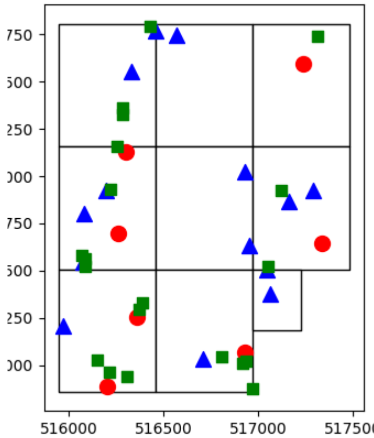


Fig. 3: The area of the central railway station in Milan with BS and vehicle positions at 8 A.M. on April 15, 2015.

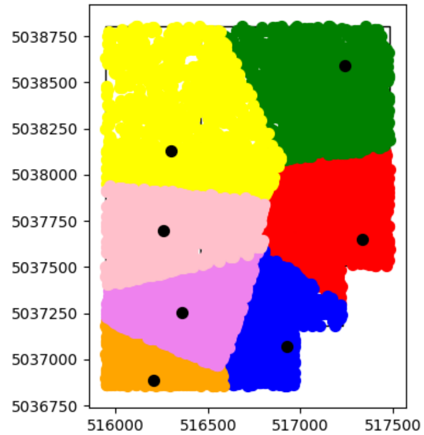


Fig. 4: UE associations to fixed BSs (i.e., without 2MN) for the topology of Fig. 3.

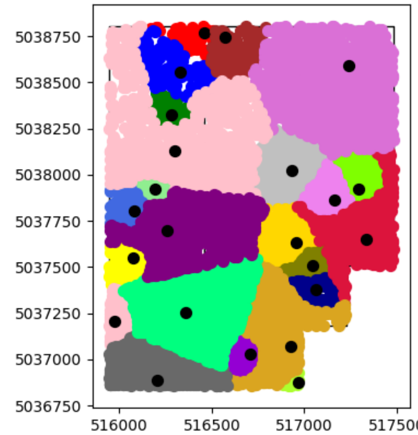


Fig. 5: UE associations to fixed BSs and MoBSs for the case of Fig. 3.

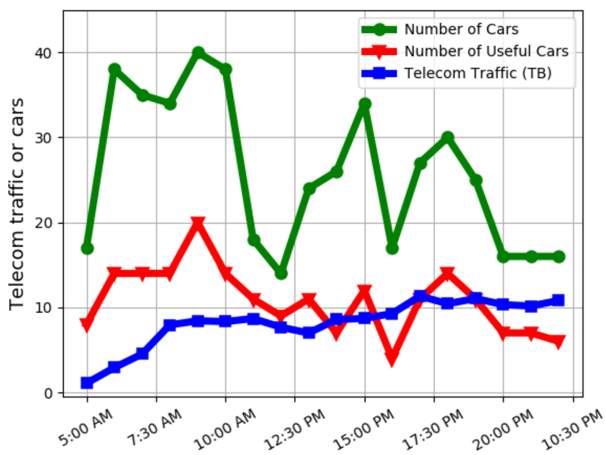


Fig. 6: Number of vehicles, number of MoBSs and data traffic (in TB) in the area of the central railway station in Milan on April 15 from 5 A.M. to 10 P.M.

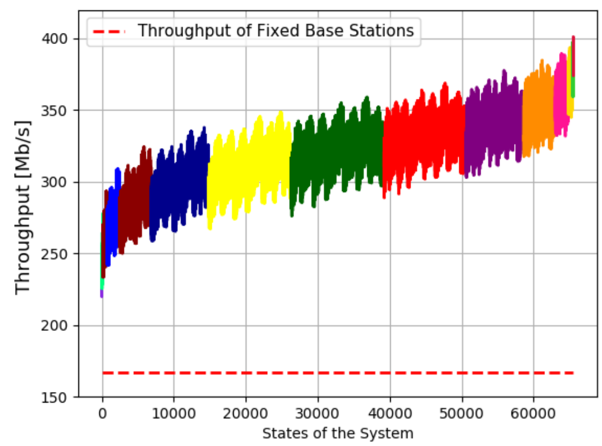


Fig. 7: Throughput of the $2^{16}$ MoBS configurations in the area of the central railway station in Milan on April 15 at 8 A.M.; configurations are ordered according to increasing number of active MoBSs (colors identify the number of active MoBSs; for equal number of active MoBSs the order follows the binary representation). The red dashed horizontal line refers to the case of only fixed BS, with users attached to fixed BS only.

one-hour spacing. The total number of cars, the number of useful (i.e., preselected) MoBSs in the area and the total data traffic for each time slot are reported in Fig. 6.

