Milano Digital City: Planning the Municipal Wireless Network of Milano

Stefano Bregni, *Senior Member, IEEE*, Maurizio Décina, *Fellow, IEEE*, Paolo Giacomazzi, Alessandro Poli

Politecnico di Milano, Dept. of Electronics and Information, Piazza Leonardo Da Vinci 32, 20133 Milano, ITALY
Tel.: +39-02-2399.3503 – Fax: +39-02-2399.3413 – E-mail: {bregni, decina, giacomaz, poli}@elet.polimi.it

***Abstract* — Planning municipal wireless access networks is a challenging task, since many optimization choices must be taken in large metropolitan areas while, in turn, the number of free variables is very large, on the order of several millions. The aim is to optimize the position of wireless access points, as well as their connection to the backbone network. This paper is focused on the "Milano Digital City" project, i.e. the municipal wireless access network of Milano. We formalized the problem of choosing appropriate access points' locations and connecting the wireless access network to the backbone network. We designed an optimization algorithm, based on a fast heuristic approach, and applied it to a real-world scenario: the 51-km^2 city area of Milano (Italy). The proposed heuristic algorithm was extended to support mobility. Results show that the additional cost for supporting user mobility is limited to few percent.**

***Index Terms* — Access networks, wireless networks, municipal networks, network planning.**

I. Introduction

Planning Municipal Wireless Access Networks (MWAN) has become a hot topic lately. Worldwide, about 500 projects have been started [1], and the interest of municipalities in this field is rapidly increasing, due to the significant and important services for citizens enabled by these infrastructures.

A municipal wireless access network is a viable solution to provide the community with a broadband network paying a relatively low deployment cost, if compared to wired networks [2]. Though, the success of MWANs greatly varies from city to city. Cities, where a well-planned risk-sharing model between the private and the public sectors has been implemented, typically obtained greater success.

Many works in literature focus on economic or social issues of municipal wireless networks. In [3], the role of municipalities as wireless broadband access providers is examined, also presenting current business models. Article [4] provides a high-level framework, for guiding communities that seek to implement a MWAN, which consists on three steps: identification of goals, planning and implementation. Article [5] analyzes the motivation driving MWAN deployment in three U.S.A. major metropolitan areas, considering standards and technology evolution. A variety of technologies and options for wireless access networks is explored in [6], in addition to actual deployment examples. Finally, article [7] is an attempt to study the feasibility of a MWAN in a specific context, exploring political issues and technological options; a coarse-grained estimation of costs is also reported.

However, the topic of MWAN planning is not treated thoroughly in current literature, mainly due to the difficulty of the problem. This complex task requires the identification of access point sites and the connection of the wireless access network to a backbone infrastructure.

This paper formalizes the problem and outlines an optimization algorithm that minimizes the total cost of the infrastructure to be deployed. A real case scenario is studied: the 51-km^2 area of the city center of Milan. The paper also suggests an upgrade of the proposed methodology, in order to support user mobility, and illustrates the results obtained by introducing mobility support in a real case scenario.

II. Milano Digital City: Outline of the Project

The 15% of the Italian Information and Communication Technology (ICT) companies is concentrated in Milano, as well as the 40% of the national research, the 37% of patents and the 54% of the national revenues of the design industry. Moreover, the 70% of streets in the metropolitan area is passed with optical fibers, as well as the 60% of buildings.

A. Background

In 2007, when Milano was candidate for the 2015 Expo (finally assigned to Milano in March 2008), the local authority for Research and Innovation started the design of a *muniwireless* (Municipal Wireless) network based on the exploitation of the extensive optical fiber asset of the city and of wireless access technologies. This project, named *Milano Città Digitale* (i.e., Milano Digital City), has been developed in cooperation with the group of the authors of this paper at the Dept. of Electronics and Information of the Politecnico di Milano.

