Ref. Ares(2016)2657656 - 08/06/2016

D1.1: Consolidated State of the Art Surveys (ESRs 1-2) and Individual Research Proposals

Project Name: Anticipatory Networking Techniques in 5G and Beyond

Acronym: ACT5G

Project no.: 643002

Start date of project: 01/05/2015 **Duration:** 48 Months

This project has received funding from the European Union's Horizon 2020 research and innovation programme under the Marie Skłodowska-Curie Actions.

Document Properties

Document ID	EU-H2020-MSCA-ITN-2014-643002-ACT5G-D1.1
Document Title	D1.1: Consolidated State of the Art Surveys (ESRs 1-2) and Individual Research Proposals
Contractual date of delivery to REA	Month 10
Lead Beneficiary	Linköping University (LiU)
Editor(s)	Vangelis Angelakis, Di Yuan
Work Package No.	2
Work Package Title	Network Anticipation
Nature	Report
Number of Pages	39
Dissemination Level	**PUBLIC**
Contributors	LiU: C. Tatino, V. Angelakis, D. Yuan. POLIMI: D. Weibel, A. Capone, M. Cesana ALUD: I. Malanchini
Version	1.0

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1 Executive Summary

Work package 1 (WP1) is structured around the networks data analysis and wireless link status prediction. In particular, WP1 will focus on collecting and analysing data from realistic mobile wireless networks, identification of comprehensive KPIs in order to develop new approaches for wireless link status prediction on different time-scales, giving particular attention to computational complexity and accuracy. The main goal of this report is to show the evolution of new mobile networks generations, driven by the rising of new use cases and requirements, and to identify where network data analysis and link status prediction can provide benefits. From the ESR2 point of view, more attention should be given to link estimation and prediction with adaptive and tracking techniques, identifying the methodologies and the approaches implemented up to now, the new challenges that the rising technologies can lead in order to develop new solutions.

2 Introduction

In the last years, the always dramatically growth of mobile traffic demand is making the current networks technologies not more suitable to provide the required capacity. As reported in [2], in the next 5 years, the worldwide data traffic demand will exponentially increase due to the more and more mobile users, the opening up on the market of new devices (i.e. wearable), the growth of M2M communications and greedy demand applications. To respect the new demands, a new generation of mobile networks is needed; as stated in [3], the 5th generation of mobile networks (5G) is going to be standardised by 2020; the requirements, the new possible use cases and data rate demand include, but not limited to the following:

- High data rate: up to 1 Gb/s per user in particular environments i.e. (indoor), while at least 50 Mb/s everywhere.
- Very low latency: 10 ms end-to-end (E2E) latency in most cases and 1 ms for the use cases which require extremely low latency.
- High user mobility: up to 500 km/h for high speed train and 1000 km/h for airplane connectivity.
- High connections density: Up to several hundreds thousand active connections per square kilometre at the same time.

To reach the challenges goals described above, and to fulfil the high growth of traffic demand and users density, different solutions can be deployed; in particular, as stated in [4, 5], mainly three approaches can be followed:

- Increase the number of antennas at the transmitter and the receiver.
- Decrease the cell size increasing the densification.
- Increase the spectrum resources, by exploiting the new frequency bands;

The aforementioned solutions allow to identify three basic 5G enabler technologies: massive MIMO, millimetre-waves (mm-waves) and small cells. Massive MIMO consists in developing base station (BS) equipped with antenna array, composed by much more elements than the number of served devices. While on the one hand, as stated in [6], it allows to improve the performance thanks to better spectral efficiency, spatial diversity, multiplexing and diversity gain, on the other hand it requires architectural changes with higher complexity.

The most currently 4G communications and telecom operators mainly operate from 800MHz to 3 GHz and only during the last years, frequency bands around 5-6 GHz have started to be exploited; nevertheless, it is still not enough to face the growing traffic demand. Millimetre-waves technology allows to use huge unused frequency bands, from

30 GHz to 300 GHz, where unlicensed free band spectrum is available. On the other hand, the high frequencies enormously impact the radio performance in terms of path loss and shadowing, decreasing the cell dimension. Simultaneously, more cells with a smaller coverage size allow much more networks capacity by improving the spectral reuse and reducing the number of users competing for resources [4]. It could also be possible to deploy networks where macro cells, i.e. 4G, overlap small cells belonging to different mobile technologies (i.e. WiFi); this kind of networks take the name of heterogeneous networks (HetNets). Even if HetNets are already standardised in 4G, the latter doesn't natively support them [5]; in fact, many aspects and issues of a such dense environment have to be taken in account (i.e. inter-cell interference, frequent handovers), which require coordination and cooperation between different technologies with different cells size. Another important technology that can play a key role in 5G are the device-to-device (D2D) communications. In fact, enabling the devices to communicate directly between them or to act as relays, maybe with different support from macro cells, can improve the network performance, by increasing coverage size and spatial reuse.

In these much more complex networks deployment introduced above, networks data analytics and wireless link status anticipation can play a key role to improve the networks performance; in the following Sections both the solutions are better explored highlighting on the different aspects involved in 5G enablers technologies.

3 Network Data Analytics

3.1 Context

3.1.1 Basics of mmWave Communication

Millimetre waves (i.e. the frequencies between 30 and 300 GHz) are generally regarded as one of the key technologies of future International Mobile Telecommunication (IMT)[1] systems, including 5G (see e.g. statements from academia [7, 8], industry [9, 10], and standardisation bodies [11, 12]). In November 2015, the ITU World Radiocommunication Conference 2015 (WRC-15) has declared a set of mmWave frequency bands to be studied for a potential IMT use. These are the bands 24.25–27.5 GHz, 37–40.5 GHz, 42.5–43.5 GHz, 45.5–47 GHz, 47.2-50.2 GHz, 50.4-52.6 GHz, 66-76 GHz and 81-86 GHz [13]. Further decisions about mmWave IMT bands can be expected from WRC-19. Regarding these initiatives, it is likely that in the future there will be at least one officially licensed IMT band in a mmWave frequency up to 100 GHz.

Millimetre waves have very different propagation characteristics from the traditional microwaves between 700 and 2600 MHz that are currently used for IMT. One of the main differences is a much higher propagation loss. Figure 1 shows the free-space propagation loss of the frequencies between 10 and 400 GHz in dB per kilometre. As can be seen, generally, a higher frequency causes a higher propagation loss. Furthermore, there are some irregular spikes, which are due to the absorption of the radio waves of these particular frequencies by gas molecules in the atmosphere. In particular, there are two oxygen (O_2) absorption bands at 60 and 119 GHz, and three water vapour (H_2O) absorption bands at 22, 183, and 323 GHz [14].

A consequence of the high path loss of mmWaves is that, given the same a transmit power level, the communication range is much shorter than for traditional microwaves. An effective countermeasure against this is to use directional antennas with a high gain, rather than conventional omnidirectional antennas. In this way, the emitted power is bundled towards the receiver rather than dispersed uniformly in all directions. It has been shown that in this way reliable transmission ranges up to 200 meters can be achieved in outdoor scenarios [15].

In general, we can distinguish between omnidirectional, semi-directional, and fully directional communication. Omnidirectional communication, as mentioned, radiates the power uniformly in all the directions of the horizontal plain around the antenna. Semi-

[1] IMT is the ITU (International Telecommunication Union) term for the global mobile cellular network, and we will use this term throughout this report.

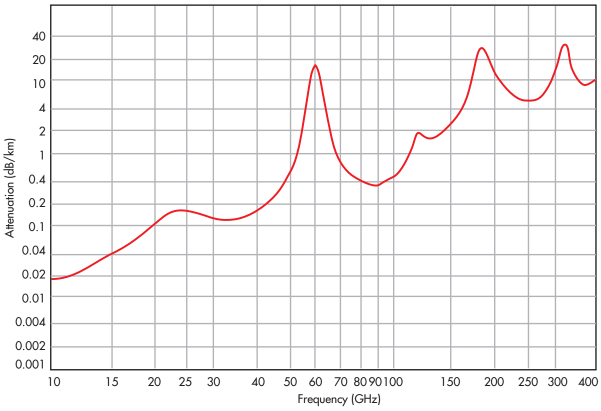


Figure 1: Free-space attenuation on sea-level of radio waves between 10 and 400 GHz. Note that both axes are logarithmic. Figure from [1].

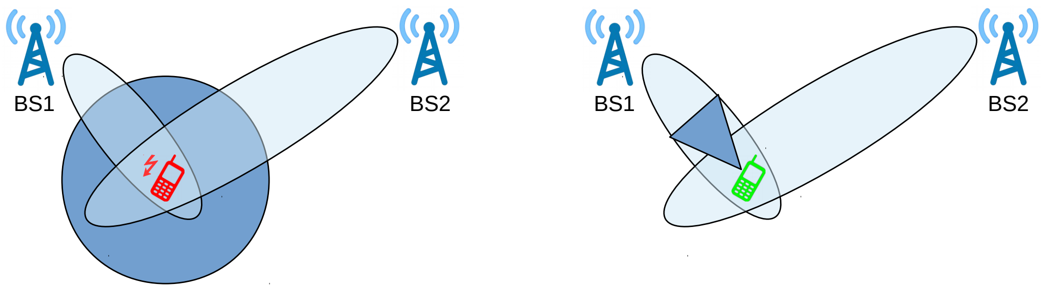
directional communication means that one of the communication partners uses a directional antenna, whereas the other uses an omnidirectional one. In the case of IMT, typically, the base station would have a directional antenna, and the UEs an omnidirectional one. Finally, fully directional communication means that both communication partners use directional antennas [16].

