IEEE Access
Multidisciplinary ⋮ Rapid Review ⋮ Open Access Journal

Received October 15, 2016, accepted November 5, 2016, date of publication November 15, 2016, date of current version November 28, 2016.

Digital Object Identifier 10.1109/ACCESS.2016.2628917

Facing the Millimeter-Wave Cell Discovery Challenge in 5G Networks With Context-Awareness

FRANCESCO DEVOTI, ILARIO FILIPPINI, (Member, IEEE), AND ANTONIO CAPONE, (Senior Member, IEEE)
Politecnico di Milano, Dipartimento di Elettronica, Informazione e Bioingegneria, I-20133 Milan, Italy

Corresponding author: I. Filippini (ilario.filippini@polimi.it)

This work was supported by the EU 7th Framework Program (FP7-ICT-2013-EU-Japan) through the MiWEBA Project under Grant 608637.

ABSTRACT The introduction of millimeter-wave (mm-wave) technologies in the future 5G networks poses a rich set of network access challenges. We need new ways of dealing with legacy network functionalities to fully unleash their great potential, among them the cell discovery procedure is one of the most critical. In this paper, we propose novel cell discovery algorithms enhanced by the context information available through a C-/U-plane-split heterogeneous network architecture. They rely on a geo-located context database to overcome the severe effects of obstacle blockages. Moreover, we investigate the coordination problem of multiple mm-wave base stations that jointly process user access requests. We show that optimizing the resource allocated to the discovery has a great importance in defining perceived latency and supported user request rate. We have performed complete and accurate numerical simulations to provide a clear overview of the main challenging aspects. The results show that the proposed solutions have an outstanding performance with respect to basic discovery approaches and can fully enable mm-wave cell discovery in 5G networks.

INDEX TERMS 5G networks, mm-wave communications, context information, directional cell discovery, obstacle blockage, reflected paths.

I. INTRODUCTION

High-speed mobile connectivity is one of the main topics in wireless networks, and its importance is destined to rise in the near future, when a fully-connected society asking for the availability of throughput-intensive mobile applications is expected to boost the mobile data demand. Facing this exponential traffic escalation, current mobile technologies are heading towards an imminent "capacity crunch". In order to avoid the network collapse, network providers are focusing their effort in the definition of a new generation of mobile cellular networks. The 5G standardization is born to meet high expectations, promising an improvement of several orders of magnitude in latency, peak data rate, and cell-edge data rate. These expectations have elicited intense interest in exploring new network architectures and proposing advanced transmission technologies.

The deployment of Heterogeneous Networks (HetNets) is the way brought forward by operators to inject capacity in the wireless access network and face the severe issue of a system capacity shortage. Different wireless technologies can be used together to provide a mosaic of coverage, with handover capabilities among network elements. 5G access networks will be based on heterogeneous architectures wherein continuous connectivity is provided everywhere by legacy/advanced microwave technologies organized in macro cells, while additional capacity will be provided by the deployment of a large number of small cells under the coverage of the macro cells. This will significantly increase the user rates in the proximity of small cell Base Stations (BSs) by reducing the distance between the user and the access base station and balancing the traffic between small and macro cells.

In addition to HetNets, the huge amount of wireless resources available in millimeter-wave (mm-wave) bands has stimulated the interest of both industry and academia to make mm-wave transmission technologies ready for playing a key role in the future 5G wireless systems. Although promising several GHz of spectrum, mm-waves are characterized by strong signal attenuations and huge penetration losses [1], which are the main challenges to be addressed to fully harvest their potential. To mitigate these problems, devices typically resort to beamforming in order to increase the received power. Thanks to the small wavelength, indeed, highly-directional array antennas consisting of many elements can be integrated with small form factors.

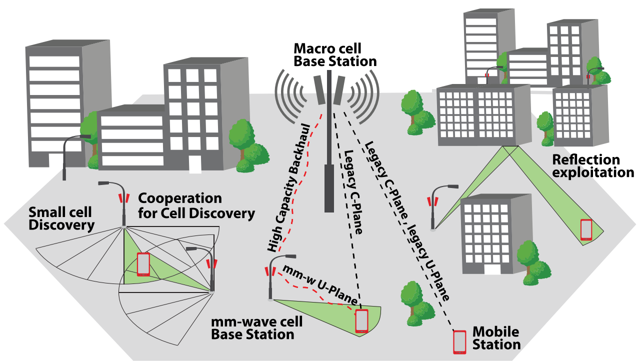


FIGURE 1. **Mm-wave access network: C-/U-plane split architecture and scenarios.**

Despite the technology advances in array antenna manufacture, the harsh propagation conditions, together with the transmission directionality and the presence of obstacles, make the exclusive deployment of mm-wave BSs not viable, as it is not possible to provide a mm-wave service guaranteeing a continuous coverage, especially in urban environment [2]. Hence, in order to provide a reliable service, the current network operating at lower frequencies has to be maintained. In this perspective, a promising solution is the architectural solution represented in Fig. 1, which has started to be considered by 3GPP and many projects on 5G networks (e.g., MiWEBA,[1] MiwaveS,[2] 5grEEn,[3] etc.). It consists in a functional split between the user (U) plane and the control (C) plane. This split guarantees the necessarily ubiquitous signaling connectivity through large cells equipped with legacy technologies, while small cells provide on-demand ultra-high capacity for data transmissions [3], without being involved in the main signaling activities. The new architecture brings two big advantages: i) it favors HetNets, as new technologies for data transmissions can be easily integrated in the network supported by a holistic C-plane layer, ii) relying on lower frequencies, legacy technologies form a continuous coverage layer that provides connectivity where the mm-wave service is not available.

Although showing clear advantages, the C-/U-plane split brings in additional complexity. While legacy network control functions assume that the service requests are collected and served by the same network entity, the functional separation abstracts the resource management: service request and resource allocation can be carried out at different BSs, thus, not only the communication between the user and the access BS must be managed, but also the QoS achievable at every other possible BS for data transmission must be estimated. Therefore, richer user-context information is required in order to properly activate data network elements and approach the optimal utilization of the system resources. However, the broad coverage and the superior reliability of a separated C-plane provide a natural way of conveying context information from the user to the network. This is essential for the operation of mm-wave networks.

Introducing mm-wave technologies in cellular access networks is not a seamless process, many important network functions are impacted by their physical-layer properties [3]. Among the most critical network functions, the *Initial Cell Discovery* is particularly critical. Differently from the previous specifications, where synchronization signals are typically broadcast into the cell, the directional nature of mm-wave communications forces the transmitter and the receiver to be spatially aligned in order to exchange synchronization signals. Therefore, there will be a phase where the BS and the user must sweep through the available antenna configurations until they find the one that allows them to communicate. This phase, if not properly managed, may introduce significant latency in the initial access, impairing delay-sensitive applications. The very same discovery procedure is repeated at each handover, thus, reducing the discovery time is fundamental also to limit service interruptions. Smart directional cell discovery procedures are needed in order to maintain a reasonable discovery delay.

We believe that a main role in the directional cell discovery can be played by the user-context information. The knowledge about user position, channel status, user mobility, applications needs, terminal capabilities, etc., can help to better explore the set of possible alternatives, making the discovery faster. Additional knowledge can be collected from the past history as well. Indeed, not only the information on the current status, but also the information about the outcome of past choices can be a valuable tool to improve the access performance.

In this article, we discuss the challenges of the Initial Cell Discovery procedure in mm-wave access networks and present smart cell discovery schemes based on context information supporting the new split architecture. Our analysis shows how the use of more and better information can help to reduce the discovery delay. Moreover, we show how obstacles can severely harm cell discovery procedures. To limit this issue, we propose a geo-located context database able to speed up the cell discovery by storing and processing the information about the previous attempts. The management of this database is critical, therefore, we investigate how the type of stored and extracted information can influence both dynamic and asymptotic discovery performance. Finally, in a scenario with multiple BSs, we analyze the behavior of

[1] FP7-ICT EU-Japan Millimetre-Wave Evolution for Backhaul and Access (MiWEBA) project, http://www.miweba.eu

[2] FP7-ICT EU Beyond 2020 Heterogeneous Wireless Network with Millimeter Wave Small Cell Access and Backhauling (MiWaveS) project, http://www.miwaves.eu

[3] EIT-ICT Towards Green 5G Mobile Networks (5grEEn), http://wireless.kth.se/5green

the whole access network highlighting the main aspects of the mm-wave BS coordination impacting on the discovery performance. At the best of our knowledge, the proposed framework is the first complete work dealing with all main issues arising in the mm-wave cell discovery in realistic scenarios: directionality, obstacle impacts, context management and BS coordination.

The article is organized as follows. In Section II, we discuss the cell discovery problem in mm-wave access networks, highlighting the benefits of a rich context information. In Section III, we overview the literature about directional transmissions and mm-wave network access, providing the current state-of-the-art and summarizing the main novel contributions of this article. In Sections IV, we present advanced directional cell discovery algorithms to be performed by a single mm-wave BS, while, in Section V, we discuss the problems arising when multiple mm-wave BSs are involved in the discovery phase and provide effective solutions. Section VI concludes the paper with some final remarks.

II. THE CHALLENGE: CONTEXT-AWARE mm-WAVE CELL DISCOVERY

Mm-wave technologies have been used for years as a reference technology for point-to-point links, adapting mm-waves to the Radio Access Network (RAN) realm is one of the challenges of the 5G standardization. Although this new scenario could seem straightforward, severe propagation losses, combined with an adverse propagation environment, require to redesign several network functions: among them, the cell discovery process is surely one of the most critical.