### *B. Results*

By applying the procedure outlined in Section III, 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 combination of active/inactive (i.e., transmitting/silent) MoBSs. If the number of useful MoBSs in the area is equal to $n$, the 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. 7 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 MoBSs, and so on, until the configuration with all active MoBSs is reached. Different colors identify different numbers of active MoBSs. For equal number of active MoBSs, configurations are ordered according to their binary representation (0 means inactive and 1 means active; the all 0 configuration thus mutes all MoBSs, while the all 1 configuration has all MoBS active). Since the number of possibly active MoBSs is 16, the total number of

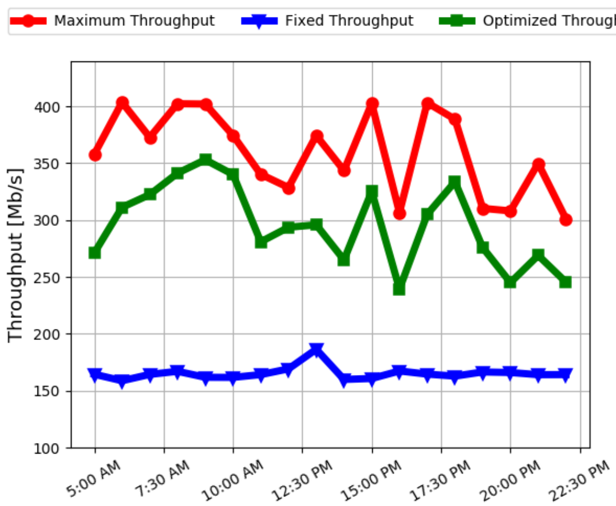


Fig. 8: Throughput with only fixed BSs, throughput of the MoBS configuration yielding maximum throughput and throughput of the time schedule that optimizes fairness (in Mb/s) in the area of the central railway station in Milan on April 15 from 5 A.M. to 10 P.M.

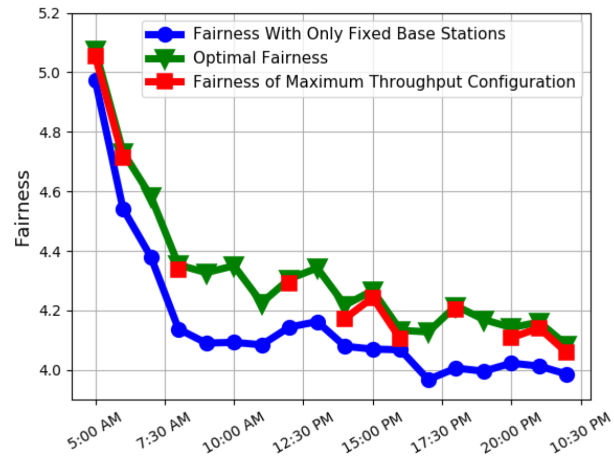


Fig. 9: Fairness per user in the cases: i) only fixed BSs, ii) MoBS configuration yielding the maximum throughput (points not reported correspond to maximum throughput configurations where some users receive zero throughput), and iii) optimal fairness time scheduling, in the area of the central railway station in Milan on April 15 from 5 A.M. to 10 P.M.

configurations is 65536. The red dashed horizontal line refers to the case of only fixed BS, with users attached to fixed BS only.

In this case, the maximum throughput is reached when all 16 MoBSs are active, i.e., at the rightmost point in the graph. However, this is not always the case: at multiple times, maximum throughput configurations exclude some MoBS. In particular, at 7 and 9 A.M. and at 5 and 7 P.M. one MoBS is excluded, and at 10 and 11 A.M. and at 1 P.M. two MoBSs are excluded.

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. 8 we report for each time slot of April 15 three throughput values: the throughput with only fixed BSs (and all UEs associated to just fixed BSs), the throughput of the MoBS configuration yielding maximum throughput, and the throughput of the time schedule that optimizes fairness. Of course, the throughput of the MoBS configuration yielding maximum throughput is highest, and the throughput with only fixed BSs is lowest. It is remarkable to see that by using MoBSs we can achieve gains of about 150% if fairness is not an issue, and gains of almost 120% when fairness is optimized.

Fig. 9 reports the fairness values in the same three cases. We can see that the fairness achieved when MoBSs are present is always higher than in the case of only fixed BSs. 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 MoBSs 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.

## V. Related work

Several authors have proposed the use of cars as active elements of a telecommunication network. Studies in vehicular networking looked at the possibility to integrate a Wi-Fi Acces Point (AP) in cars, so that they can provide connectivity to neighboring vehicles. For example, [16] suggested mobile vehicular gateways to exploit Wi-Fi for vehicle-to-vehicle (V2V) communications and LTE for vehicle-to-infrastructure (V2I) communications. The authors of [17] proposed Virtual APs to extend the reach of roadside access points: when a vehicle receives a message, it stores it, and it will later rebroadcast it into non-covered areas. The authors of [18]–[20], suggested the use of parked vehicles, in addition to roadside units, to improve the performance of services requested by moving cars. In [21], mobile nodes were used for the collection of data from sensors.

These approaches are different from a 2MN, which is based on the use of vehicles to carry SCBSs that achieve an adaptive densification of the RAN. The 2MN concept allows a seamless integration of MoBSs with “standard” macro- and micro-BSs at fixed locations. MoBSs provide additional capacity, when and where needed, to the end users of an otherwise traditional RAN. UEs can thus seamlessly transfer their services from a standard BS to a MoBS and back. The 2MN concept generalizes the idea underlying the early deployments of SCBSs on public transport vehicles to serve passengers [22]–[25], and the proposal of using vehicle-carried SCBSs in public safety networks [26]. A concept similar to 2MN has also been hinted at in recent works [27], [28], where 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.

## VI. Conclusions

In this paper we have looked at cellular 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 in Milan, Italy, and using real data about data traffic and number of vehicles, we have computed the throughput achievable with and without mobile small cell base stations, showing possible capacity increases of about 150%. In addition, optimizing fairness among individual users, we have showed that throughput gains up to about 120% are possible even when strict fairness constraints are enforced.

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 new radio access networks in 5G and beyond.

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