Both, semi-directional and fully directional communication would be options for an IMT mmWave network. However this choice has important implications for the interference and resource management. In the semi-directional case, UEs receive signals equally from all angle of arrivals (AOA). Consequently, if a UE is connected to a specific beam and at the same time in the coverage of another beam from a different AOA, then these interfere in the UE reception antenna. In the fully directional case, on the other hand, the UE “listens” only into the direction of the serving beam, and thus does not “hear” the signal from the other beam, it is “deaf” for the second beam. Consequently in this case the second beam does not cause interference at the UE. This fact is illustrated in Figure 2.

3.2 Problem Description

In the last section we described the basics of mmWave communication, the new resource allocation use cases that it gives rise to, and that to tackle these tasks a broad range of context information might be beneficial. In this section we describe concretely how we are planning to confirm this thesis.

First of all, we propose to structure the landscape of resource allocation tasks that might occur in mmWave networks into three categories. These categories, depicted in Fig-



(a) Semi-directional: interference at UE. (b) Fully directional: no interference at UE.

Figure 2: Interference scenario for a UE connected to a beam of BS1 and being in the coverage of another beam of BS2.

ure 3, are *intra-mmWave*, *inter-mmWave*, and *inter-RAT*. These categories correspond to levels of spatial and co-operational granularity. The lowest level, intra-mmWave, contains all resource allocation use cases that are decided independently by a single mmWave base station. The second level, inter-mmWave, includes all use cases that require cooperation of two ore more mmWAve base stations. Finally, the highest level, inter-RAT, includes the use cases that involve at least one mmWave and at least one non-mmWave base station (e.g. a microwave macro, pico, or femto cell, or WiFi).

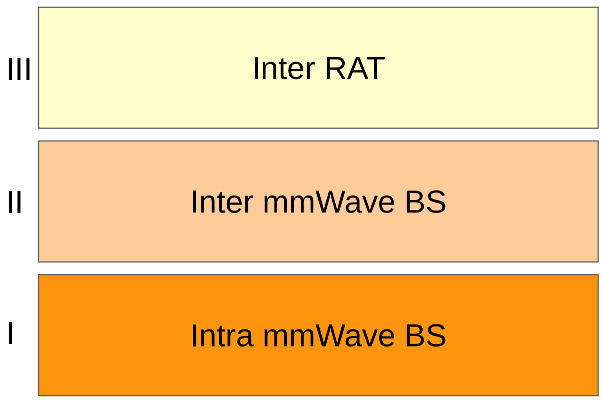


Figure 3: Proposed framework for structuring resource allocation tasks in mmWave networks.

3.2.1 Intra-mmWave BS Use Cases

One intra-mmWave use case is the initial connection establishment between a UE and a mmWave BS, a problem known as *initial access* or *cell discovery*. The difficulty here is that since directional communication is used, BS and UE must point their beams exactly against each other in order to be able to start communicating and, in the first place, to learn about each other's presence. This is unlike in traditional omnidirectional communication where synchronisation signals emitted by a BS can be received by any UE in the coverage area of the BS. Proposed solutions employ the repeated emission of synchronisation signals of the BS in different directions, either exhaustively across the entire coverage area of the BS [17], iteratively, by starting with a wide beamwidth to narrow down the search space, and then iteratively decrease the beamwidth [18], or randomly, by emitting the synchronisation signals in random directions [19]. Another approach is to have the UE determining its own approximate position (e.g. via GPS) and feeding this information back to the mmWave BS via an omnidirectional macro cell. The mmWave BS can then directly point its beam in the UE's direction and refine the search from there [20, 21, 22]. This last approach can be seen as leveraging a type of context information (UE's location). A survey of proposed initial access procedures can be found in [23].

Another large group of intra-mmWave resource allocation use cases in concerned with the beam management for data transmission, once the initial access and connection establishment between UE and BS has been completed. The problem can be subdivided into *beam alignment* and *beam selection*. Beam alignment are procedures for choosing beam directions at both BS and UE so that a sufficiently high SINR is achieved on both sides. Since UEs might be mobile and channel conditions might change over time, beam alignment procedures generally need to be executed repeatedly during a data transmission.

First of all, we would like to point out that beam alignment is part of the IEEE 802.11 ad standard [24, Sec. 9.35] from 2012, and thus complete solutions that are embedded in the corresponding MAC and PHY layers exist for already some of years now[2]. There are two different beam alignment approaches in IEEE 802.11 ad, beamforming training (BFT) and beam tracking (BT). In BFT, a beam alignment procedure is executed at the beginning of each beacon interval, which has a typical length of 100 ms [26]. The procedure consists of a sector-level sweep (SLS) and an optional beam refinement protocol (BRP). In the SLS, the access point starts by sending out a sequence of synchronisation frames in a set of different directions, called sectors. These frames are received by the terminal using a quasi-omnidirectional antenna configuration. The terminal records the best-quality frame, and then the process is reversed, that is, the terminal sends out directed synchronisation frames whereas the access points listens with a quasi-omnidirectional antenna setting. The IDs of the best sectors received by terminal and access point are exchanged, the two entities set their beams accordingly, and then the data transmission starts. On the

[2]Similar beam alignment procedures are also already specified in the older IEEE 802.15.3c standard (60 GHz WPAN) from 2009 [25, Sec. 13].

other hand, beam tracking (BT), works by appending synchronisation frames directly to the data packets. In this way the beams are kept aligned in "real-time" during the data transmission, rather than just at the beginning of a longer transmission interval as in BFT [24].

Several beam alignment procedures based on the IEEE 802.11 ad and IEE 802.15.3c standards have been proposed, e.g. [27, 28]. These works are targeted mainly at indoor scenarios. In [29], the authors propose a beam alignment procedure for use in outdoor mmWave backhauls. The procedure is based on a hierarchical beamforming codebook (predefined set of beams) and starts by sampling the coverage space with a coarse granularity and then iteratively narrows down the beamwidth in the appropriate sectors until the receiver is located with a narrow enough beam that can be used for data transmission.

The second sub-group of beam alignment tasks is beam selection. It deals with beam management on a higher level than beam alignment, and decides basically which of several possible beam forms and constellation to use. For example, [30] proposes mechanisms to switch from a line-of-sight (LOS) beam to a non-line-of-sight (NLOS) beam in case the (preferable) LOS beam gets blocked (e.g. by a passing person). In particular, the authors propose an instant-decision based and an environment learning based mechanism to select a NLOS beam. In the instant-decision based case, the procedure considers only instant information such as SINR and angle of arrival (AOA) on the terminal side. In the environment learning based case, the procedure takes into account recorded NLOS beam experiences from the past.

Another beam selection task is to group UEs that are to be served by the same beam of a base station. The need for this arises when the number of UEs to be served is larger than the maximum number of RF chains (i.e. beams) of base station (which is determined by the antenna hardware). However, also in other cases UEs might need to be put in the same group, if, for example, they are co-located and a separate beam to each of them would cause interference [16]. A number of such user grouping schemes has been proposed in [31, 32]. At this point we should note that fully directional communication greatly increases the degrees of freedom of user grouping, with respect to semi-directional communication. This is because in the semi-directional case, UEs that are co-located tightly enough are *forced* to be in the same group, because any second beam to one of the UEs would be likely to cause interference to the other co-located UEs. In the fully directional case, on the other hand, there may be more than one beams arriving at a set of co-located UEs, and as long as these beams arrive from different AOA (e.g. a LOS and a NLOS beam), they do not cause any interference to the other co-located UEs, because the UEs are "deaf" to any signals that arrive from other directions than the one that they are listening to [16]. Thus, co-located UEs can be assigned to different groups if a sufficient diversity of AOA of the different beams can be provided.

3.2.2 Inter-mmWave BS Use Cases

The inter mmWave BS category includes resource allocation tasks that involve multiple mmWave base stations. One such use case is the association of a UE to one of several possible mmWave base stations. This is necessary because due to the concept of dynamic cell and the needed high density of mmWave base station deployment for combating shadowing, a UE will often be in the coverage area of multiple mmWave base stations. For example, there exist indoor deployment scenarios with almost fully overlapping coverage areas of multiple mmWave base stations inside a room [26]. This is unlike in the traditional network concept with its Voronoi diagram-like cells, where (other than at the cell edges) UEs are usually in the unambiguous coverage area of only a single base station, and hence, cell association can be done according to simple rules [16]. In mmWave networks, on the other hand, this is not the case. This problem can be furthermore refined as the association to a specific beam of a specific base station.