The cell discovery initializes the connection between a user and a BS at the very beginning of a data exchange. This process requires the periodical transmission of synchronization signals by the BS, and, despite dynamic beamforming and multi-antenna technologies are already supported in current cellular systems [4], it is typically carried out with omnidirectional or fixed antenna pattern transmissions. This cannot be done when considering mm-wave access, directional transmissions must be used in the initial cell discovery. Otherwise, this would lead to a big mismatch between the omni-directional discovery range, the range within a user can discover a mm-wave BS, and the highly-directional communication range, the range within a user can be served by the same mm-wave BS. The former would extend only few meters from the BS, while the latter would extend farther away due to the antenna directivity. This causes a reduction of the service availability, wasting precious wireless resources [5], [6].

The cell discovery process in mm-wave cells requires user and BS to scan different beam directions until they point each other. Upon the reciprocal beaming, tracking and tracing procedures allow the mm-wave BS to start the association phase and, then, begin a data exchange. Therefore, once the cell discovery process provides the initial contact, these tracking procedures will manage user mobility. Current antenna technologies, such as Modular Antenna Arrays (MAA), provide a large number of antenna pattern configurations [2], so that the discovery process may require to sweep through a large number of antenna configurations . Therefore, we must design smart algorithms to explore the antenna configurations space.

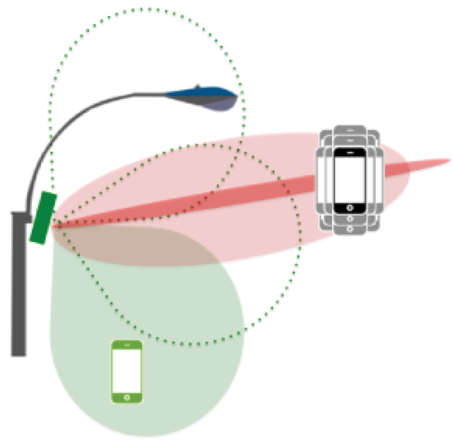


FIGURE 2. A mm-wave base station involved in a directional cell discovery. The green terminal is perfectly localized, while the black one is affected by localization error.

In order to speed up the cell discovery, we have to consider some fundamental aspects related to the propagation conditions and the antenna technology, an example is shown in Fig. 2. First, a proper beam-width selection is fundamental: large beam-widths allow to scan over the surrounding space faster - fewer switches -, but with a relatively short transmission range. Vice versa, narrow beams can increase the range, but they require a large number of antenna configuration changes to scan the entire space [7]. Another important aspect to consider is the presence of obstacles. On the one hand, obstacles may become a big challenge, as mm-wave communications are characterized by strong fading effects, almost every object is opaque and causes path obstruction. On the other hand, obstacles may represent an opportunity, indeed, the mm-wave propagation has a quasi-optical nature, thus, flat surfaces can be considered as mirrors [8] and reflected paths are consequently exploitable [8], [9]. Experimental measurements have shown that NLOS paths can have, indeed, a non-negligible received power [10], thus, spatial scheduling solutions may reach hidden users.

In this complex scenario, it is clear that a blind search within the beamforming space cannot be a viable solution. The context information can provide the needed guide to light the search path towards good configurations in a limited number of attempts. As an example, the knowledge of the estimated user position is extremely important to reduce the discovery time. Additional information about the accuracy of the estimated position can further narrow down the region where a user is searched. Similarly, information on the past beamforming attempts can provide a significant performance improvement by testing the most successful configurations at each access. The richer the information, the more illuminated the search path, thus, a better set of candidate configurations can be explored first. Clearly, the effect of the context information on the performance depends on the scenario characteristics and the quality and the amount of collected information. Therefore, in the next sections, we investigate these trade-offs by showing how additional context information can be turned into smarter algorithms and when the quality of the information is important. Indeed, we will see that in some cases more information can be even detrimental.

Context management and mm-wave technologies are facilitated by the emerging C-/U-plane split architecture. Besides providing full connectivity and mitigating the handover issues of the patchy mm-wave coverage, this architecture perfectly fits mm-wave communication needs. Not only users can be informed through the C-plane about the availability of high-speed connectivity to start a mm-wave cell discovery, but also, the reliable C-plane connection can be used to convey context information, thus speeding up the discovery process. Rich context can enable advanced scenarios where the knowledge about the type of user application requesting the data service can be used to assign the most appropriate wireless resource (e.g., legacy, mm-wave or other RAN technology). Moreover, additional knowledge about user mobility can help the resource allocation algorithm to identify which, where, and how many mm-wave cells to prepare in advance for future handovers. Improving the handover procedures will be fundamental for mm-wave 5G networks. Indeed, differently from legacy technologies, mobile obstacles produce a much stronger shadowing effect on the signal propagation. In addition, human bodies can interrupt the established connection, as well as a rotation of the mobile terminal can misalign directional antennas. Few papers exist on this topic [11], [12] and considerable work has still to be done. Several criteria can be taken into account to optimize handover triggers, also considering the opportunity of falling back to legacy technologies when the mm-wave service cannot be guaranteed.

While cell discovery algorithms can be performed by each BS individually, many interesting behaviors emerge when multiple BSs running a cell discovery algorithm coordinate to detect an incoming user. The availability of more BSs reduces the discovery time due to the search parallelism, however, more BSs involved in the discovery of a single user imply a bigger resource allocation, thus a higher load for the network. Furthermore, the use of multiple BSs can alleviate blockage problems in case of obstacles. At same time, if obstacles completely shadow a user, many BSs will be stuck in a fruitless discovery. In Section V, we investigate on these issues as key factors of the directional cell discovery process.

III. RELATED WORK

Directional communications are one of the main pillars of mm-wave access networks. Advanced antenna array systems are expected to be the key for unleashing the full potential of the next 5G networks. Nevertheless, the study of the main challenges related to the use of directional transmissions has started several years ago within ad-hoc wireless networks. Polling-based MAC protocols for limited-coverage environments have been introduced in [13] to cope with the initial synchronization problem, while authors in [14] discuss the problem of association and discovery. In [15], the technology challenges arising in directional ad-hoc networks are pointed out. The paper presents a complete framework for directional antennas proposing a neighborhood discovery algorithm based on omnidirectional broadcast heartbeats. Stations take advantage from this type of context information speeding up the discovery.

The above works, as well as the whole literature on directional ad-hoc wireless networks, underline the complexity introduced by directional transmissions. Despite the benefits of the spatial reuse and the link range extension, deafness issues lead to a more complicated neighbor discovery, and to severe hidden terminal problems. Therefore, most of the works assume a control plane management by means of omnidirectional transmissions, used to orchestrate directional transmissions [16]. When omnidirectional transmissions are not viable solutions, a blind spatial search to detect the incoming signal is performed [17].

Millimeter-wave communication and directional transmissions have been studied also in Wireless Personal Area Networks (WPANs). Devices are usually assumed to have omnidirectional sensing capabilities, and directionality is used only towards incoming signals by using beam tracking algorithms, as shown in [18]. Beamforming algorithms and route deviation to avoid obstacles have been proposed in [19].

The millimeter-wave revolution has touched Wireless Local Area Networks (WLANs) as well. This resulted in the release of the IEEE 802.11ad standard, also known as WiGig, and the ongoing definition of the IEEE 802.11ay amendment. These standards leverage the information collected during a periodic beam training period to fully exploit beamforming techniques in order to improve spectral efficiency and spatial reuse. An interesting solution is proposed in [20] wherein the best access point beam parameters are selected to reach all subsets of surrounding users. Considering uplink transmissions, the work in [21] analyzes the optimal information needed for directional beamforming. In addition, a novel MAC protocol proposes a training period to select the best beam to connect to relay stations during bad channel conditions. The problem of the joint beamwidth selection and power allocation is considered in [22] to maximize the network throughput of a mm-wave wireless network characterized by misalignments and deafness. The authors present two standard compliant schemes to maximize the reuse of the available spectrum with very limited computational effort. Finally, the work in [23] proposes to exploit past location history to narrow down the search space while users move.

Although the previous works did not explicitly addressed the cell discovery problem of cellular networks, they have inspired the development of new solutions to cope with the directionality of mm-wave communications. Recently, this has become a hot topic because mm-waves have started to be considered a promising technology to enable the high performance expectations of 5G networks. Therefore, several works have appeared with the aim of discussing and solving the peculiar issues of mm-wave access networks.

In [5], an overview on possible physical-layer problems of cell discovery is presented, and the importance of using directional transmissions in the initial synchronization phase is underlined. Authors in [6] focus their attention on acquiring channel synchronization when directional transmissions are used. In [24], an analytical model for the network performance is developed by relying on distance-dependent Line-Of-Sight (LOS) probability functions. Based on such a model, the authors have proven that dense mm-wave networks can achieve much higher spectral efficiency than conventional networks. However, transmission blockages and coverage discontinuity prevent a full mm-wave deployment from being a practical solution.

At MAC layer, the work in [25] identifies the main challenges and presents a cell discovery process wherein, after time and frequency synchronization, a random spatial search is performed. In addition, it considers a scenario with multiple mm-wave BSs where user association and dynamic cell structuring are orchestrated to balance the network load and to satisfy users' QoS requirements. Differently from this approach, we propose more advanced discovery methods and evaluate scenarios with multiple mm-wave BSs focusing on the cell discovery activation, which is somehow orthogonal to this prospective. Moreover, authors provide an accurate analytical model for the discovery delay considering semi-directional or fully-directional mm-wave antennas. The model, however, assumes a first step where pilots are directionally transmitted to synchronize users and BSs, then a directional discovery is performed to align BSs' and users' antennas. Despite its effectiveness, this two-step procedure could introduce additional delay into the discovery process, therefore, we propose a one-step algorithm. Authors in [26] propose a cell discovery algorithm that reduces the search space among the possible antenna configurations. It is based on the a-priori omission of angular sectors based on the sole user location. This solution, however, may preclude the association of users without LOS conditions, which rely on reflected path to avoid obstacles.