B. Foreground

The first goal of the "Milano Città Digitale" project is to define the architectural, functional and service components of the municipal network infrastructure. The network must be robust, scalable and durable. It must be able to support new technologies, spanning from the current WiFi and 3G HSDPA (High Speed Downlink Packet Access) to 4th generation systems such as WiMAX and LTE (Long Term Evolution).

The municipal infrastructure will be the basic platform for provisioning a rich set of value-added services for the citizen, e.g.: video surveillance, info-mobility, environmental control, telemedicine, tourism, services for students and aged/disabled persons. These services require independence from the network platform and the possibility of guaranteeing different performance and quality levels in different zones of the city.

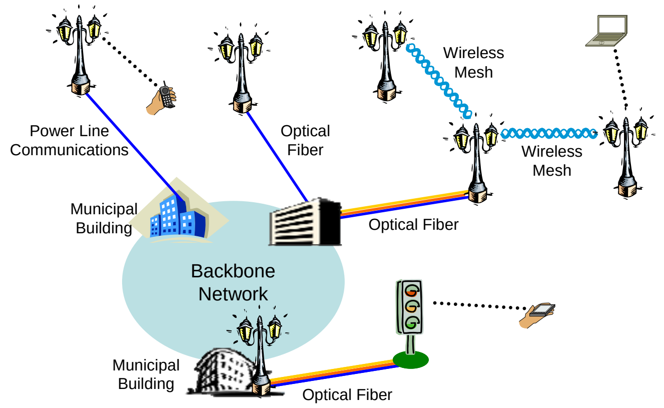

Fig. 1: Interconnection of wireless access points to the backbone network. Connections can be shared among access points through wireless meshing.

In conclusion, the services provided by the "Milano Città Digitale" platform are among the main objectives of the current modernization activities of the city. The Department of Information Systems of the municipality contributes to the definition of the technological platform for service provisioning.

The "Milano Città Digitale" project differs from other National muniwireless projects for its special focus on institutional services for security, road traffic control, environment, and social services such as communications for students and underprivileged citizens, assistance to the aged, and so on. Institutional community services on the net will become one of the distinctive features of a municipality.

C. Underground and Above-Ground

The technical project is based on the concept of exploiting to the utmost scale the large variety of infrastructure assets of the Milano's Municipality in the metropolitan area, namely:

- the poles of the public illumination systems,
- the street lights,
- the network for the monitoring of the metropolitan area,
- the control network of the public transport company (ATM),
- the Campus-II optical fiber network connecting about 800 municipal buildings,
- the optical fiber network of the Direction of Transportation and Mobility,
- the large optical fiber network of Metroweb,
- the electric grid of A2A (the public energy utility) that can be used to carry Power Line Communications (PLC).

The poles of the public illumination system and street lights can be used to hold wireless access points. Backhauling (i.e., connecting the radio access network to the fixed backbone network) can be obtained with radio mesh networks, optical fibers, or power line communications (Fig. 1).

D. Network Planning and Trials

In this complex picture, we developed MUWI, a software tool for the optimal cost-oriented design of a MUnicipal WIreless network infrastructure. MUWI optimizes both radio coverage with diverse bandwidth requirements and wired backhauling, in very large metropolitan areas with extensions on the order of hundreds of square kilometers. MUWI minimizes the cost of the entire infrastructure and it provides the detailed design and budget of the infrastructure. In the next phase of the project, MUWI will be used to assess the relevance and utility of the available assets, as well as the sensitivity of costs to system parameters.

Forthcoming activities in the "Milano Città Digitale" project will focus specifically on services for the city and the community, by providing a detailed analysis of the portfolio of priorities and needs, and by defining the requirements of the platform for the provisioning and management of services.

Trial systems will be deployed in two significant areas of the city, in order to demonstrate some sample services. In the selected trial areas, the Municipality is completing the deployment of a significant asset: the fiber optic network and the infrastructure for public video-surveillance.

In the San Siro area, around the soccer stadium, the fiber-wireless infrastructure will be used to experiment control services such as surveillance on public transportation vehicles and car parking management. In the central Duomo area, advanced services for tourism will be tested (virtual guide, interactive video maps, context aware services on transportation, parking, restaurants and so on).