In [33], the authors propose a distributed cell association algorithm with the objective to minimise the maximum base station utilisation. That is, the goal is to distribute the total load evenly over the available base stations. Sakaguchi et al. [26, Sec. 3] propose to administer cell association and beam selection of a group of access points (AP) with overlapping coverage areas centrally by an access point controller (APC). The APC bases its decisions on the so-called "fingerprint database". This database is collected in an offline phase by collecting received signal strength (RSS) readings of UEs at known locations to all the APs in the APC's management domain. Based on this information, the APC can then estimate the position of UEs during the operation of the network. The APC furthermore derives AP-specific radio maps from the fingerprint database. These include RSS maps showing the UEs' RSS at different locations in the AP's coverage area, and best-sector maps that indicate the best beam configuration for each location. Furthermore, the APC also determines "bad beams" for each beam and UE location, that is, beams from other APs that would cause interference at the given UE. Based on all this information, the APC then chooses an AP and a beam configuration for any data transmission by a UE.

The work in [16, Sec. 5.D] lists three factors which a cell association algorithm should take into account: *(1)* the UE's traffic and QoS demand, *(2)* the channel state between UE and BS, and *(3)* the loads of the BS. The cell association algorithm should have the following objectives: *(1)* the UE's traffic and QoS demands are met, *(2)* the tradeoff between fairness and spectral efficiency is improved, and *(3)* the chosen connection is robust to blockage. For the latter objective, the authors propose to associate a UE not only to one but to two base stations at the same time. Based on this framework a cell association algorithm is formulated as an optimisation problem and simulated for semi-directional, and fully directional communication cases. It is shown that a higher number of beams per base station positively affects the total system rate.

Another problem that arises from the overlapping coverage areas of mmWave base stations is the one of scheduling the transmissions of the different base stations in order to avoid collisions. Again we can point to IEEE 802.11 ad which contains a mechanisms with which several APs operating on the same frequency can form a cluster and schedule their transmissions in non-overlapping time periods [24, Sec. 9.34]. Sakaguchi et al. [26, Sec. 2.4] propose to extend the beamforming training of IEEE 802.11 ad to multiple remote radio head (RRH) covering the same area. That is, the best beam alignment is searched not only for a single base station, but across multiple ones of them. This requires however coordination between these base stations, and a scheduling of their sector level sweeps (SLS). This scheduling is ensured by a central baseband unit (BBU) to which the individual base stations are connected.

A work by Shokri-Ghadikolaei [34] investigates the tradeoff between beamwidth and network throughput. A larger beamwidth decreases the beam alignment overhead, but, on the other hand, might require a less efficient transmission scheduling. This is because broader beams are more likely to cause interference, and transmissions that interfere with each other should not be scheduled simultaneously.

Another use case that can be classified as inter-mmWave is the combination of multiple beams from different base stations on the UE side. Clearly this use case requires fully directional communication, and the UE must support multiple reception beams. This approach has been demonstrated in [35] on 28 and 73 GHz carrier frequencies, and it has been shown that combining up to four beams at the UE can significantly improve the received signal quality and extend the link coverage.

3.2.3 Inter-RAT BS Use Cases

This category includes resource allocation use cases that involve at least one mmWave base station and at least one non-mmWave base station, such as a microwave macro cell. These use cases assume a scenarios with several overlaid RAT layers, for example, a number of small mmWave cells overlaid in the coverage area of a large macro cell. The main question is then to which RAT to associate a specific UE? Such a decision is typically based on the capabilities of the different RAT, the demands of the UE, and the current state of the network (e.g. load, link qualities).

In [36], the authors describe a cell association algorithm for a two-layered architecture consisting of traditional macro cells and randomly overlaid mmWave cells. The objective of the algorithm is to maximise the system rate, that is the total data rate capacity of the network. The association is done based on the traffic demand of each user, the available bandwidth at each cell, and the current spectral efficiency of the links. The algorithm results in a significantly higher system rate compared to a pure SINR based cell association.

A lot of work has been done on multi-tier cell association algorithms for heterogeneous networks (HetNets). These algorithms typically try to improve the system performance (measured e.g. in average user throughput or system rate) by biasing cell associations toward small cells (pico cells, femto cells). This can be done, for example, by modifying the traditional SINR based cell association so that UEs are associated with a small cell even though the macro cell would provide a better SINR. Two examples of this work are [37, 38]. However, these solutions do not take into account mmWave cells, and are assuming Voronoi diagram coverage areas. They might thus not be applicable to a mmWave network with its inherent dynamic cell concept.

3.3 Research Question, Expected Results, and Methodology

Our research proposal can be summarised in an observation and a thesis. The observation is that mmWave communication gives rise to fundamentally new resource allocation problems. The reason for this is the inherent directionality of mmWave communications and the ensuing concept of dynamic cell. A cell is no longer a static contiguous geographical area, but a flexible and ephemeral collection of directed beams. A host of new resource allocation problems concerned with the management of these beams emerges. Furthermore, with fully directional communication mmWave network shifts from an interference-limited regime to a noise-limited regime [16]. Our thesis is that these new resource allocation problems can be more effectively and efficiently solved by leveraging an extended set of context information. With an extended set of context information we mean information that is not typically used in resource allocation solutions of traditional networks, nor in the current mmWave resource allocation literature (as reviewed in Section 3.2). This context information may range from device-level, application, user, network, to environment context.

For providing evidence for our thesis, we propose to focus on one specific use case of each of the resource allocation categories that we identified in Section 3.2 (intra-mmWave, inter-mmWave, and inter-RAT). We will develop a detailed solution for each use case, including a broad range of context information. Then we will compare the performance of these solutions to comparable solutions from the literature which include. We plan to use different performance metrics, such as total system data rate, average user data rate, average packet delays, to name just a few examples.

The expected results of the study are three novel resource allocation algorithms for mmWave networks using an extended set of context information. We furthermore expect these algorithms to show the benefit of using context information that at the present time is not used for resource allocation tasks.

Regarding the methodology, we plan to use a hybrid of real-world testbed measurements and simulations. We plan to collect data in the testbed, especially context information and link measurements, and then to use this data as the basis for a simulation study. The algorithms will be implemented and executed exclusively in the simulation. We make use of simulations because on one hand it increases flexibility, and on the other hand, because there does not exist a lot of available mmWave hardware at the moment. An option for the simulation tools is the mmWave module for ns3 developed by NYU WIRELESS [39].

Regarding the testbed, we plan to equip a room with 2–3 mmWave base stations, a non-mmWave base station, different types of obstacles, and a mmWave-capable terminal device. The data is then acquired while playing through different scenarios with the terminal device, such as different application usage patterns, and moving on certain trajectories through the room. Given the scarcity of available mmWave-capable devices, we plan to resort to IEEE 802.11 ad, the currently most popular consumer-oriented mmWave technology. IEEE 802.11 ad is an extension of WiFi in the 60 GHz ISM band, and a range of compatible consumer devices has been released in the last quarter of 2015 and the first quarter of 2016. These include a USB dongle[3], an access point (combining 2.4, 5, and 60 GHz WiFi)[4], a notebook[5], and a smartphone[6].

[3] http://www.perasotech.com/gp_product/consumer-ic-products/
[4] http://www.tp-link.com/en/products/details/AD7200.html
[5] http://us.acer.com/ac/en/US/press/2016/175243
[6] http://www.techgrapple.com/letv-x910-with-snapdragon-820-certified-by-tenaa/

4 Wireless Link Status Anticipation and 5G promising technologies

Wireless link status anticipation and prediction have been widely proposed in the past for many purposes i.e. rate adaption, handover and mobility management and reliable routing algorithms. In 5G, the complexity of a high dense environment and the challenging goals to reach (data rate, high speed mobility, user density) make the prediction a promising, in some cases a mandatory, tool to aim the previous requirements. In the following Sections the main 5G potential enabler technologies are explored, with particular focus on the several aspects where the wireless link status anticipation and prediction have been applied, and where it can contribute to enhance the performance. In the end, a brief overview on several wireless link prediction scope of applicability and methodologies is presented.

4.1 Massive MIMO

In according to [6], massive MIMO is one of the most promising solution for increasing users density and networks capacity; It consists in developing base stations with a number of antennas that is at least 10 times the amount of users in the cell, thanks to which it is possible to reach high performance in terms of multiplexing and diversity gain.

On the other hand, massive MIMO requires an accurate channel estimation for the precoding; the widely number of antennas needs a large number of pilot signals in order to estimate the channel state. To reduce the overhead and to make the massive MIMO a more scalable solution, a great attention is given to methodologies for decreasing the number of feedback required for the channel tracking. TDD can contribute in this, in fact, thanks to the reciprocity of the channel, only the uplink channel estimation should be performed, which depends only on the number of users.

The authors in [6] show how TDD can tremendously decrease the number of pilot signals required for precoding, although pilots contamination can still mitigate the performance. Another issue that affects the quality of channel estimation and, consequently, the massive MIMO precoding is the channel aging;

In this case the prediction can highly improve the performance, in fact [40, 41] propose an asymptotic analysis of the delayed CSIT (channel state information at the transmitter) effects, evaluating the gain that a Wiener predictor can obtain by estimating the current channel state information (CSI). More precisely, the CSI prediction is performed with a time-horizon equal to the delay (supposed to be known) on the basis of the past and dated

CSI observations.