In [7] and [9], we have initially proposed several fast cell discovery algorithms based on context information and extended them to deal with obstacle obstructions and reflected paths. Authors in [27] present an evolution of the 3GPP user association remarking that preventing connection losses is one of the most important mm-wave challenges. Two initial synchronization alternatives are proposed: *i*) omnidirectional synchronization signals covering the entire mm-wave cell area or *ii*) sequences of directional synchronization signals with a fixed and narrow beamwidth scanning through every direction. Differently from that, we analyze more advanced solutions with different combinations of beamwidth and direction, this allows us to shed light on the main trade-offs of cell discovery mechanisms. An overview of iterative and exhaustive cell discovery schemes is provided in [28], where different algorithms have been compared. Very recently, in the work-in-progress paper [29], an obstacle-free approach based on context information and directivity at user side has been proposed.

With respect to the above literature, in this paper we jointly face many fundamental aspects of the cell discovery process and we provide the following novel contributions:

- We propose and evaluate smart cell discovery procedures that can adapt the search space according to both the estimated user position and the accuracy of this estimation. They rely on a novel network architecture characterized by a separation between the C-plane and the U-plane.
- We advance the use of mm-wave path reflections to avoid obstacles and reach hidden users.
- We introduce a framework based on a context database where past network access history is exploited to boost the discovery phase of new users. We thoroughly investigate its performance, evaluating both fixed and time-variant scenarios.
- We consider scenarios with multiple mm-wave BSs and investigate the problem of how to select the group of mm-wave BSs in charge of managing the access of a new user.
- We propose a method to limit the resource occupancy caused by badly positioned users in a multi mm-wave-BS scenario.
- We perform accurate and complete simulations to provide a clear overview of the main challenging aspects to be faced when dealing with the cell discovery problem in mm-wave access networks. In addition, we show that the proposed solutions have an outstanding performance with respect to basic discovery approaches.

IV. SINGLE BASE STATION CELL DISCOVERY

This section is dedicated to the description of the techniques we propose to perform the cell discovery procedure. After introducing the main assumptions, we present discovery algorithms with different levels of knowledge on the user context information. Starting by leveraging only the estimated user location, we then include the information on the location accuracy, and finally, we add the knowledge on the past successful beaming attempts at a given location.

A. MAIN FEATURES AND ASSUMPTIONS

We consider a scenario where the mm-wave BS and user can get information about the respective locations through the C-plane connection. We assume that locations are estimated through an external positioning system (e.g. GPS). Furthermore, we assume that the propagation model and antenna capabilities are available as well. The discovery procedures will then be performed by taking advantage of the available knowledge. Although we are aware that antennas have to be pointed both on the mm-wave BS side as well as on the user side, we consider a simplified scenario, which is able to catch the fundamental trade-offs of the cell discovery problem without introducing secondary effects. In the remainder of the paper, we assume that only the mm-wave BS has to point towards the user and that the user is equipped with an omni-directional antenna. In this perspective, we can boil down the cell discovery problem to a user search problem performed by each mm-wave BS. Moreover, as the cell discovery delay will be in practice a short time period (millisecond order or less), we can assume that user mobility is not a main issue in this phase. Indeed, thanks to smart discovery algorithms and advanced hardware, we can reasonably expect that the position of the user at the beginning and at the end of the discovery will not substantially change, i.e., the same beam can be used to cover the user.

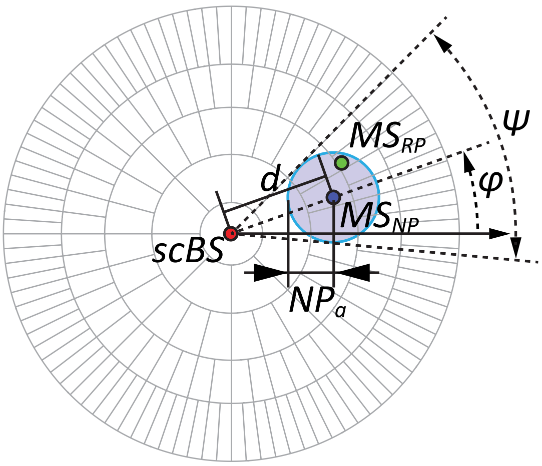


FIGURE 3. Beam pattern and context information.

In Fig. 3 is represented the overall view available at the mm-wave BS thanks to the context information. $scBS$ is the position where the mm-wave BS is installed within the small cell. MS_{NP} is the user's nominal position, the one declared to the network, which is unavoidably affected by an error that depends on the location accuracy. In order to model this error, we define MS_{RP} to be the user's real position.

The nominal position MS_{NP} is used to estimate the distance to be covered d and the pointing direction φ. Thanks to the knowledge about the channel model and the antenna capabilities, the mm-wave BS is able to estimate the coverage of different antenna configuration patterns, which are represented with the gray polar grid. Note that, a proper beam selection implies the perfect knowledge of the path loss between the user and the BS, however, it could be only estimated within a given accuracy by using channel models [30] or anchor based prediction systems [31]. For the sake of simplicity, we consider path loss and user location errors merged together in a unique equivalent positioning error. Mm-wave BSs and users are placed in a 2D environment (i.e., with a fixed elevation angle) and mm-wave BSs are equipped with a steerable antenna, with a discrete set of beamwidths and pointing directions. The number of pointing directions is given by $M = 2\pi/w_{3dB}$, where w_{3dB} is the half-power beamwidth of the selected configuration.

The user location accuracy in the figure is represented with the light blue circle of radius NP_a. If this information is provided together with MS_{NP} by the positioning system, the mm-wave BS can compute the angular sector where is more likely to find the user, which is indicated with ψ. Finally, we can assume that the position of the mm-wave BS is perfectly known, as deployed in a planned location.

B. DISCOVERY ALGORITHMS

The discovery algorithm is used by mm-wave BSs to calculate the beam sequence to explore in order to find a beam configuration able to cover a user requiring a connection in the service area. The algorithms are based on the context information previously described. We have included some supplementary video clips where the behavior of the following algorithms can be visualized. They will be available at http://ieeexplore.ieee.org.

1) DYNAMIC SECTOR-LEVEL SWEEP (D-SLS)

This is a benchmark algorithm that we presented in [7], which extends the standard SLS procedure of IEEE 802.11ad BF protocol. The search starts considering the widest beam that can reach the user at MS_{NP}. If the user is not detected, the mm-wave BS sequentially scans through every direction, keeping the same beamwidth. The scan stops when the selected beam allows a sufficient signal power to reach the user, and thus decoding the synchronization signal. If no user is found again, the mm-wave BS restarts the circular sweep with a narrower beam. The new circular scan will cover a larger area and will require more steps. The procedure repeats until every combination of beamwidth and pointing direction is explored. The rationale behind D-SLS is the idea of exploring the close-by neighborhood through wide beams, this allows to reach nearby users faster than in SLS, which performs just a single circular sweep with the narrowest beamwidth.

2) ENHANCED DISCOVERY PROCEDURE (EDP)

We derive this algorithm from the one presented in [7], we extended it as follows. When a new user joins the network, the serving mm-wave BS quickly computes the correct beamwidth and pointing direction to properly beam the user, based on the estimated user position MS_{NP}. If the positioning information is not accurate, the user might not be spotted, thus, the BS scans the surrounding area relying on N circular sectors, each $(2\pi/N)$-radian wide. In Fig. 4 is represented the case of $N = 4$ angular sectors, corresponding to $(\pi/4)$-radian wide circular sectors.

Named β_n the central direction of the sector S_n, the algorithm computes it as: $\beta_n = \varphi + \left(\frac{2\pi}{N}(n-1)\right)$, with $n = 1, \ldots, N$ and φ the direction of the nominal user's position MS_{NP}. The discovery is performed sector by sector, starting from the one pointing towards the nominal user's position and alternating clockwise and counter-clockwise directions. Referring to Fig. 4 sectors are scanned in this order: S1, S4, S2, S3. Antenna configurations are then grouped according

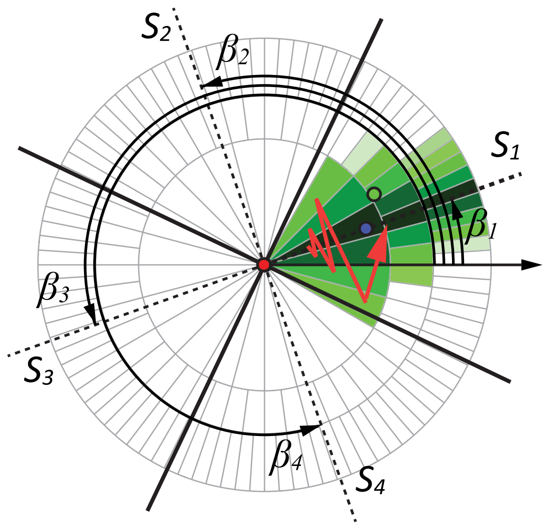


FIGURE 4. Example of Enhanced Discovery Procedure (EDP).

to the sector split in order to completely scan the area of each sector.