III. The Optimization Problem

The goal of the optimization algorithm is the outdoor coverage of a given metropolitan area with a wireless network at minimum cost. All chosen access points must be connected to a backbone network.

A. Physical Requirements

First, the physical requirements of the municipal wireless network have been specified formally.

- The reference area conformation is described by the *metropolitan area map matrix* $\mathbf{M} = \{m_{ij}\}$, identifying, for each latitude-longitude pair, the height in meters of the highest construction in the point, from a fixed reference altitude rh.
- For each ij-point in the metropolitan area map, the *coverage requirement map* $\{c^{req}_{ij}\}$ identifies whether an outdoor point must be covered by the wireless network (1) or not (0). A *coverage ratio requirement* parameter cr^{req} (typically ~1) defines the minimum acceptable ratio of points actually covered by the wireless network to the total number of points that are required to be covered.

Since different zones in the metropolitan area map have different environmental peculiarities, different population densities and users with different behavior, the resulting wireless network should be designed accordingly. Different requirements are taken into account by defining, as further input data:

- the *coverage radius map* $\mathbf{R} = \{r_{ij}\}$, defining, for each point, the maximum distance from any access point to the points it is requested to cover;
- the *cluster size map* $\mathbf{S} = \{s_{ij}\}$, defining, for each point, the maximum size of a cluster of access points that should share one connection to the backbone network; cluster size greatly affect the wireless network available bandwidth;
- the *backhaul radius* br, defining the maximum distance between a pair of access points that can reciprocally communicate, and thus possibly form a wireless mesh *cluster*; ac-

cess points in the same cluster share a single connection to the backbone network.

B. Technology Resources

The infrastructural resources are defined as follows.

- A set of available *backbone connection technologies* is given as input. For each connection technology ct_k, the *cost* *c* is given, as a function of the link length. This cost also includes a fixed cost for the activation of the connection.
- A set of all the available *backbone interconnection points* b_j is considered. An interconnection point can be connected directly to the backbone network or to another interconnection point. For each interconnection point, a set of properties is defined, namely position, interconnection type, costs, backbone interconnection points that can be reached, etc.
- A set of all the poles p_j in the metropolitan area that can host a wireless access point. For each pole, properties are defined, namely the position, the reachable backbone interconnection points, the height, costs, etc.

C. Decision Variables

The optimization algorithm must decide, among others:

- whether a pole is used or not for hosting an access point;
- every access point is assigned to a particular *cluster* of access points; for each cluster, one access point is chosen for being connected to the backbone network;
- whether a backbone interconnection point is used or not for receiving ingoing connections;
- what connection technology for each access point,
- whether access points are connected directly to the backbone network or to another interconnection point.

D. Line of Sight and Coverage Evaluation

In the 3D map of the area, points are said to be in *sight* when, for every *ij*-position, the height *z* of the straight line is above the area m_{ij} quota, i.e. no obstacles are in between. To cope with rounding and approximation issues, this constraint is relaxed, allowing the existence of a limited overall length occupied by obstacles.

For each *ij*-point in the metropolitan area map, the *coverage map* $\mathbf{C} = \{c_{ij}\}$ identifies how many access points are able to reach and cover the specific point. An *ij*-point is said to be covered by an access point placed on a pole if the 3D point is in sight of the point placed on the top of the pole and the distance between the two points is no greater than the radius identified by the coverage radius map r_{ij}.

E. Additional Constraints

Also other constraints are enforced, viz. the coverage ratio, that all interconnection points are connected, that the same connection technology is used on both sides, the maximum number of connections for each point, the max number of access points per cluster, that each access point not connected to the backbone is in sight with another access point, etc.

F. Objective Function

The objective function to minimize is the total cost of the municipal wireless network, i.e. the sum of following items:

- sum of connection costs of used interconnection points (function of the number of ingoing connections for each technology plus the cost of the specific connection technology for the outgoing connection);
- sum of connection costs of used interconnection points not directly connected to the backbone;
- sum of connection costs of poles hosting an access point;
- sum of connection costs of poles hosting an access point connected to the backbone.