4.2 Millimetre-Waves (mm-waves)

The 5th generation of mobile communications will be characterised by much more data rate per user; to reach the previous goal, one possible solution is to use much greater spectrum resources. In this process, millimetre-waves (mm-waves) technology will play a key role, since it will allow to exploit unused frequency band, higher than 30 GHz, where huge unlicensed free bands spectrum are available. The mm-waves introduce new opportunities, but, on the other hand present new challenges for the telecom operators due to the new propagation models; the [42] is an interesting overview on the main aspects of the mm-waves.

The first aspect to consider is the lack of an accurate channel model and a high signal path loss that reduces the coverage area and the cell dimension. In according to [43, 44] the path loss doesn't create huge obstacles to the propagation. The latter collect the results from measurements in urban (New York City) and sub-urban (university campus in Austin) environments, at 28, 38GHz and 73GHz, where it is shown that if a high directivity antennas array are used, it is possible to reach cell size of 200 m, which is a typical dimension for a high density urban environment.

The main problems are due to the shadowing and the outdoor-indoor communications; in fact, high frequencies communications are more subject to the obstacles due to the less penetration depth [45] and still humans and fornitures can cause loss of connectivity. Many solutions are proposed for the obstacles blockage, based on different approaches i.e. [46]; the latter consider fixed transmitter and receiver, which use beamforming protocol to compute the best NLOS path in case the LOS is lost in order to avoid human blockage.

The Beamforming and antenna directivity, as introduced in [47], will represent two key points in the mm-waves to focus the transmitted and/or received signal in particular direction in order to mitigate the high path loss. Increasing the number of the cells, by decreasing the dimensions, can be another solution to improve the mm-waves coverage and to avoid the blockage. Obviously, increasing the number of the cells can make the number of the handovers and the inter-cell interference higher.

In conclusion mm-waves can be play a key role for the future telecommunications, by exploiting new large spectrum. It can be for sure used for reducing infrastructure cost, by building high speed wireless backhauls, and small wlan for indoor environment. The use of mm-waves in outdoor urban and sub-urban environment is still under analysis, due to the path loss, user mobility and shadowing. User mobility prediction can be an useful solution to predict shadowing, obstacles, human blockage and handovers. Furthermore the location aware communications and mobility prediction could be useful to keep the transmitter and receiver beamforming aligned in order to exploit high directive antenna gain and small beam-width as stated in [42].

Moreover, mm-waves present many connections with the other 5G enabler technologies that can make this technology a cornerstone for new mobile communications generations:

- At first with Massive MIMO, since the small wavelenght allow to antenna array composed by a large number of elements with a small form factor.
- CoMP, since the high dense environment and small cells could allow coordinated transmission solutions for avoiding the blockage.
- As introduced above, the small cells can play a key role for mm-waves solutions, since a large number of cells with small dimension increase the coverage, mitigating the path loss and the blockage.
- D2D communications are strictly connected to mm-waves; as is shown in 4.5 a device can act as relay for antiblockage system, while obviously, thanks to the use of high directive antennas, small beam-width and proper beamforming, mm-waves can allow to increase spatial reuse and spectrum efficiency; it can contribute to decrease the interference between D2D and macro cell communications.

4.3 Heterogeneous Networks (HetNets)

Instead of increasing the bandwidth or the number of antennas, the other possibility to largely improve the user data rate is to deploy a high dense cells environment, where different nodes with different transmissions power and coverage size share the same area [6]. This type of networks, composed by high power nodes (HPN) and low power nodes (LPN), take the name of heterogeneous networks (HetNets). Heterogeneous networks create new opportunities and advantages like spectrum spatial reuse; but on the other hand they can lead to several issues as inter-cell interference and frequent handovers, which can lead to new challenges such as resource allocation problems, inter-cell interference cancellation, scheduling coordination and mobility management. In [48], the authors provide an interesting overview on different aspects of heterogeneous networks for 4G; It highlights how the received signal to interference noise ratio (SINR) is mainly affected by the interference caused by the other cells, while the noise terms is negligible. Moreover, user devices connect with the strongest base station, which is not necessary the one that can provide the best capacity or that can be less loaded. In fact, HPNs and LPNs present high differences in terms of transmitted power; a 4G RRU usually transmits 40 Watt, while a Wifi access points up to 4 Watts in according to the regulatory domain and frequency bands. For this reason, in order to achieve the maximum capacity and improve the load balancing a proper and intelligent access method is needed.

Other particular attentions are paid for mobility management; for this reason mobility prediction can act a key role, in fact, as stated in 4.6, it can be applied to the handover management in order to avoid communications interruptions or to maintain QoS along the user mobility. In [49] ch. 7, mobility prediction is applied trough a heterogeneous network composed by 3G and WiFi cells, to maximise the user's throughput. It proposes a user trajectory prediction, based on the past movement information, in order to estimate in ahead which sequence of handovers can be carried out to maximise the throughput. The network capacity information, in according to the user position, is available thanks to a database fingerprint.

4.4 Coordinated Multipoint (CoMP)

As stated above, a high dense cell environment needs some coordination mechanism to mitigate the inter-cell interference; coordinated multipoint transmissions (CoMP) is a promising candidate solution to achieve this purpose; It consists in coordination and cooperation between a cluster of cells in order to increase the performance in terms of interference reduction and spatial diversity. In [50] the authors show different coordinated multipoint transmissions schemas that are available, and which challenges and opportunities CoMP offers; in particular, cell synchronisation and the feedback overhead can represent challenging obstacles for the deployment of this solution.

In [51] is shown how join transmission coordinated multipoint (JT CoMP) can be a powerful tool in 5G; they focuses on several impairments like feedback overhead and channel estimation accuracy. The latter is mainly affected by dated channel state information, an issue that can be mitigated by CSI prediction as shown in the same work and in 4.1. A more accurate analysis of the channel aging effect on CoMP can be found in [52] for point-to-point MIMO link in LTE clustered cellular networks; the authors highlight how imperfect and dated CSIs cause inter-user interference and they investigate the enhancements that several predictors (i.e. recursive least squares) can obtain for channel estimation in terms of root mean square error (RMSE).

4.5 Device to Device Communications (D2D)

As shown in 4.2, D2D communications can play a key role in mm-waves communications, i.e. [53] shows how D2D communications are strictly connected to mm-waves; the paper introduces a new antiblockage system that exploits mobile user devices as relays in case the line-of-sight (LOS) path is blocked.

In [54] the authors propose an interesting overview on how D2D communications can allow to increase the performance in terms of spectral efficiency, overall capacity and transmission range. In fact, a node can act as relay for another device in order to exchange required data with or without the cooperation of the base station infrastructure in according to several communication schemas. Device to device transmission can be developed by sharing with the macrocell base station the same time-frequency resources or they can operate on different one, with inevitable waste of resources; on the other hand, in the first case, interference management and BS-devices cooperation is needed. To mitigate interference and to enhance the spatial reuse, beamforming and high directive antenna can be promising solutions, but a dynamic environment can decrease this gain. Another aspect to consider is the privacy that is mentioned in [54]; the latter introduces a closed access solution in order to mitigate this problem.

4.6 State Of The Art In Wireless Link Status Anticipation

In the previous Sections, some 5G promising enablers technologies have been introduced, highlighting on several aspects where the wireless link status anticipation techniques can play a key role; in general where the channel estimation is essential for wireless communication, the prediction can tremendously improve the performance. In fact, to the best of our knowledge, from the previous analysis, basically the following types of prediction are applied:

- Channel state prediction, which is applied to channel estimation for CoMP and Massive MIMO.
- User mobility prediction for handover and mobility management in HetNets and D2D communications.

In the past, wireless link anticipation and prediction have been widely proposed for many purposes, included but not limited to:

- Rate adaption techniques: more precisely, the channel state prediction can improve the performance of adaptive modulation and coding schema.
- Handover and mobility management; user mobility prediction can help the networks to provide in advance enough resources to incoming users, or to avoid ping-pong handovers.
- Routing algorithm and link reliability; the channel state and mobility prediction can help the nodes to estimate the best reliable path, to avoid retransmissions and to decrease the control packets overhead.

Starting from the latter, channel estimation and prediction are largely exploited in wireless ad-hoc networks in order to establish the reliability of a link. In particular, many works try to estimate or predict the link reliability in order to set a proper metric for computing the best routing path, or at least the most reliable. Many link quality estimators for wireless ad-hoc networks are proposed, like [55, 56]; the first uses an exponentially weighted moving average (EWMA) link quality estimator for wireless sensor networks that exploits cross-layer information in a compress way. In fact, only *4 bit* of information are needed for the estimation, 1 from the physical layer, 1 from the MAC and 2 from the network layer; these are obtained by the received and transmitted data packets and the periodic beacon frames. The second one proposes a short term link estimator (STLE) for wireless sensor networks trying to solve two main issues that the first approach has, like slow adaptability and low accuracy for intermediate link quality.

Tao Liu and Alberto E. Cerpa in [57] propose *4C*, an algorithm that applies the prediction to the wireless link for routing protocols. It is a machine learning data driven packet reception rate (PRR) prediction in according to physical features (SNR, RSSI, LQI) with off-line training. Three different types of machine learning predictors are tested: bayes classifier, logistic regression and neural networks. Starting from a window of previous packets for which SNR, RSSI, LQI and PRR are known, *4C* tries to predict the PRR of the next packet. The algorithm mainly suffers of slow adaptability, due to the off-line training, for this reason, the same authors propose *Talent* [58], which is an evolution of *4C*, trying to solve the off-line training issue, applying an on-line training method to logistic regression, that was the tool with the best accuracy for PRR prediction.