Within the sector S_n, the BS starts exploring the beam directions adjacent to β_n, considering the largest beamwidth that allows to cover the distance d and discarding those with an estimated range less than d. Then, a beam sequence is built sorting the beams according to the increasing angular difference between their pointing directions and β_n. If no user is reached, the BS reduces the beamwidth switching to the next available width in the antenna set, points the beam again towards β_n, and similarly explores adjacent beam directions within the sector. This allows to explore a larger region than the previous round in the hope of finding a farther away user. Clearly, exploring the whole sector with this new beamwidth requires a larger number of switches.

The same per-sector beam scanning is repeated for all the other sectors according to the sector scan order. The process ends when the user has been detected or when all N sectors have been explored without finding a user.

3) DYNAMIC-SECTOR EDP (DSEDP)

The EDP algorithm controls the discovery considering as input only the nominal position MS_{NP}. It does not take into account the accuracy of user location estimation, so it is exposed to location errors. Starting from the EDP algorithm, we propose an advanced version of it, which takes into account also the location accuracy NP_a. Once the accuracy is known, it is possible to have a more precise idea of the area that has to be scanned in order to likely find the user. This algorithm dynamically tunes EDP sectors' width in accordance with the available level of accuracy, hence the name *Dynamic-Sector EDP* (DSEDP).

With reference to Fig. 3, the accuracy NP_a, together with the locations $scBS$ and MS_{NP}, is used to compute the angle ψ. Then, the number of sectors N is computed as $N = \lfloor 2\pi/\psi \rfloor$. Once we have N, the discovery is performed similarly to the EDP algorithm. The maximum number of sectors N depends on the beamforming capabilities of the antenna, provided that the minimum number is always $N = 1$. For example, if the minimum available beamwidth is 2-deg, the maximum number of sectors will be $N = 360/2 = 180$.

Note that the width ψ of the angular sector depends both on the provided location accuracy NP_a and on the distance d between the mm-wave BS and the user. Once the accuracy level is fixed, the number of sectors N varies in such a way that if the distance d is large, the sector narrows down and search priority is given to areas far away from the BS. On the contrary, when the user is nearby the BS, the sector is wider, and thus, the search in the immediate vicinity of the BS is favorited.

In addition to dynamically varying the sector width, we also consider the maximum range to be covered, $d_{max} = d + NP_a$. We compute the minimum beamwidth BW_{min} that can reach d_{max}. According to BW_{min} the antenna configurations that lie inside the sector ψ are divided in two sets. Configurations with beamwidth larger or equal to BW_{min} are moved to the beginning of the beam sequence, while the other group of configurations is moved to the end. Configurations outside the sector ψ are not touched, as no assumption can be made about them. The idea behind this solution is to first check the area where the user is expected to be with the highest probability, postponing the use of "longer" beams that go beyond that area.

C. OBSTACLE AVOIDANCE WITH CONTEXT DATABASE

Real mm-wave scenarios are characterized by several objects scattered in the service area, they force mm-wave BSs to reach users through NLOS paths that, reflecting off walls and obstacles, go around the obstruction. These objects, however, may notably delay the cell discovery process, even when advanced discovery algorithms are implemented. Indeed, two main considerations must be made about them:

1) Discovery algorithms are designed to focus their search around the nominal user's position. However, a reflected path can substantially deviate from the LOS direction in order to avoid an obstacle, thus a long sequence of candidate beams could be explored before finding the one that can cover the user.
2) Discovery algorithms independently consider each user-BS connection, without taking into account past choices, thus neglecting the useful information that past attempts can offer.

Referring to Fig. 5, the main effect caused by the presence of obstacles is a shift between the direct beam covering the nominal user position (the red beam) and the successful beam that can actually reach the user (the green beam). This shift is very similar to that caused by a location error. However, if obstacles are fixed, like walls and buildings, this is a deterministic effect and, once the user is found, next discovery attempts can be improved by the knowledge of the

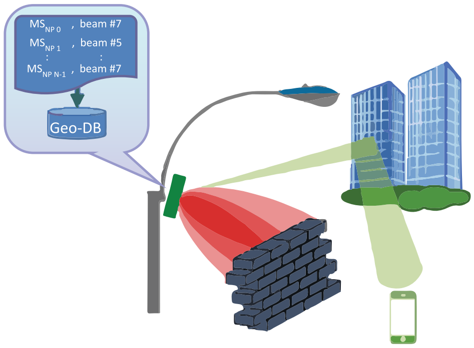


FIGURE 5. Geo-located database for obstacle avoidance.

previous choices. Note that we explicitly consider only static obstacles as mobile objects produce random signal shadowing, which is already included in the radio propagation model.

The work in [9] originally proposes to deploy a geo-located user-context database (DB) that stores (*antenna configuration*, MS_{NP}) pairs related to the past successful discovery processes. This allows to best exploit the previous search effort and speed up new discoveries when a user must be served in a position close to one stored in the DB. Furthermore, a range m is used to spatially filter the context information: when a new user at position $\mathbf{p}$ requires connectivity, the DB lookup provides the antenna configurations associated to a position within a maximum distance m from $\mathbf{p}$. The beam corresponding to the closest DB entry is selected and activated before resorting to a proper cell discovery algorithm if the user is not found. We will refer to this mechanism as *Mem 1*.

We have extended the *Mem 1* approach by introducing the possibility to modulate the number of beam configurations to be tested before activating a discovery algorithm, f.i., EDP or DSEDP. We will refer to this mechanism as *Mem k*, with k equal to the number of returned configurations in a DB lookup. Note that, in a set of h DB entries we usually have $k \leq h$ unique antenna configurations. Indeed, the same antenna configuration could have been a successful selection for several nearby users in the past. Selected antenna configurations are ordered by increasing distance from the nominal position of the new user and sequentially activated to explore the surrounding area. If this initial discovery phase fails, the process continues by activating one of the proposed discovery algorithms. This allows to better exploit the DB information than in the *Mem 1* case. Finally, we name *Mem All* the case where all stored antenna configurations in the range m are tested before moving to the next phase.

In the *Mem 1* case, and even more in *Mem k* and *Mem All*, it is crucial to properly tune the range m in order to avoid the selection of antenna configurations which have been collected at distant locations, and thus, are weakly correlated with the current user position. This would result in a useless sequence of unsuccessful discovery attempts before activating a discovery algorithm.

1) LIMITING DB SIZE

So far no limits have been imposed to the size of the geo-located DB. However, it is also important to investigate the effect of the DB size on the discovery performance. It is reasonable to expect that, as the number of stored entries increases, a more detailed picture of the surrounding environment can be obtained. However, the use of a very large DB may not be a viable solution in some scenarios, and even detrimental in some others. From a quality of information point of view, an extremely large DB introduces useless redundancy in the stored information, and, after a scenario change, it may lead to rely on outdated information because the obstacles disposition may have changed. In order to investigate the effects of the DB size on the discovery performance, we have introduced a mechanism that limits the number of saved records.

The DB is initially empty. As accesses to the network occur, the memory stores antenna configurations and positions as in the normal setting. Once the DB size reaches an arbitrary limit, at each new successful access, the new pair (*nominal position*, *beam configuration*) is saved by overwriting the oldest entry, according to timestamps. We will refer to this case as *Mem Lim (x)*, where x is the maximum number of storable records.

D. NUMERICAL RESULTS

We assess the performance of the proposed cell discovery algorithms by means of numerical simulations. Results are obtained through an ad-hoc MATLAB® simulator.

We consider the following environment. One mm-wave BS is placed in the center of a rectangular, $450m \times 350m$, area. The area is surrounded by four reflecting walls and a variable number of $20m \times 20m$ squared obstacles are randomly dropped inside. Obstacles are placed in such a way they do not overlap each other, with the surrounding walls and with the BS. After generating the playground, 2000 mm-wave users are dropped random uniformly inside the rectangular area; users falling inside obstacles are discarded and re-dropped until they are all placed in the area not occupied by obstacles. Obstacles and user locations are changed at every instance. All results we show are obtained as an average over 100 simulated instances.

The antenna gain is modeled with a Gaussian main lobe profile [32]:

$$G_{dB}(\theta, \phi) = 10 \log_{10}(G_0) - 12 \cdot \left(\frac{\phi}{\phi_{-3dB}}\right)^2 - 12 \cdot \left(\frac{\theta}{\theta_{-3dB}}\right)^2 \quad (1)$$

$$G_0 = \frac{16\pi}{6.76 \cdot \phi_{-3dB} \cdot \theta_{-3dB}} \quad (2)$$

The half power beamwidth for elevation angle is set to $\phi_{-3dB} = \pi/3$, while θ_{-3dB} depends on the number of antenna pointing directions.

The pathloss model used for LOS transmissions is defined as [7]:

$$PL = \alpha + k \cdot 10 \cdot \log_{10}\left(\frac{d}{d_0}\right) \text{ [dB]} \tag{3}$$

Where d is the path length, $\alpha = 82.02dB$ and $d_0 = 5m$. The propagation factor k is: $k = 2.36$ if $d > d_0$, $k = 2$ otherwise.

When transmissions undergo reflections on walls or obstacles, the reflection losses are added to the path loss. Reflections are modeled with parameters R, B and F defined as [32]:

$$R = 20\log_{10}\left(\frac{\sin\psi + \sqrt{B}}{\sin\psi - \sqrt{B}}\right) \text{ [dB]} \tag{4}$$

$$B = \varepsilon_r - \cos^2\psi \tag{5}$$

$$F = \frac{80}{\log 10}\left(\frac{\pi \sin\psi\sigma_w}{\lambda}\right)^2 \text{ [dB]} \tag{6}$$

where ψ is the incidence angle.