IV. The Optimization Algorithm

Our heuristic methodology for planning the municipal network comprises two phases: a) wireless *coverage* of the designated area; b) *connection* of access points *to the backbone* network. Phases are independent. However, the phase a), while exploring its solution space, also takes into account the impact of its choices over the objective function because of phase b).

A. Wireless Coverage

This algorithm aims at finding a set of poles where to install access points, so that coverage requirements are satisfied. The heuristic algorithm explores iteratively the space of solutions, aiming at minimizing the totals cost.

Access points must be grouped in clusters, where wireless mesh network communication is feasible. Even though the minimization of overlaps among the wireless coverage of different access points is not a requirement, our algorithm also tries implicitly to minimize such zones.

B. Connection to the Backbone Network

This goal of this phase is identifying, in each cluster, the access point to connect to an interconnection point and the interconnection points to use. Also in this case, the heuristic algorithm explores iteratively the space of solutions, aiming at minimizing the totals cost.

V. Planning Results: the Network of Milano

A. Optimization Scenario

Our algorithm has been applied to a 51-km^2 rectangular area of the city center of Milan. Since the information about the height of the buildings is not extensively available, the area map matrix **M** only discriminates between points where there is a street or a building (two possible values). The coverage requirement map specifies that all streets and all parks in the area are required to be covered by the wireless network (Fig. 2). The coverage ratio requirement parameter was set to $cr^{\text{req}} = 0.97$. The cluster size map **S** has been set to 3 in all points. The backhaul radius has been safely set $br = 200$ m.

The available backbone connection technologies are: two classes of *Optical Fiber* (respectively provided by a Third Party company or by the Municipality of Milan), *Power Line Communication* (PLC) and *Direct Connection* with a local area network link. A direct connection is a connection that can be reached with a local link, for example when the access point is located on the same building as the interconnection point. The cost of the Third-Party optical fiber is 7 €/m, while the optical fiber of the Municipality of Milan is free. A PLC link has fixed cost 95 €, accounting for the PLC client installation, plus 480 € every 150 m (for signal repeaters, if the link is longer than 150 m). A direct connection has fixed cost 500 €.

We considered four types of backbone interconnection points, each one with associated market costs:

- *Third-Party Cabinets*, owned by a 3rd-party company (8 in the area) and directly connected to the backbone; they can terminate unlimited 3rd-Party Optical Fibers and 3 PLC connections;
- *CampusII Buildings* owned by the Municipality of Milan (319 in the area) and directly connected to the backbone; they can terminate unlimited Third-Party Optical Fibers, 3 PLC connections and one Direct Connection;
- *Municipal Traffic Control Facilities sites*, owned by the Municipality of Milan (582 in the considered area), directly connected to the backbone; they can terminate unlimited Municipal Optical Fibers and one Direct Connection;
- *Medium- to Low-Voltage Electric Cabins*, owned by the Local Electric Grid Company of Milan (one per electric cell, 778 in the area), not directly connected to the backbone; they can reach any 3d-Party Cabinet and any CampusII building with 3rd-Party Optical Fibers and terminate 3 PLC connections.

We considered 3 types of poles:

- *Streetlamp poles*, owned by the Local Electric Grid Company of Milan (85,285 in the area); they can reach any Third Party Cabinet and any CampusII building with Third Party Optical Fibers, or the nearest Medium to Low-Voltage Electric Cabin with PLC technology.
- *CampusII poles*, in CampusII buildings, owned by the Municipality of Milan (319 in the considered area); they can reach CampusII buildings with a Direct Connection.
- *Traffic Lights and CCTV poles*, owned by the Municipality of Milan (909 in the considered area); they can reach any Municipal Traffic Control Facility with Municipal Optical Fibers, the nearest Medium to Low-Voltage Electric Cabin with PLC technology, and one specific Municipal Traffic Control Facility with a Direct Connection.