To mitigate the effects of the overtraining and the low-adaptability of the machine learning based predictors, in [59] a nonparametric short-term link quality prediction is proposed, which is based on time series analysis. In particular *Talent* and *4C* are packets-driven solution, that could have feedback problem with variable data rate links. In [59], the authors use an interpolation and filtering to obtain a solid time series using a non-parametric autoregressive model to predict the one way delay(OWD) and RSSI link.

Another work that proposes a reliability link prediction for ad-hoc routing algorithm is [60]. The latter tries to predict the nodes mobility, and the link reliability, by observing the link SNR. Each node in a distributed way, collects the links SNR observations; with the assumption that the SNR presents some periodicity along the time, it tries to predict the future SNR values performing a pattern matching, by computing the crosscorrelation between a query (a window of values for which the prediction is performed) and the training set (the collected SNR observations). In case the pattern matching doesn't provide enough accurate results, the algorithm provides a fallback solution that is a Kalman filter, a first order autoregressive link model AR(1).

The [61] proposes an average channel-gain predictor trying to exploit both the time and space correlation of the channel fading. It is based on the assumption that the channel fading presents two terms; one is due to slow fading, spatially correlated for static users, and the second caused by fast-fading only temporally correlated. The proposed solution tries to predict long-term average channel gain (from 200 ms to 3s ahead) exploiting temporal and location information combining an autoregressive (AR) model with functional linear regression (FLR). The simulation results show how the location information combined with the user channel feedbacks outperforms only temporal information-based predictor. In fact, as stated in [62] location-aware communications can play a key role in 5G, contributing in each layer, from physical layer for channel state prediction to application layer for context awareness. During the last decade, many works were done on location-aware wireless communications, starting from ad-hoc and mesh networks, where the mobility of the users can tremendously affect the link reliability. The work presented in [63] proposes a predictive mobility and location-aware routing algorithm (PMLAR), that uses node's velocity and position to establish and recovering the routing path between a source and a destination through intermediate nodes; the main goals of [63] is to exploit the location information and mobility prediction to improve the data packet delivery ratio and to limit the packet forwarding area. First of all, the authors consider a velocity-aided routing (VAR) algorithm, that determines the feasible intermediate nodes for packet forwarding; VAR use two type of motion prediction models based on relative velocity and motion direction between the forwarding node and the destination; besides VAR, other schemas are applied to PLMAR to improve the link maintenance and recovery in case of interruption for mobility reasons. In conclusion, from the results, it is possible to observe that using a location-aware routing algorithm with nodes mobility prediction is possible to improve the networks performance in terms of data packet delivery ratio, end-to-end delay, control packet overhead and route life time. In [60], mobility prediction is applied to several ad-hoc wireless networks routing algorithms to estimate the link stability. The proposed predictor tries to estimate the link expiring time starting from node mobility information (GPS location, direction and velocity) and the correlation between the node's location and the received signal strength through a simple channel propagation model. Even if the channel propagation model is totally based on a free space path loss, [60] shows how the predictor reduce the packet loss and retransmissions; using a distance vector routing algorithm it can also contribute to reduce the overhead due to hello packets for checking the topology changes.

As shown in [64], mobility prediction can be applied also to adaptive modulation and coding schema (AMC). In [64], the authors show how user's position and mobility information, combined with a SINR fingerprint database for channel state information, can improve the performance, demonstrating that position aware adaptive systems operate close to the channel capacity. Position aware adaptive modulation and coding schema are capable to perform a channel capacity mid/long term prediction and they are more robust to outdated CSI than no predictive AMC. Instead of using the user location information for rate adaption, as already introduced in 4.3, an interesting scope for mobility prediction is the handover management; as stated in [65, 66] hidden Markov chain are interesting tool to predict and model the user mobility in a cellular networks and to estimate in advance the handover direction in order to allocate enough resources for maintaining the communications along the mobility.

5 ESR-2 Research Proposal: Mobility-aware Predictive Beamforming Algorithm in Mm-waves

As introduced in 4.2, mm-waves communications are characterised by extreme propagation conditions; the path loss, which is proportional to the square of the frequency, and a very small penetration depth represent two big issues for such high frequency bands. The latter causes high sensitivity to the shadowing and obstacles as such even a human body can produce 20-30 dB of signal loss. In order to mitigate the effect of the path loss, an extremely high antenna directivity is desired; by considering large antenna array composed by many elements, and a proper beamforming techniques, it is possible to obtain this goal. High directivity and gain correspond to narrow beams, but due to the mobility nature of the users, a mechanism to quickly adapt the beams alignment between BS and UE is mandatory. In this case, tools for mobility prediction and tracking can provide serious advantages in terms of SINR and connection time.

5.1 Introduction And Related Works

As stated before, by considering large antenna array, we can provide high directive narrow beams by using proper beamforming techniques; in general we can distinguish three type of beamforming:

- Analog beamforming: it operates only on the phase shifters and/or on the variable gain amplifiers (VGAs) of each antenna element, in order to focus the array radiation pattern in a particular direction and/or change the beam-width. This is the simplest bemforming techniques, but in general it provides lower performance in terms of array gain than the digital one.
- Digital beamforming: it provides better performance by using digital precoders that work in baseband, but it needs analog-digital-converters (ADC) and viceversa (DAC) for each antenna elements; it is a more complex and higher time/energy consuming solution.
- Hybrid beamforming: it represents a combination between the two previous solutions. It tries to combine the low-complexity of steering the beam via phase shifters and the degree of freedom provided by the digital precoder [47]. As the digital beamforming, it considers a digital precoding applied to several RF chains, which number is less than the number of antennas; in fact, the latter are grouped in sub-groups and connected to the RF chains.

Possible approaches for directional beamforming are based on eigen-beamforming or the direction of arrival (DOA) estimation by acquiring the channel matrix; these approaches are complex, time consuming and it requires many training symbols, especially when the antenna array has many elements. A possible technique for analog beamforming [67] represents the antenna array as a FIR filter (i.e. Wiener filter) using the least-mean-square estimation (LMS) for adapting the filter weights. The latter are a function of the direction of arrival (DOA), which is consequently estimated.

Other recent works propose some efficient beam searching algorithms for mm-waves with a discrete number of beams described by a codebook; but most of them are used only for the first cell discovery in a stationary scenario where the transmitter (Tx) and the receiver (Rx) are static.

The work in [68] proposes a beamforming protocol based on an efficient searching algorithm for the BS and UE; it is based on the MAC frame of the standard 802.15.3b (high rate WPAN for 60 GHz) and the proposed algorithm performs an exhaustive best beams pair searching, along the codebook. In particular, in each time slots, before starting the data communications, the transmitter sends a number of training symbols, which depends on the number of possible beams, and the receiver can recover which beam provides the best SINR.

The authors in [69, 70] propose a beam pair searching algorithm based on context information (i.e. user position) in order to quick establish the best beams for the first cell discovery. Finally, the work [46] proposes a beam-switching from line-of-sight (LOS) path to a non-line-of-sight (NLOS) path when the LOS communication is lost for static Tx and Rx. In particular the BS and UE compute a backup NLOS path in case the LOS path is obstructed by human body.

5.2 Problem Description And Assumptions

The main idea is to develop a method that exploits the user location and the user mobility prediction in order to shape the beam-width and to focus the beam angle toward a particular direction that maximizes the SINR. We will consider the following assumptions:

- We suppose that the UE is equipped with a positioning system (i.e. GPS) and it can recover its position, speed and direction.
- The BS and the UE are equipped with a linear array of antenna of M_t and M_r elements respectively.
- As introduced in 5.1, some works consider a discrete set of beams, while for an analytical analysis we will consider a continuous case.
- We will start with a line-of-sight (LOS) scenario from the BS point of view. We will

extend the work in the future for the mobile user and in NLOS communications.
In order to guarantee a continue communication with enough gain between BS and UE in LOS communication, the BS has to focus the beam along the UE direction and viceversa. While the position of the BS is fixed and we can suppose that is well-known by the UE, the latter is continuously moving; we can suppose that the UE can predict and send to the BS its position over the time by using the following information: current position P_t, speed V_t and direction D_t. The details of the solution are described in the following Sections.

5.3 Proposed Solution

In this Section we will show how the UE can perform the mobility prediction and how the BS can adapt the transmitting beam (the UE beam adaption will be taken in account in the future). In general the proposed solution includes the following steps:

1. The UE predicts (as shown in the following) its speed and direction for the next time steps.
2. The UE sends the above mentioned information to the BS
3. The BS tracks the user by exploiting the information received.
4. The BS selects the best beam in terms of width and direction.

In the following Sections, each step is explained in details.

5.3.1 User Mobility Prediction

As we introduced in the previous Sections, the goal can be the following:

- Adapt the beam direction in according to the predicted position.
- Adapt the beam-width in according to the prediction error caused by the stochastic nature of the user's movement.