We assume concrete obstacles and walls, both with relative dielectric constant $\varepsilon_r = 4 + 0.2i$ and surface roughness standard deviation $\sigma_w = 0.2mm$, more details are available in [32]. We considered only LOS and single-reflection paths.

In all simulations, we consider a minimum signal level for acquisition, which is directly derived from the empirical measurements presented in [6], where the Signal-to-Noise-Ratio must be greater than $10dB$, that is corresponding to a sensitivity $S = -73dBm$. The user is covered by the mm-wave BS only if the received power P_r is $P_r \geq S$. The transmitter power is set at $P_t = 30dBm$, and the received power Pr is computed as:

$$P_r = P_t + G_{BS} + G_{MS} - PL - R - F \tag{7}$$

where G_{BS} is the mm-wave BS antenna gain and G_{MS} is the user antenna gain, assuming $G_{MS} = 0dB$ due to the omnidirectionality.

At the mm-wave BS side, we considered a steerable array able to concentrate energy up to beamwidths of $\theta_{-3dB} = 1deg$, i.e., 360 beams are needed to entirely scan the surrounding area. Larger beamwidths are obtained by proportionally reducing the number of directions to 180; 120; 90; 72; 60; 48; 24; 12; 8; 6; 4; 3; 2; 1, for a total number of 990 available configurations [6].

The user-location uncertainty is modeled as a symmetric and independent bivariate normal distribution centered in the nominal user's position with parameter $\sigma_x = \sigma_y = \sigma$. Referring to Fig. 3, we consider a location error $NP_a = 3\sigma$.

1) DISCOVERY ALGORITHMS PERFORMANCE EVALUATION

In the first set of results we want compare the performance of the proposed discovery algorithms D-SLS, EDP and DSEDP. We recall that both D-SLS and EDP use only user's location information MS_{NP}, while DSEDP considers also the location error NP_a. Algorithms are always compared in terms of average number of antenna configuration switches necessary to find the user, which represents an indirect measure of the access delay. The actual delay depends on the available technology and can be easily obtained from the number of required switches. The EDP algorithm is simulated with a fixed number of sectors, $N = 4$. It means that each sector is fully explored by a set of $990/4$ directional beams.

Fig. 6 shows the simulation results. The figure does not report results related to the standard SLS techniques, which considers the narrowest beamwidth (1 degree) and no context information. SLS needs more than 160 switches in all considered cases, this means that smart context-based discovery algorithms are essential if we want to exploit the potential of advanced antenna systems.

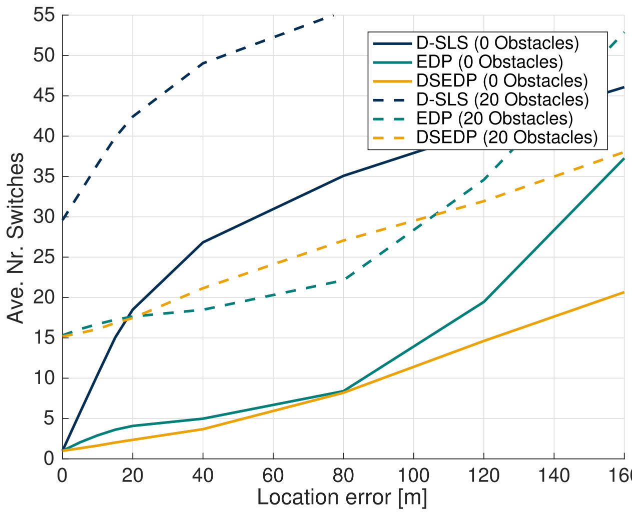


FIGURE 6. Performance comparison among the proposed discovery algorithms.

For all tested algorithms in Fig. 6, it is evident that the discovery time increases both with the growth of the location error and with the increase of the number of obstacles placed in the scenario. We start by focusing our attention on the scenario without obstacles, hence, a scenario where the only aspect that hinders the user discovery is the location error. The results show that EDP is able to reach the user in much fewer attempts than D-SLS. This is because EDP, by dividing the search in sectors, provides beam sequences able to better confine the beams in the neighborhood of the declared position. D-SLS instead, by sweeping around through 360 degrees, is much less efficient. The price to pay is that the EDP algorithm, being more elaborated, may require more computational resources at the base station with respect to the D-SLS. However, if the quality of the information received from the positioning system is very low, it becomes less and less relevant to use a sophisticated algorithm like EDP. Indeed, the received position is highly corrupted by the error, and thus the research would focus on the wrong area.

DSEDP algorithm is an advanced version of EDP able to adapt the search area to the user location error. In obstacle-free scenarios, the advanced mechanism of DSEDP leads to a reduction of the discovery time in case of both small and large location errors. In particular, if the nominal position is very precise, it can better focus the research on the proximity of the user, vice versa, if the location error is big, it can enlarge the considered area, and consequently, it is less sensitive to the error. When obstacles come into play, the behavior of D-SLS, EDP and DSEDP algorithms is similar, but the performance is remarkably worsened. DSEDP's relative performance slightly decreases because the frequent occurrence of path obstructions limits the efficiency of privileging beams pointing towards the region where the user is expected to be.

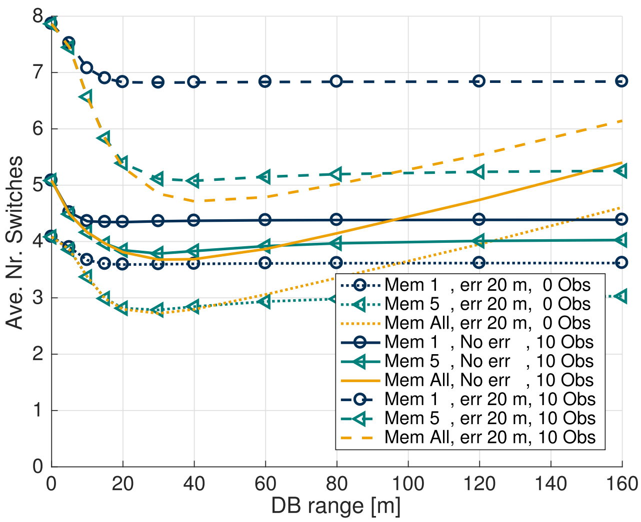


FIGURE 7. Performance comparison of ***Mem k*** context database with different values of ***k***, location error and number of obstacles.

2) CONTEXT DATABASE PERFORMANCE EVALUATION

The goal of the context DB is to avoid a long search through possible antenna configurations and reflected paths after the first successful access at a given location. The Fig. 7 shows the performance, in terms of the number of switches required to connect incoming users versus the DB range m. The value $m = 0$ indicates that the DB is not used. In the figure three sets of results are reported: no obstacles and $20m$ location error, 10 obstacles and no location error, 10 obstacles and $20m$ location error. We do not consider the case of no obstacles and no location error because it is not realistic. Indeed, in that case, users can be reached by directly beamforming on their nominal positions, so, the discovery does not require the presence of a geo-located history DB, and even a cell discovery algorithm is redundant. Results show that the introduction of the DB has a remarkable effectiveness when obstacles are present in the area, so, exploiting the past accesses is a good strategy to manage reflected paths and reduce the discovery time. Furthermore, the DB is able to reduce the discovery time even when the user nominal position MS_{NP} is affected by location error and no obstacles are placed. This is because the range m filtering effect provides only beam configurations that were previously used to cover users in the MS_{NP}'s neighborhood, so it enhances the focusing capability of the discovery algorithm.

The behaviors described above are closely related to the value of the DB range m. This parameter gives the possibility to modulate the number of stored antenna configurations used in the discovery process. The impact of the DB range m on the performance can be better understood from the curves related to *Mem All* mechanism, where a minimum point is clearly visible. This minimum is the result of a trade-off between two aspects. First, with small m, the past information is used in a very limited geographical neighborhood, reducing its benefit. Second, excessively increasing m causes the inclusion of candidate beam configurations that are poorly correlated with the current users' position, thus resulting in a waste of unsuccessful beamforming attempts.

Let's now move our attention to the different memory implementations, recalling that by varying the parameter k of *Mem k* we modify the weight of the past access history in the discovery process. We analyze the performance of *Mem 1* and *Mem All* as the two extreme cases, while *Mem 5* is an example of intermediate condition. Results in Fig. 7 show that the achievable gain is proportional to the parameter k and when more obstacles are present the gap is more remarked. Small k values strongly limit database benefits, while high k values allow the full exploitation of the database potential. However, similarly to what happens with the DB range m, a value of k too big leads to test useless antenna configurations. Finally, k is a secondary parameter with respect to m, since the DB range m has an intrinsic filtering effect on the number of configurations extracted by the DB. Nevertheless, k may prevent performance degradation if m is not properly chosen.

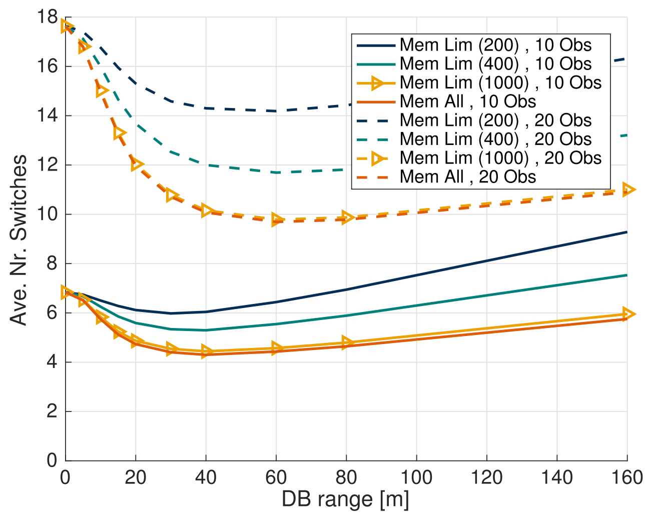


FIGURE 8. Performance comparison of ***Mem Lim (x)*** context database with different values of ***x*** and number of obstacles.