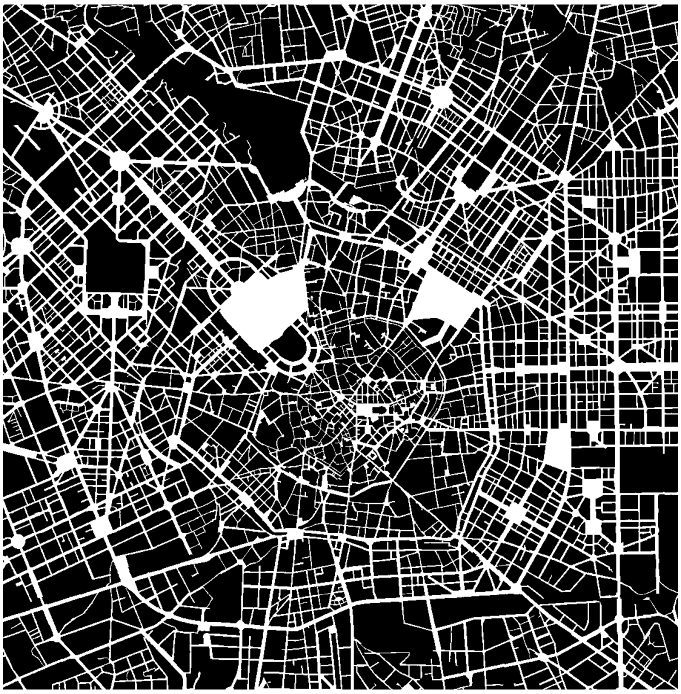

Fig. 2: Coverage requirement map of the 51-km^2 area of the city center of Milan under planning (areas to be covered in white).

B. Optimization Results

The MUWI optimizer was run on scenarios as above, for different values of the coverage radius maps. Fig. 3 shows an example of results. Optimizations were carried out on the following 5 different scenarios.

1. THIRD PARTY: only Third Party Cabinets interconnection points and Streetlamp poles are available.
2. CAMP+TC: Third Party Cabinets, CampusII Buildings, and Municipal Traffic Control Facilities interconnection points are available; Streetlamp, CampusII, Traffic Lights and CCTV poles are available.
3. TC+PLC: Third Party Cabinets, Municipal Traffic Control Facilities and Medium to Low-Voltage Electric Cabins interconnection points are available; Streetlamp, Traffic Lights and CCTV poles are available.
4. CAMP+PLC: Third Party Cabinets, CampusII Buildings and Medium to Low-Voltage Electric Cabins interconnection points are available; Streetlamp and CampusII poles are available.
5. CAMP+TC+PLC: Third Party Cabinets, CampusII Buildings, Municipal Traffic Control Facilities and Medium to Low-Voltage Electric Cabins interconnection points are available; Streetlamp, CampusII Traffic Lights and CCTV poles are available (the full scenario).

The execution of the algorithm for one optimization took about 3 hours on a PC equipped with two Intel Xeon E5440 quad-core 2.83 GHz.