To consider the mentioned objectives, we will consider a predictive mobility model that takes in account both the time-dependency and the stochastic nature of the direction and speed of the user; moreover, in order to make the problem tractable from the analytical point of view we will consider the well-known Gauss-Markov mobility model (GMM) [71], which have been widely used in ad-hoc mobility model and can model a wide range of mobility pattern.

$$D_{t+1} = \alpha_t D_t + (1 - \alpha_t)\bar{D}_t + \sqrt{1 - \alpha_t^2} X_{D_t} \tag{1}$$

$$V_{t+1} = \beta_t V_t + (1 - \beta_t)\bar{V}_t + \sqrt{1 - \alpha_t^2} X_{V_t} \tag{2}$$

Where V_{t+1} and D_{t+1} are the predicted speed and direction respectively. $X_{V_t} \sim N(0, \sigma^2_{V_t})$ and $X_{D_t} \sim N(0, \sigma^2_{D_t})$ are zero-mean Gaussian-distributed random variables, while $0 \leq$

$\alpha, \beta \leq 1$ are two parameters that describe the randomness of the user's movement. In particular, the GMM is able to represent both the linear mobility model, with constant speed and direction when $\alpha, \beta = 1$, and the Browonian motion, when $\alpha, \beta = 0$.$\bar{V}_t$ and $\bar{D}_t$ are the asymptotic mean of the speed and direction. Once the BS receive the values P_t, speed V_{t+1} and direction D_{t+1}, it could predict the position as follows:

$$x_{t+1} = x_t + V_t \delta t \cos D_t \tag{3}$$

$$y_{t+1} = y_t + V_t \delta t \sin D_t \tag{4}$$

Where (x_{t+1}, y_{t+1}) represent the coordinates of the predicted position and δt is the prediction step. The parameters α, β can be estimated by the UE through a recursive least square (RLS) estimation, as stated in [63].

It easy to observe in the formulas 3 and 4, that $D_t \sim N(\beta_t D_{t-1} + (1-\beta_t)\hat{D}_t, (1-\beta_t)^2\sigma^2_{D_t})$ and $\delta t V_{t+1} \sim N(\delta t \alpha_t V_{t-1} + \delta t(1-\alpha_t)\hat{V}_t, \delta t^2(1-\alpha_t)^2\sigma^2_{V_t})$ are Gaussian distributed random variables. Moreover, they represent the polar coordinates of the predicted position (x_{t+1}, y_{t+1}) respect to the previous one (x_t, y_t). Then, the predicted position can be modelled as a bidimensional random variables, which in polar coordinates is distributed as a bidimensional Gaussian random variable as shown in Figure 4.

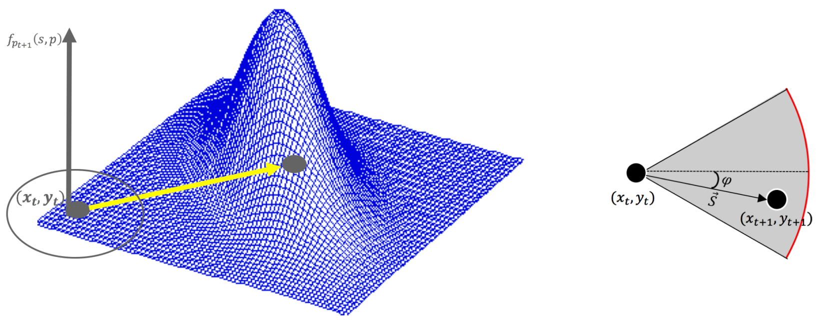


Figure 4: Polar coordinates and predicted position probability distribution.

5.3.2 Adaptive Beamforming

Let's define the beam $\mathbf{B}(\theta, \mu)$, where θ represents the direction toward which the beam is focused, while μ is the beam-width. We can consider the received power by the UE in the position (x, y), $P_r(x, y)$; the latter is a function of the the transmitted power, the path loss, the antenna gain at the receiver (G_r) and $G_t(\mathbf{B}(\theta, \mu))$ that is the antenna gain at the transmitter, which depends on the selected beam. The beam-width μ and the gain

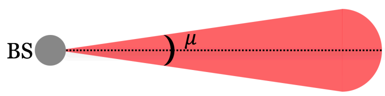


Figure 5: Beam coverage area.

$G_t(\mathbf{B}(\theta, \mu))$ identify a coverage area $A(\mathbf{B}(\theta, \mu))$, that represents all the position in the space such that:

$$A(\mathbf{B}(\theta, \mu)) = \{(x, y) \in \mathbb{R}^2 \mid P_r(x, y) \geq \gamma\} \tag{5}$$

Finally, we can formulate the problem as follows:

$$\mathbf{B}(\hat{\theta}, \hat{\mu}) = argmax_{\mathbf{B}(\theta,\mu)} \iint P_r(\varphi, s) f_D(\varphi) f_{\delta tV}(s)\, ds\, d\varphi \tag{6}$$

subject to:

$$P(outage) = 1 - \iint_{A(\mathbf{B}(\hat{\theta_n}, \hat{\mu}_m))} f_D(\varphi) f_{\delta tV}(s)\, ds\, d\varphi \tag{7}$$

The equation 6 means that we select the beam $\mathbf{B}(\theta, \mu)$ that maximizes the received power by the UE. The second equation 7 defines a constraint on the probability of outage $P(outage)$. The latter is defined as the probability that the UE is not covered by the beam $\mathbf{B}(\hat{\theta_n}, \hat{\mu}_m)$, and it is necessary to make the solution more robust to the user's mobility. In Figure 6, it is possible to observe the area that is covered by the beam $\mathbf{B}(\hat{\theta_n}, \hat{\mu}_m)$, that represents the area on which the double integral of the equation 7 is computed.

5.4 Expected Results And Conclusion

In conclusion we can analyse and create a mechanism to adapt the beam direction in according to the users' predicted position and the beam-width based on the prediction error. At the moment we are considering a specific mobility prediction model, but it can be generalised by considering any predicted position distribution. Since the current positioning system, in some condition, cannot provide enough accuracy, we can analyse

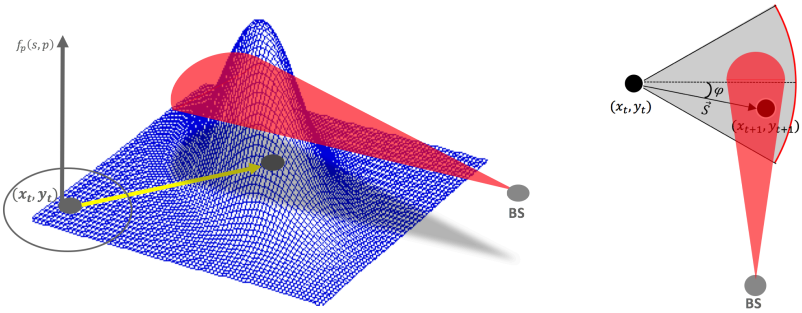


Figure 6: Covered area by the beam $\mathbf{B}(\theta, \hat{\mu})$ and the probability density function of the predicted position.

the application of the proposed solution combined with one of the previous approach i.e. DOA estimation, evaluating which improvements the knowledge of the position and the mobility prediction can lead. In general, we expect the following outcomes:

1. By exploiting mobility information for beamforming it is possible to keep the beam alignment without processing an exhaustive beams pair searching algorithm every time the devices want to communicate or the DOA tracking that needs many training symbols, which can lead to a gain in terms of overhead and power consumption.
2. The shaping of the beam-width in according to the random distribution of the users' position can lead to make the communication more robust in term of connection time.
3. Moreover, exploiting mobility information for beamforming prediction will allow fast handovers between mm-waves cells.
4. The use of mobility information and prediction for an adaptive beamforming approach, combined with a fingerprint database for the environmental knowledge can lead to create solution for the obstacles avoiding and LOS communication recovering.

6 Conclusions

In conclusion the 5th generation of mobile networks could present all the requirement to aim the goals described in the Section 2, but instead of presenting a prevailing solution, it should consider the cooperation and coordination of several promising technologies i.e. Massive MIMO, mm-waves, D2D and small cells. From the wireless link state anticipation point of view, the previous Sections have shown how it can play a key role in several scopes mainly related to channel estimation and mobility prediction.

It has been shown as the channel state prediction has been applied in several scopes i.e. rate adaption and routing algorithms in order to improve the performance in terms of throughput, end to end latency, retransmissions number and packet reception rate. In massive MIMO and CoMP, channel prediction are promising solutions to mitigate the inter-user interference due to inaccurate channel estimation caused by the outdated CSI. Mobility prediction has been widely used, both because the channel fading present a strong spatial-correlation, and for handover and mobility management; in particular, it can be a cornerstone for high dense cells environment and high mobility users. For these reason HetNets, mm-waves and D2D communications can obtain extraordinary benefits. From the side of methodologies, many solutions has been taken into account: time series analysis with autoregressive model (i.e. kalman filter), machine learning approaches (i.e. neural networks and bayes classifier), markov chains and fingerprint database. Each of them presents peculiar advantages and weak points; in fact, machine learning can occur in slow-adaptability and long training phases, while time series analysis can present a not accurate long-term prediction. For this reason more effort should be made in finding hybrid approaches that in a light way combine different solutions. Another aspect to be taken into account is the feedback overhead for channel estimation and prediction. in the last year big efforts were made in this direction in order to reduce the number of pilot signals keeping an acceptable channel estimation accuracy; under specific assumptions, like sparse multipath channels, compressive sensing can be an efficient solution.