We now consider the *Mem Lim (x)* scenario, where x is the maximum number of records storable in the whole DB. Fig. 8 shows the effect (in terms of number of switches versus the DB range m) of the introduced limit in the case of DB with the *Mem All* mechanism. The first important aspect to note is that the DB performance is strongly related to its size. Indeed, as the limit becomes more stringent, the performance worsens due to the consequent reduction of stored details. However, even greatly increasing the DB size is not a good approach.

Indeed, much information will be redundant as the DB is storing more information than it is needed. This aspect is evident by comparing *Mem All* and *Mem Lim (1000)* curves, which are basically overlapped. A further aspect is that, similarly to what happens with the *Mem k* approach, the effect of increasing the storage has a stronger impact in the scenarios with more obstacles. This is due to the fact that obstacles break the spatial coherence of the beam type used to reach every region, making the information stored in the DB less redundant.

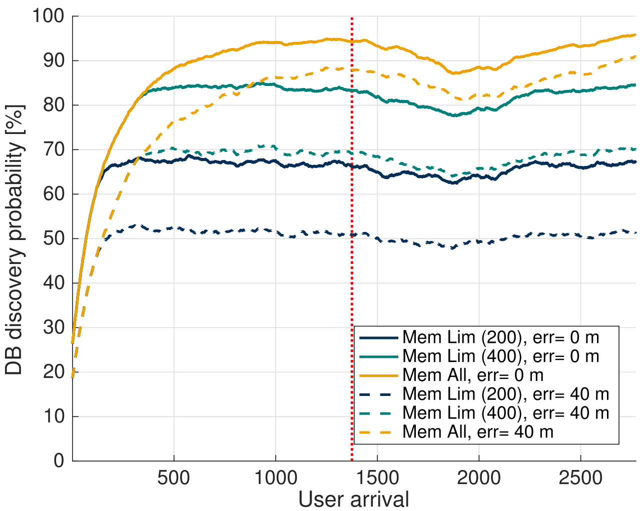


FIGURE 9. Context database after an environmental change. Performance for different values of location error and database size.

Finally, we have analyzed the system behavior in the event of a change in the surrounding environment. Results are obtained by modifying the arrangement of the obstacles when the DB is fully populated. We have sequentially dropped the users in a scenario with 20 obstacles and we have made the change in the middle of the simulation. Note that the x-axis expresses the elapsed time in terms of number of connected users. Results are shown in Fig. 9, they report the probability that a user is discovered with only the information stored in the DB, without resorting to any discovery algorithm. Following the curves evolution, we can distinguish several phases. At the beginning of the simulation, the DB is empty, so the success probability is null. Then, as new users arrive and get access, the probability increases as the memory fills up, until it is full. Then, since the memory has reached the maximum level of information details, there is a phase where the curves are flat. After the change (around 1375 users), the curves have a notch: the probability decreases because part of the stored information is no longer valid. However, after some time, the curves start to rise again due to the information refresh. Note that the sensitivity to the environmental change is proportional to the size of the memory and the location error. In the former case, if the DB size is limited, the system has less inertia, it is less sensitive to environmental changes and the refresh is quicker. In the latter case, in a scenario with high location errors the DB has a blurred view of the users' location and successful beamforming. An obstacle displacement in this scenario has a lower impact on the performance than in a scenario where the DB is filled with almost perfect user locations.

V. COORDINATION FOR CELL DISCOVERY

In the previous section, we have dealt with cell discovery algorithms, focusing the attention on how a single and independent mm-wave BS can smartly exploit the context information to speed up the search for new users. Now, we shift the focus to the point of view of a whole mm-wave access network.

5G network architectures provide an incremental access capacity by installing several mm-wave BSs within a macro cell area. In addition, the C-/U-plane split facilitates the signaling management in a centralized position. Therefore, in the new network architecture users can establish a C-plane connection by means of legacy technologies with a centralized signaling entity (e.g., an eNodeB) and get U-plane radio resources through one or more mm-wave BSs, coordinated by the signaling entity. As a new user requires the access via the C-plane connection, the coordinator is in charge of selecting the best mm-wave BSs able to cover and find the user. It can build the candidate set leveraging context information, such as user and BS location, user density distribution, network load, etc. Once the mm-wave BS set is defined, the central coordinator dispatches a discovery command to the BSs, which will activate a discovery procedure in order to provide the user with a synchronization signal to establish a U-plane connection.

In this section, we want to analyze the behavior of a group of mm-wave BSs involved in the discovery of new users accessing the network, we are interested in understanding how the choices in the selection of the BSs involved in the discovery can impact the access delay and the maximum user arrival rate the network can support. In order to proceed with a simplified scenario that can capture all the essential characteristics, we assume that the group of mm-wave BSs have a synchronous timeline divided in two alternating time periods. A data transmission period, during which BSs exchange data with associated users, and a user discovery period, where all BSs are involved in the discovery of new users. This is compatible with current mm-wave standards [3], which defines periodical frames with slots entirely devoted to the user discovery. Investigating the aspects related to the user discovery period allows us to show the fundamental properties of the "pure" discovery procedure, without secondary effects.

A. MAIN FEATURES AND ASSUMPTIONS

For the sake of presentation, we can consider the sample scenario represented in Fig. 10. Here, the macro eNodeB (with the role of central coordinator) and mm-wave BSs simultaneously enter the user discovery period, where the selected mm-wave BSs try to find each incoming user, and, once a user is found by at least one mm-wave BS, they notify the coordinator.

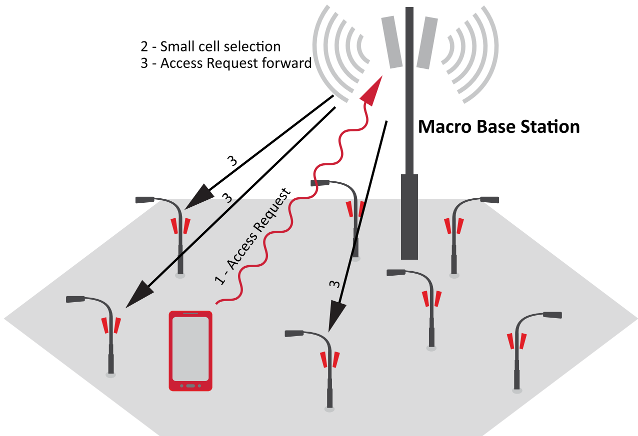


FIGURE 10. Base station selection example.

We reasonably assume that mm-wave BSs cannot search for more than one user at a time. Therefore, during the user discovery period, we can find a BS in two different states: i) "*Idle*" when it is free to accept access requests and, as a new request arrives, immediately activate the discovery procedure in order to provide the service; ii) "*Busy*" when it is occupied in searching a user. We assume that when a discovery command is received by a busy BS from the central coordinator, it is inserted in a local queue and postponed. Once the BS becomes free, queued requests are served according to a FIFO policy.

The coordinated discovery ends when the user is reached by at least one of the selected BSs. The eNodeB is immediately informed about the successful access, thus, it can broadcast a *discovery procedure abort* command to all involved BSs in order to either stop their ongoing search or to remove the related discovery command from their queues. If the user can be reached by none of the selected mm-wave BSs, the cooperative discovery ends when every BS has concluded its beam sequence with an unsuccessful discovery, then the user can be marked unreachable.

B. BS SELECTION ALGORITHMS

In this article, we analyze the following mm-wave BS selection algorithms:

1) ALL BSs SELECTED (ALL-BS)

As a new access request arrives, the eNodeB forwards the request to all mm-wave BSs deployed in the macro cell, which will be all involved in the coordinated discovery of the user. In this algorithm, the central coordinator is exploiting little context information, indeed, it relies only on the information about the presence of the user in the macro cell area.

The rationale behind *All-BS* algorithm is maximizing the search parallelism among mm-wave BSs, at the expense of a non-optimized allocation of resources. Indeed, it may lead to involve BSs that, due to the presence of obstacles, or simply because they are too far away from the selected user, will never conclude a successful discovery. They may remain occupied unnecessarily wasting precious resources.

2) K SELECTED BSs (K-BS)

In order to avoid resource wasting, we assume eNodeB can build a mm-wave BSs set under the constraint of the maximum number k of elements that can be activated for serving a single access request. These k BSs are the k closest BSs to the user position. Compared to *All-BS* algorithm, *k-BS* algorithm takes in input a richer context as it considers, in addition to the access request of a user in the macro cell area, the positions of the mm-wave BSs and the user.

C. DEALING WITH OBSTACLES

We have seen in Sec. IV how the presence of obstacles can be challenging due to the huge signal penetration loss at millimeter-wave frequencies. The primary effect introduced by their presence is that not all users can have a LOS path available. Therefore, some of them will be reachable through reflected paths, while some others, surrounded by obstacles, are out of reach of mm-wave communications. These isolated users can be covered only by resorting to the macro cell legacy communication technologies.

The big drawback is that users who are covered by a NLOS path engage mm-wave BSs in long lasting discovery phases, while those that cannot be covered have an even more detrimental effect. Indeed, the central coordinator cannot determine whether or not a user is reachable only relying on his position, because obstacle obstructions are a-priori unknown. This leads mm-wave BSs selected for the discovery to fully explore their beam sequences in vain, unnecessarily keeping the network busy for a long time. Consequently, obstacles increase the user discovery backlog of the network, worsening the access delay and reducing the acceptable user arrival rate.