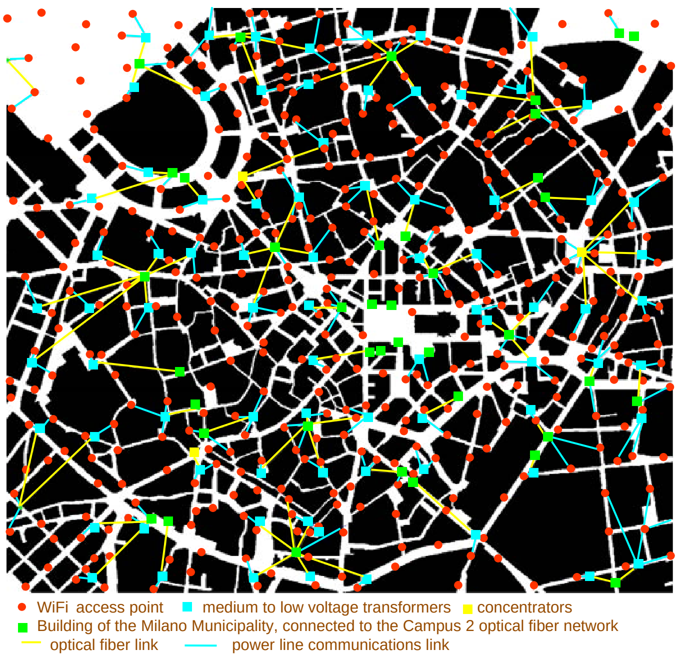

Fig. 3: Example of planning in MUWI of the radio coverage and backhauling of the central area of Milan (about 5 km^2).

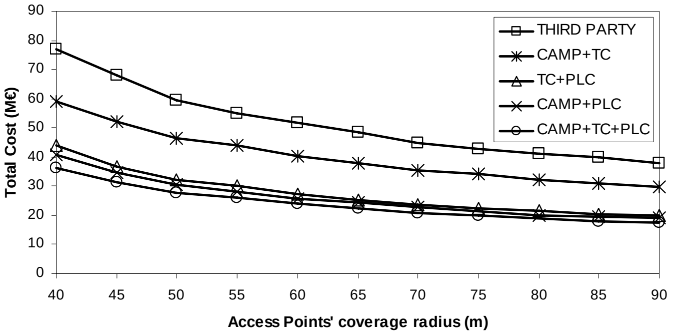

Fig. 4: Total cost of the municipal wireless network in various scenarios.

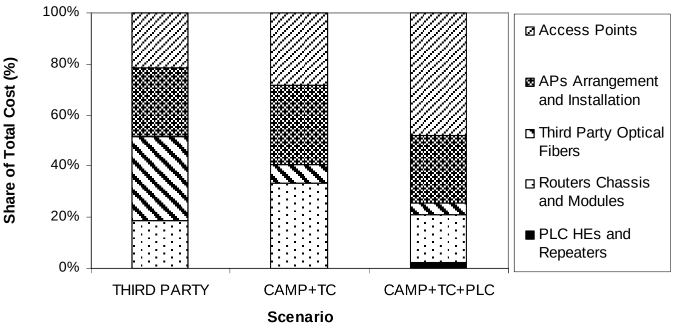

Fig. 5: Cost shares of the solutions in 3 scenarios (coverage radius = 50 m).

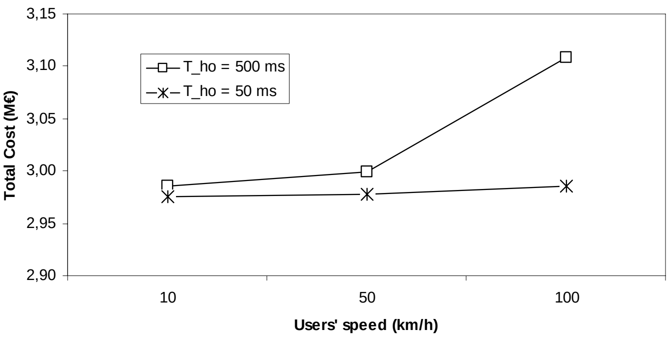

Fig. 6: Total cost of the municipal wireless network with different requirements over the mobility of users and with different handover times.

The total costs of the municipal wireless infrastructures, evaluated by the optimization algorithm in the 5 scenarios considered, are shown in Fig. 4. Total cost doubles when coverage radius decreases from 90 m to 40 m in all scenarios. However, smaller radiuses allow offering higher bandwidth capacity per unit of area, depending on the specific wireless technology. The use of only the third party company's infrastructures brings to the highest cost network. When preexisting municipality-owned infrastructures are taken into account (CAMP+TC scenario), a cost reduction of about 20% can be achieved in all coverage radius options. The PLC technology has the highest positive impact on lowering the infrastructure cost, while an additional 40% (CAMP+TC+PLC scenario compared to CAMP+TC scenario) can be gained by installing PLC Head End on designated Medium to Low-Voltage Electric Cabins and PLC Clients on well-chosen city poles.