References

[1] L. E. Frenzel, "Millimeter waves will expand the wireless future," http://electronicdesign.com/communications/millimeter-waves-will-expand-wireless-future, April 2013.

[2] Cisco, "Cisco visual networking index: Global mobile data traffic forecast update, 2014-2019," Tech. Rep., 2015.

[3] J. E. Rachid El Hattachi, "Ngmn 5g initiative white paper," Tech. Rep., 2015.

[4] J. Andrews, S. Buzzi, W. Choi, S. Hanly, A. Lozano, A. Soong, and J. Zhang, "What will 5g be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, June 2014.

[5] F. Boccardi, R. Heath, A. Lozano, T. Marzetta, and P. Popovski, "Five disruptive technology directions for 5g," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 74–80, February 2014.

[6] T. Marzetta, "Massive mimo: An introduction," *Bell Labs Technical Journal*, vol. 20, pp. 11–22, 2015.

[7] J. G. Andrews, S. Buzzi, W. Choi, S. V. Hanly, A. Lozano, A. C. K. Soong, and J. C. Zhang, "What will 5g be?" *IEEE Journal on Selected Areas in Communications*, vol. 32, no. 6, pp. 1065–1082, June 2014.

[8] F. Boccardi, R. W. Heath, A. Lozano, T. L. Marzetta, and P. Popovski, "Five disruptive technology directions for 5G," *IEEE Communications Magazine*, vol. 52, no. 2, pp. 74–80, February 2014.

[9] NGMN Alliance, "5G white paper," February 2015.

[10] Anritsu, "Whitepaper: Understanding 5G," February 2016.

[11] ITU-R, "Report M.2320-0: Future technology trends of terrestrial imt systems," https://www.itu.int/pub/R-REP-M.2320-2014, November 2014.

[12] ——, "Report M.2376-0: Technical feasibility of imt in bands above 6 ghz," http://www.itu.int/pub/R-REP-M.2376-2015, July 2015.

[13] ITU-R, "Final acts of the world radiocommunication conference (WRC-15)," http://www.itu.int/en/ITU-R/conferences/wrc/2015/Pages/default.aspx, 2015.

[14] F. Giannetti, M. Luise, and R. Reggiannini, "Mobile and personal communications in the 60 ghz band: A survey," *Wireless Personal Communications*, vol. 10, no. 2, pp. 207–243, 1999. [Online]. Available: http://dx.doi.org/10.1023/A:1018308429332

[15] T. S. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. N. Wong, J. K. Schulz, M. Samimi, and F. Gutierrez, "Millimeter wave mobile communications for 5g cellular: It will work!" *IEEE Access*, vol. 1, pp. 335–349, 2013.

[16] H. Shokri-Ghadikolaei, C. Fischione, G. Fodor, P. Popovski, and M. Zorzi, "Millimeter wave cellular networks: A mac layer perspective," *IEEE Transactions on Communications*, vol. 63, no. 10, pp. 3437–3458, Oct 2015.

[17] C. Jeong, J. Park, and H. Yu, "Random access in millimeter-wave beamforming cellular networks: issues and approaches," *IEEE Communications Magazine*, vol. 53, no. 1, pp. 180–185, January 2015.

[18] V. Desai, L. Krzymien, P. Sartori, W. Xiao, A. Soong, and A. Alkhateeb, "Initial beamforming for mmwave communications," in *2014 48th Asilomar Conference on Signals, Systems and Computers*, Nov 2014, pp. 1926–1930.

[19] C. N. Barati, S. A. Hosseini, S. Rangan, P. Liu, T. Korakis, S. S. Panwar, and T. S. Rappaport, "Directional cell discovery in millimeter wave cellular networks," *IEEE Transactions on Wireless Communications*, vol. 14, no. 12, pp. 6664–6678, Dec 2015.

[20] A. Capone, I. Filippini, and V. Sciancalepore, "Context information for fast cell discovery in mm-wave 5g networks," in *European Wireless 2015; 21th European Wireless Conference; Proceedings of*, May 2015, pp. 1–6.

[21] A. Capone, I. Filippini, V. Sciancalepore, and D. Tremolada, "Obstacle avoidance cell discovery using mm-waves directive antennas in 5g networks," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on*, Aug 2015, pp. 2349–2353.

[22] I. Filippini, "How a fast cell discovery turn out the ultra-capacity mm-waves networks," To appear, 2016.

[23] M. Giordani, M. Mezzavilla, and M. Zorzi, "Initial access in 5g mm-wave cellular networks," 2016, http://arxiv.org/abs/1602.07731.

[24] IEEE, "Standard 802.11ad-2012 (amendment 3 to ieee std 802.11-2012, as amended by ieee std 802.11ae-2012 and ieee std 802.11aa-2012): Wireless lan medium access

control (mac) and physical layer (phy) specifications: Enhancements for very high throughput in the 60 ghz band," https://standards.ieee.org/about/get/802/802.11.html, pp. 1–628, December 2012.

[25] ——, "Std 802.15.3c-2009 (amendment 2 to ieee std 802.15.3-2003): Millimeter-wave-based alternative physical layer extension," https://standards.ieee.org/about/get/802/802.15.html, pp. 1–200, Oct 2009.

[26] K. Sakaguchi, E. M. Mohamed, H. Kusano, M. Mizukami, S. Miyamoto, R. E. Rezagah, K. Takinami, K. Takahashi, N. Shirakata, H. Peng, T. Yamamoto, and S. Nanba, "Millimeter-wave wireless LAN and its extension toward 5G heterogeneous networks," *IEICE Transactions on Communications*, vol. E98-B, no. 10, pp. 1932–1948, October 2015.

[27] B. Li, Z. Zhou, W. Zou, X. Sun, and G. Du, "On the efficient beam-forming training for 60ghz wireless personal area networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 2, pp. 504–515, February 2013.

[28] A. Maltsev, V. Erceg, E. Perahia, C. Hansen, R. Maslennikov, A. Lomayev, A. Sevastyanov, A. Khoryaev, G. Morozov, M. Jacob *et al.*, "Ieee 802.11-09/0334r8: Channel models for 60 GHz WLAN systems," May 2010.

[29] S. Hur, T. Kim, D. J. Love, J. V. Krogmeier, T. A. Thomas, and A. Ghosh, "Millimeter wave beamforming for wireless backhaul and access in small cell networks," *IEEE Transactions on Communications*, vol. 61, no. 10, pp. 4391–4403, October 2013.

[30] X. An, C. S. Sum, R. V. Prasad, J. Wang, Z. Lan, J. Wang, R. Hekmat, H. Harada, and I. Niemegeers, "Beam switching support to resolve link-blockage problem in 60 ghz wpans," in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept 2009, pp. 390–394.

[31] J. Nam, A. Adhikary, J. Y. Ahn, and G. Caire, "Joint spatial division and multiplexing: Opportunistic beamforming, user grouping and simplified downlink scheduling," *IEEE Journal of Selected Topics in Signal Processing*, vol. 8, no. 5, pp. 876–890, Oct 2014.

[32] A. Adhikary, J. Nam, J. Y. Ahn, and G. Caire, "Joint spatial division and multiplexing–the large-scale array regime," *IEEE Transactions on Information Theory*, vol. 59, no. 10, pp. 6441–6463, Oct 2013.

[33] G. Athanasiou, P. C. Weeraddana, C. Fischione, and L. Tassiulas, "Optimizing client association in 60 GHz wireless access networks," *CoRR*, vol. abs/1301.2723, 2013. [Online]. Available: http://arxiv.org/abs/1301.2723

[34] H. Shokri-Ghadikolaei, L. Gkatzikis, and C. Fischione, "Beam-searching and transmission scheduling in millimeter wave communications," in *2015 IEEE International Conference on Communications (ICC)*, June 2015, pp. 1292–1297.

[35] S. Sun, G. R. MacCartney, M. K. Samimi, S. Nie, and T. S. Rappaport, "Millimeter wave multi-beam antenna combining for 5g cellular link improvement in new york city," in *2014 IEEE International Conference on Communications (ICC)*, June 2014, pp. 5468–5473.

[36] K. Sakaguchi, G. K. Tran, H. Shimodaira, S. Nanba, T. Sakurai, K. Takinami, I. Siaud, E. C. Strinati, A. Capone, I. Karls, R. Arefi, and T. Haustein, "Millimeter-wave evolution for 5g cellular networks," *IEICE Transactions on Communications*, vol. E98-B, no. 3, pp. 388–402, March 2015.

[37] H. S. Jo, Y. J. Sang, P. Xia, and J. G. Andrews, "Heterogeneous cellular networks with flexible cell association: A comprehensive downlink sinr analysis," *IEEE Transactions on Wireless Communications*, vol. 11, no. 10, pp. 3484–3495, October 2012.

[38] Q. Ye, B. Rong, Y. Chen, M. Al-Shalash, C. Caramanis, and J. G. Andrews, "User association for load balancing in heterogeneous cellular networks," *IEEE Transactions on Wireless Communications*, vol. 12, no. 6, pp. 2706–2716, June 2013.