1) ADAPTIVE THRESHOLD

We propose here a method that enables each individual mm-wave BS to abort an ongoing discovery procedure if it is lasting too long. The idea is to cut off the uncoverable users by means of a threshold on the maximum duration of the discovery procedure. The beam sequence is no longer entirely swept, limiting the extra network backlog due to the presence of obstacles.

As for the threshold calculation, the eNodeB keeps track on the number of configuration switches used to reach a user in every successful discovery. This information is collected and shared to all mm-wave BSs coordinated by the eNodeB. The threshold value is updated following the same rationale of the timeout setting of the TCP protocol, which shares a goal similar to that of this adaptive threshold. Indeed, both procedures try to stop the waiting time when a user is not reachable. Expressing the discovery delay in terms of number of antenna configuration switches and applying a moving average filter over the last successful user discoveries, the threshold is:

$$THRESH = \lceil \mu_{\#switch} + \alpha \cdot \sigma_{\#switch} \rceil \quad (8)$$

with $\mu_{\#switch}$ and $\sigma_{\#switch}$ are respectively the mean value and the standard deviation of the considered window of samples, while through the parameter α we can make the threshold more or less stringent.

D. NUMERICAL RESULTS

In order to assess the performance of the proposed BS selection algorithms, we modified the MATLAB® simulator developed for the single BS scenario. We placed 16 mm-wave BSs following a regular grid in a rectangular $1800m \times 1400m$ area surrounded by reflecting walls. We dropped 0, 80, or 160 squared 20×20 meter sized obstacles, positioned in such a way they do not overlap each other, with the surrounding walls and with the BSs. Then, 2000 users have been randomly dropped in the remaining free area. The user-location uncertainty and physical parameters characterizing the propagation are modeled in the same way as in the single BS scenario. We assume that every mm-wave BS is equipped with the same antenna array described in Sec. IV-D, and thus, the antenna configuration switching time is equal. The same omnidirectional antenna is installed at user side.

Since we are interested in analyzing the BS selection algorithms, we choose to consider two exemplifying cell discovery algorithms, like D-SLS and EDP, without introducing the context database. They have been selected due to their big difference in terms of performance, which allows us to emphasize the impact of the efficiency of the discovery algorithm. Indeed, very similar conclusions can be drawn applying more involved discovery techniques. Furthermore, we assume that all BSs adopt the same discovery algorithm.

The group of coordinated mm-wave BSs involved in the user discovery period can be seen as a queueing system, where users arrive at a certain frequency and issue an access request, the eNodeB dispatches a discovery command to selected BSs, which can either start searching for the user or put the command in a waiting queue. In light of this, we consider a discrete time system, where the timeline is divided into time slots of duration equal to the antenna configuration switching time. Varying the user arrival rate λ, expressed in terms of number of arrivals in a time slot, we measure the *discovery time*, the *waiting time*, and the *total time*.

The *waiting time* is the time from the user arrival time slot and the slot in which the discovery procedure starts in at least one of the BSs selected by the eNodeB. We assume that the time spent by the eNodeB to define the candidate set and to forward the discovery command is negligible. The *discovery time* is the time from the beginning of a discovery procedure (the end of the waiting time) to the time slot where the user is found by at least one mm-wave BS. The *total time* is the sum of *waiting time* and *discovery time*.

We group the outcomes of the simulations in two different types of scenario: with and without obstacles.

1) SCENARIO WITHOUT OBSTACLES

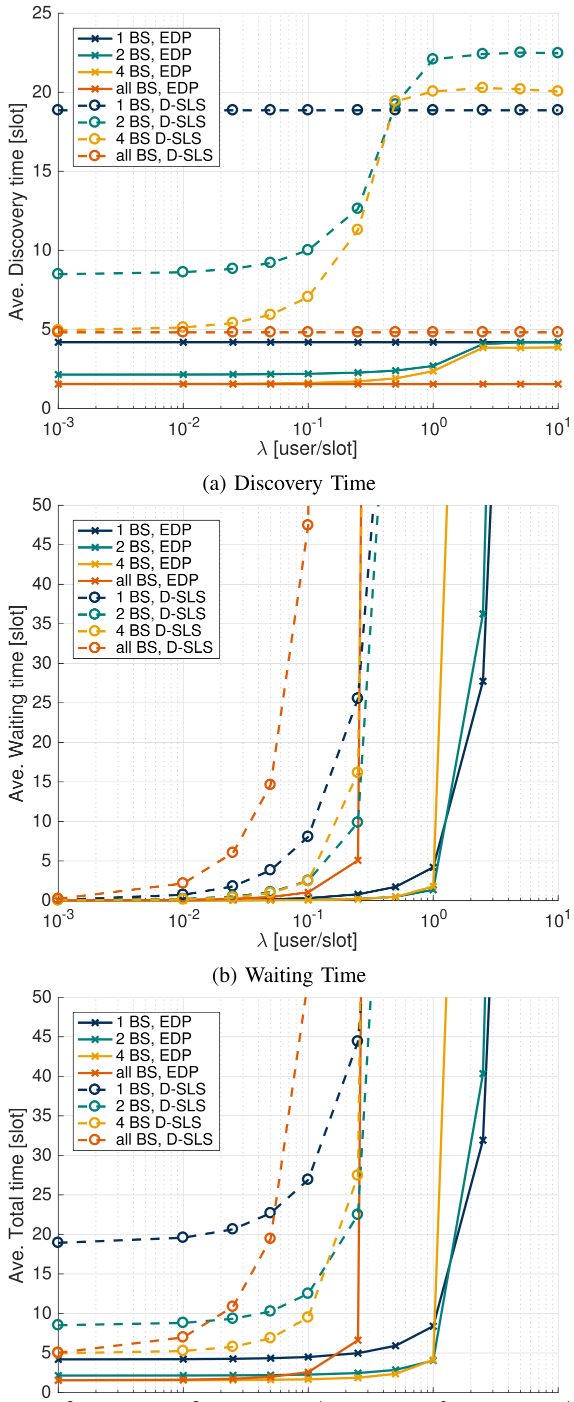
In this scenario, LOS paths are always available. Despite that, the discovery algorithm executed by the selected mm-wave BSs may be unsuccessful if the user and the BS are too far apart to provide sufficient power.

Numerical results are shown in Fig. 11, which reports the average discovery time, waiting time, and total time when varying the rate of user arrival λ, different BS selection and discovery algorithms are considered as well. We analyze the results starting from the two extreme cases: *All-BS* and *1-BS*. They show that in these cases the discovery time is independent of the arrival rate λ. This is because in the *1-BS* case there is no coordination among BSs and the resulting discovery time corresponds to the time (number of slots) required by the discovery algorithm, which is independent on the user arrival rate. Adopting the *All-BS* selection, the discovery time greatly reduces because it corresponds to the minimum time among involved BSs. It is still independent of the user arrival rate because, since all installed BSs are involved, each access request is simultaneously sent, queued, served and canceled at every BS, leading to the independence of the discovery time from λ.

As for the waiting time, if *All-BS* selection method is used, the network exhibits a small waiting time when λ is small, but, as the arrival rate increases, it dramatically grows and brings the network to the saturation. Since all resources are occupied to serve only one request, a new user will likely find the network busy, especially with large values of λ. Vice versa, adopting *1-BS* selection, the point where the network starts to show congestion is shifted to much higher arrival rates than in *All-BS* case. The reason is that now the backlog is better distributed among all BSs.

When considering *2-BS* and *4-BS*, the discovery time curves have a radically different trend: they remarkably increase with λ. This can be explained by considering that, in principle, different BSs have different queues, which are populated with different discovery commands. Therefore, the BSs involved in the search of the same user may start the discovery at different time slots, especially when the network is loaded. Consequently, there is a probability that the discovery begins with non-optimal BSs, because the optimal ones are busy in searching for other users. As soon as good BSs empty their queues, they can quickly find the user, but the service is started well before, therefore the discovery time increases. As for the waiting time, *2-BS* and *4-BS* methods present an intermediate behavior. They sometimes perform better because they may reduce the overall backlog by providing a better trade-off between involving more BSs for a short discovery time and involving fewer BSs, but accepting a longer discovery time.

Finally, by looking at the total time curve we can estimate the access latency perceived by the users. Results show a trade-off between latency and the point where the access network saturates. The network can afford to reduce the access latency by allocating more resources when there are



(a) Discovery Time

(b) Waiting Time

(c) Total Time

FIGURE 11. Performance of BS selection procedures varying user arrival rate, with different cell selection procedures and discovery algorithms. The scenario considers a user location error of 20*m*. (a) Discovery time. (b) Waiting time. (c) Total time.

few access requests, vice versa, resources must be conserved when the arrival rate increases in order to postpone the saturation. Furthermore, results clearly show that, independently of the BS selection method, the effectiveness of the discovery algorithm strongly affects the whole performance. This highlights the importance of developing effective cell discovery algorithms.

2) SCENARIO WITH OBSTACLES

The simulation results are reported in Fig. 12, they show a strong performance degradation when obstacles are present, in particular, the total time increases and the network saturation point is shifted towards very small λ values. Obstacles make the discovery more difficult, thus the network undergoes a large amount of extra discovery work, leading to a very rapid saturation, even if few BSs are included in the candidate set.