The cost shares of the devices in three different scenario variations, using a coverage radius of 50 m, are reported in Fig. 5. The use of municipality-owned infrastructures (CAMP+TC and CAMP+TC+PLC scenarios) allows a cost reduction because of a lower use of Third Party Optical Fibers, from a 32% share to 7% and 5%. Access points cost is similar, in absolute value, in the three scenario variations. The use of the PLC technology, having an impact of 2% only on costs, allows an additional cost reduction, because of a smaller amount of optical fibers to be connected to access points and to be terminated in routers.

The solution found for the full scenario (CAMP+TC+PLC), using a coverage radius of 50 m, has a total cost of 27.7M€ and uses 6949 poles/access points, 6261 of which are *Streetlamp poles*, 319 *CampusII poles*, and 369 *Traffic Lights and CCTV poles*. A total number of 2558 poles are connected by means of the PLC technology.

C. Support to Mobility

The support to the mobility of users requires that when moving from the coverage area of an access point to the coverage area of another access point, users are able to engage a handoff procedure to transfer the communication flow from the initial access point to the destination access point. This procedure takes a given amount of time, named *handover time*, for example 500 ms by using the 802.11 protocol or 50 ms with the 802.11r protocol [8].

Considering the speed of the client user, a minimum amount of overlap between adjacent coverage areas must be assured. A user moving at a speed of v m/s requires an overlap of adjacent cells, with respect to his/her trajectory, on the order of $d = v \cdot t_{HO}$ m, where t_{HO} is the time required to complete the handover procedure. Access points with coverage radius r must be placed at distance $<2r$, in order to create an overlap among coverage areas. We call it planning distance

$$pd = 2\left(\sqrt{r^2 - L^2} - \frac{d}{2}\right) \tag{1}$$

where L is the maximum width of streets. This formula allows to assure a minimum overlap d in the worst case of placement of access points, and holds when $L < r$.

Our optimization algorithm upgraded with mobility support was applied to a 7-km^2 rectangular area of the city center of Milan. Optimizations have been performed using the scenario variation CAMP+TC+PLC, with the availability of all technological resources, and using coverage radius $r = 70$ m for all points. Streets have been classified in four classes, with respect to their maximum width L (5m, 15m, 30m, and 60m). A coverage ratio requirement parameter equal to 0.97 has been used. The cluster size map has been set to 3 for all points. The backhaul radius has been safely considered equal to 200 m.

Optimizations have been carried out considering different speeds v of the users, and different handover times t_{HO}. The total cost of the resulting solutions is plotted in Fig. 6.

Results show that the additional cost for supporting the mobility of users is limited to few percents. The additional cost for allowing the handover among cells at a speed of 100km/h, compared to the solution with speed 10km/h, is in the order of +4% with a handover time of 500 ms, and less than +1% with handover time 50 ms. The reason for the limited cost required to support the mobility of users stands in the constraints over the available locations for the placement of access points: the availability of few locations already forces the choice of poles at distances smaller than the allowed planning distances *pd*, consequently forming overlaps of the coverage areas.

VI. CONCLUSIONS

In this paper, we proposed a planning algorithm for Municipal Wireless Access Networks. The algorithm is based on a heuristic iterative optimization procedure aiming at minimizing solutions cost. A heuristic approach has been followed because of the great complexity of the problem, which involves millions of decision variables when a large metropolitan area has to be taken into account all together.

The algorithm has been implemented as the MUWI software tool and applied to scenarios representing a 51-km^2 central area of the city of Milan. Five different scenario variations have been considered.

Obtained results show that the reuse of preexisting municipality-owned infrastructures allows cost reduction in the order of 20%. An additional 40% cost reduction can be gained by the extensive use of the PLC technology. The proposed heuristic algorithm has been extended to support mobility. Results show that the additional cost for supporting the mobility of users is limited to few percents.

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