[39] M. Mezzavilla, S. Dutta, M. Zhang, M. R. Akdeniz, and S. Rangan, "5g mmwave module for the ns-3 network simulator," in *Proceedings of the 18th ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems*, ser. MSWiM '15. New York, NY, USA: ACM, 2015, pp. 283–290. [Online]. Available: http://doi.acm.org/10.1145/2811587.2811619

[40] K. Truong and R. Heath, "Effects of channel aging in massive mimo systems," *Journal of Communications and Networks*, vol. 15, no. 4, pp. 338–351, Aug 2013.

[41] A. Papazafeiropoulos and T. Ratnarajah, "Linear precoding for downlink massive mimo with delayed csit and channel prediction," in *Wireless Communications and Networking Conference (WCNC), 2014 IEEE*, April 2014, pp. 809–914.

[42] Y. Niu, Y. Li, D. Jin, L. Su, and A. V. Vasilakos, “A survey of millimeter wave (mmwave) communications for 5g: Opportunities and challenges,” *CoRR*, vol. abs/1502.07228, 2015. [Online]. Available: http://arxiv.org/abs/1502.07228

[43] T. Rappaport, S. Sun, R. Mayzus, H. Zhao, Y. Azar, K. Wang, G. Wong, J. Schulz, M. Samimi, and F. Gutierrez, “Millimeter wave mobile communications for 5g cellular: It will work!” *IEEE Access*, vol. 1, pp. 335–349, 2013.

[44] S. Rangan, T. Rappaport, and E. Erkip, “Millimeter-wave cellular wireless networks: Potentials and challenges,” *Proceedings of the IEEE*, vol. 102, no. 3, pp. 366–385, March 2014.

[45] S. Singh, F. Ziliotto, U. Madhow, E. M. Belding, and M. Rodwell, “Blockage and directivity in 60 ghz wireless personal area networks: from cross-layer model to multihop mac design,” *IEEE J.Sel. A. Commun.*, vol. 27, no. 8, pp. 1400–1413, Oct. 2009. [Online]. Available: http://dx.doi.org/10.1109/JSAC.2009.091010

[46] X. An, C.-S. Sum, R. Prasad, J. Wang, Z. Lan, J. Wang, R. Hekmat, H. Harada, and I. Niemegeers, “Beam switching support to resolve link-blockage problem in 60 ghz wpans,” in *2009 IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications*, Sept 2009, pp. 390–394.

[47] W. Roh, J.-Y. Seol, J. Park, B. Lee, J. Lee, Y. Kim, J. Cho, K. Cheun, and F. Aryanfar, “Millimeter-wave beamforming as an enabling technology for 5g cellular communications: theoretical feasibility and prototype results,” *IEEE Communications Magazine*, vol. 52, no. 2, pp. 106–113, February 2014.

[48] A. Ghosh, N. Mangalvedhe, R. Ratasuk, B. Mondal, M. Cudak, E. Visotsky, T. Thomas, J. Andrews, P. Xia, H. Jo, H. Dhillon, and T. Novlan, “Heterogeneous cellular networks: From theory to practice,” *IEEE Communications Magazine*, vol. 50, no. 6, pp. 54–64, June 2012.

[49] J. Nielsen, “Location based network optimizations for mobile wireless networks: A study of the impact of mobility and inaccurate information,” Ph.D. dissertation, 2011.

[50] D. Lee, H. Seo, B. Clerckx, E. Hardouin, D. Mazzarese, S. Nagata, and K. Sayana, “Coordinated multipoint transmission and reception in lte-advanced: deployment scenarios and operational challenges,” *IEEE Communications Magazine*, vol. 50, no. 2, pp. 148–155, February 2012.

[51] V. Jungnickel, K. Manolakis, W. Zirwas, B. Panzner, V. Braun, M. Lossow, M. Sternad, R. Apelfrjd, and T. Svensson, “The role of small cells, coordinated multipoint, and massive mimo in 5g,” *IEEE Communications Magazine*, vol. 52, no. 5, pp. 44–51, May 2014.

[52] L. Thiele, M. Olbrich, M. Kurras, and B. Matthiesen, “Channel aging effects in comp transmission: gains from linear channel prediction,” in *Signals, Systems and Computers (ASILOMAR), 2011 Conference Record of the Forty Fifth Asilomar Conference on*, Nov 2011, pp. 1924–1928.

[53] J. Qiao, X. Shen, J. Mark, Q. Shen, Y. He, and L. Lei, “Enabling device-to-device communications in millimeter-wave 5g cellular networks,” *IEEE Communications Magazine*, vol. 53, no. 1, pp. 209–215, January 2015.

[54] M. Tehrani, M. Uysal, and H. Yanikomeroglu, “Device-to-device communication in 5g cellular networks: challenges, solutions, and future directions,” *IEEE Communications Magazine*, vol. 52, no. 5, pp. 86–92, May 2014.

[55] R. Fonseca, O. Gnawali, K. Jamieson, and P. Levis, “Four-bit wireless link estimation,” in *Proceedings of the Sixth ACM Workshop on Hot Topics in Networks (HotNets-VI)*, October 2007. [Online]. Available: http://www.cs.brown.edu/~rfonseca/pubs/hotnets07-4b.pdf

[56] A. Becher, “Towards short-term wireless link quality estimation.”

[57] T. Liu and A. Cerpa, “Foresee (4c): Wireless link prediction using link features,” in *10th International Conference on Information Processing in Sensor Networks (IPSN), 2011*, April 2011, pp. 294–305.

[58] ——, “Talent: temporal adaptive link estimator with no training,” in *The 10th ACM Conference on Embedded Network Sensor Systems, SenSys ’12, Toronto, ON, Canada, November 6-9, 2012*, April 2012, pp. 253–266.

[59] L. Weng, P. Zhang, Z. Feng, H. Cheng, H. Lian, and B. Fu, “Short-term link quality prediction using nonparametric time series analysis,” *Science China Information Sciences*, vol. 58, no. 8, pp. 1–15, 2015. [Online]. Available: http://dx.doi.org/10.1007/s11432-014-5270-x

[60] W. Su, S.-J. Lee, and M. Gerla, “Mobility prediction in wireless networks,” in *MILCOM 2000. 21st Century Military Communications Conference Proceedings*, vol. 1, 2000, pp. 491–495 vol.1.

[61] Q. Liao, S. Valentin, and S. Stanczak, "Channel gain prediction in wireless networks based on spatial-temporal correlation," in *IEEE 16th International Workshop on Signal Processing Advances in Wireless Communications (SPAWC), 2015*, June 2015, pp. 400–404.

[62] R. Di Taranto, S. Muppirisetty, R. Raulefs, D. Slock, T. Svensson, and H. Wymeersch, "Location-aware communications for 5g networks: How location information can improve scalability, latency, and robustness of 5g," *IEEE Signal Processing Magazine*, vol. 31, no. 6, pp. 102–112, Nov 2014.

[63] K.-T. Feng, C.-H. Hsu, and T.-E. Lu, "Velocity-assisted predictive mobility and location-aware routing protocols for mobile ad hoc networks," *IEEE Transactions on Vehicular Technology*, vol. 57, no. 1, pp. 448–464, Jan 2008.

[64] S. Sand, R. Tanbourgi, C. Mensing, and R. Raulefs, "Position aware adaptive communication systems," in *Conference Record of the Forty-Third Asilomar Conference on Signals, Systems and Computers, 2009*, Nov 2009, pp. 73–77.

[65] P. Fazio and S. Marano, "Mobility prediction and resource reservation in cellular networks with distributed markov chains," in *Wireless Communications and Mobile Computing Conference (IWCMC), 2012 8th International*, Aug 2012, pp. 878–882.

[66] H. Si, Y. Wang, J. Yuan, and X. Shan, "Mobility prediction in cellular network using hidden markov model," in *Consumer Communications and Networking Conference (CCNC), 2010 7th IEEE*, Jan 2010, pp. 1–5.

[67] S. Haykin, *Adaptive Filter Theory (5th Ed.)*. Pearson, 2013.

[68] J. Wang, "Beam codebook based beamforming protocol for multi-gbps millimeter-wave wpan systems," *IEEE Journal on Selected Areas in Communications*, vol. 27, no. 8, pp. 1390–1399, October 2009.

[69] A. Capone, I. Filippini, and V. Sciancalepore, "Context information for fast cell discovery in mm-wave 5g networks," in *European Wireless 2015; 21th European Wireless Conference; Proceedings of*, May 2015, pp. 1–6.

[70] A. Capone, I. Filippini, V. Sciancalepore, and D. Tremolada, "Obstacle avoidance cell discovery using mm-waves directive antennas in 5g networks," in *Personal, Indoor, and Mobile Radio Communications (PIMRC), 2015 IEEE 26th Annual International Symposium on*, Aug 2015, pp. 2349–2353.

[71] R. R. Roy, *Handbook of Mobile Ad Hoc Networks for Mobility Models.* Boston, MA: Springer US, 2011, ch. Random Gauss–Markov Mobility, pp. 311–344. [Online]. Available: http://dx.doi.org/10.1007/978-1-4419-6050-4_10