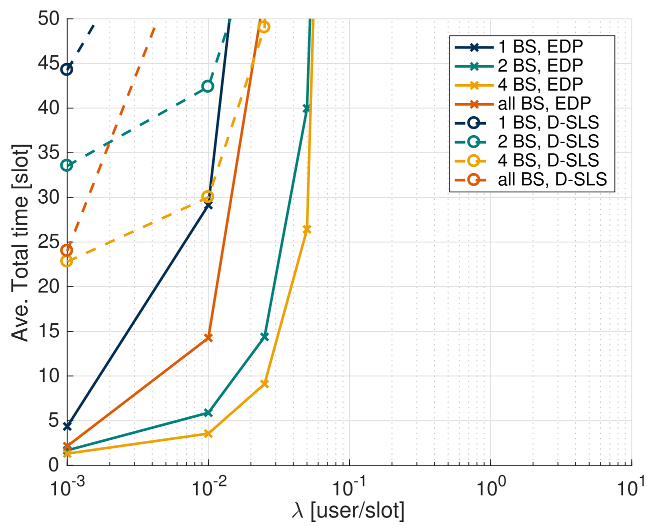


FIGURE 12. Total time for the user access when 80 obstacles are dropped in the area of 16 mm-wave BSs.

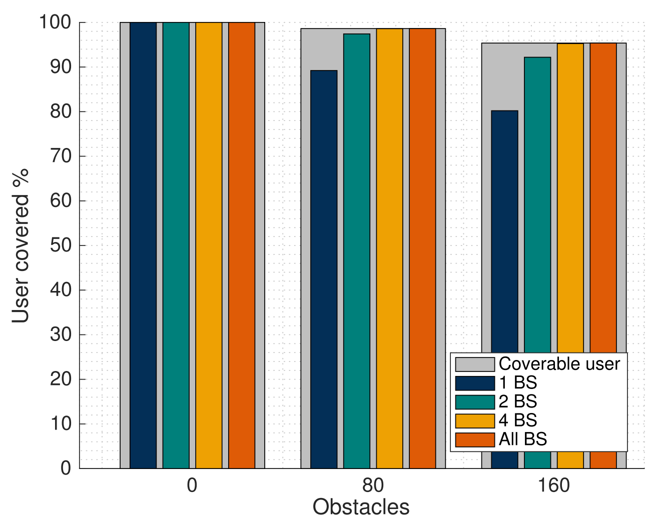


FIGURE 13. Coverable users with mm-wave BSs and covered users with different BS selection methods.

Fig. 13 shows the percentage of covered users. The percentage of users which can be reached by at least one installed mm-wave BS is plotted in gray, while other columns of the bar graph represent the users that are actually covered by using the proposed BS selection method. We can see that the mm-wave access coverage is proportional to the number of BSs involved in the discovery process. In addition, the more obstacles the more isolated users, therefore, the overall coverage percentage decreases as the number of obstacles increases.

In order to reduce the impact of obstacles we have introduced a threshold mechanism that allows mm-wave BSs to abort the discovery procedure if it is lasting too long. Here, we show the results of this threshold mechanism. We recall that high values of α mean longer discovery times allowed, and vice versa. In the simulations α is set to $\alpha = 3$ and $\alpha = 6$.

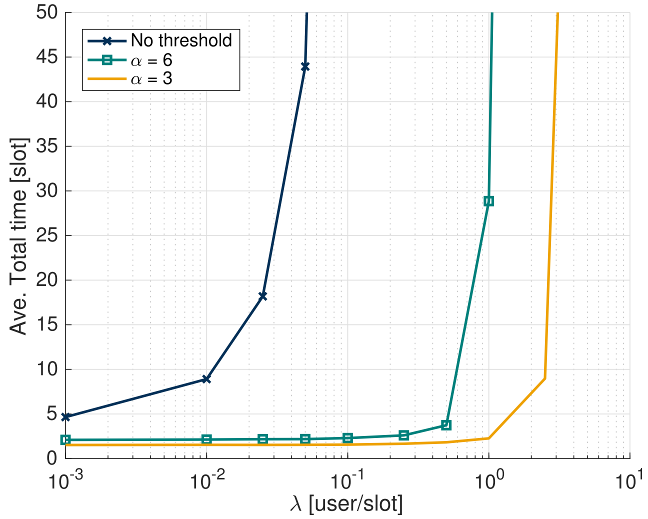


FIGURE 14. Total time for the user access when 80 obstacles are dropped in the area and the adaptive threshold mechanism is active.

Since the threshold operation is independent of the type of BS selection adopted and the discovery algorithm implemented, we choose to use only *2-BS* with EDP algorithm. In Fig. 14 we can very well see that the introduction of the threshold is able to shift right the network saturation point, making it comparable to the case where obstacles are not present. Moreover, the average total time is considerably reduced. These effects are magnified by reducing the value of α. However, we must note that the advantages of the threshold mechanism come at the expense of the overall coverage. Indeed, the percentage of covered users after the introduction of the threshold, shown in Fig. 15, reduces accordingly to α: a more stringent threshold ($\alpha = 3$), fewer users able to access the mm-wave service. This is due to the presence of badly positioned users, i.e. users that could access the network but that require longer discovery times than other users, which are consequently excluded.

We can conclude that the threshold is very effective in limiting the performance degradation due to the presence of obstacles, but it must be carefully tuned so as to not prevent too many users from connecting. However, serving badly positioned users increases the average discovery time, thus

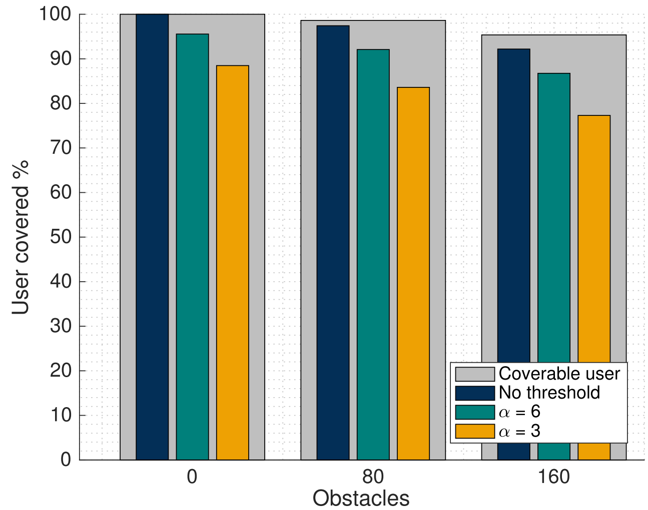


FIGURE 15. Coverable users with mm-wave BSs and covered users with different BS selection methods when the adaptive threshold mechanism is active.

the network access backlog, leading to support a smaller user arrival rate.

VI. CONCLUSION

We have thoroughly investigated the rich set of network access challenges posed by the introduction of mm-wave technologies in the future 5G networks. They call for new ways of dealing with legacy network functionalities to fully unleash their great potential, among them the cell discovery procedure is one of the most critical.

We have proposed novel cell discovery algorithms enhanced by the context information available through a separated C-/U-plane architecture. Obstacles generally undermine the efficiency of directional discovery algorithms, therefore, we have investigated the potential of a geo-located context database. The results show that it can dramatically increase the algorithms' performance by substantially reducing the impact of obstacles.

Moreover, we have investigated the case of multiple mm-wave BSs that jointly process each user access request. We have shown that selecting the best set of BSs involved in the discovery is crucial. In addition, we have demonstrated how badly positioned users can severely harm the discovery efficiency. In order to solve this issue, we have designed effective solutions that can successfully improve the network behavior.

We believe that the trade-offs and the challenges highlighted in this article, together with the proposed solutions, can be a major contribution to enable mm-wave cell discovery in 5G networks.

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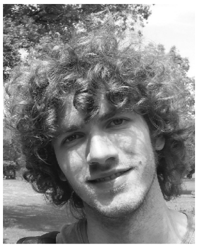

FRANCESCO DEVOTI received the B.S. and M.S. degrees in telecommunication engineering from the Politecnico di Milano, Milan, Italy, in 2013 and 2016, respectively. He is currently pursuing the Ph.D. degree with the Electronics, Information and Bioengineering Department, Politecnico di Milano. His research interests include millimeter-wave technologies in 5G networks.

ILARIO FILIPPINI (S'06–M'10) received the B.S., M.S., and Ph.D. degrees from the Politecnico di Milano in 2003, 2005, and 2009, respectively, all in electrical engineering. In 2008, he was a Visiting Researcher with the Department of Electrical and Computer Engineering of The Ohio State University in Columbus. He is currently an Assistant Professor with the Information, Communication and Bioengineering Technology Department (Dipartimento di Elettronica, Informazione e Bioingegneria), Politecnico di Milano. His research interests are in networking, planning, optimization, performance evaluation and protocol design of wireless access, and multi-hop networks. He serves as the Editor of Wiley/Hindawi *Wireless Communications and Mobile Computing*.

ANTONIO CAPONE (S'95–M'98–SM'05) received the M.S. and Ph.D. degrees in electrical engineering from the Politecnico di Milano in 1994 and 1998, respectively. He is currently a Full Professor with the Information, Communication and Bioengineering Technology Department (Dipartimento di Elettronica, Informazione e Bioingegneria), Politecnico di Milano, where he is the Director of the Advanced Network Technologies Laboratory. He is a Co-Founder and the CTO of MobiMESH, a spin-off company of Politecnico di Milano. His expertise is on networking and his main research activities include protocol design including MAC and routing, and performance evaluation of wireless access, and multi-hop networks, traffic management and quality of service issues in IP networks, and network planning and optimization. He served as the Editor of the IEEE/ACM Transactions on Networking. He currently serves as the Editor of the IEEE Transactions on Mobile Computing, *Wireless Communications and Mobile Computing* (Wiley), *Computer Networks* (Elsevier), and *Computer Communications* (Elsevier).