Enabling 5G Backhaul and Access with millimeter-waves

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Abstract—**This paper presents the approach of extending cellular networks with millimeter-wave backhaul and access links. Introducing a logical split between control and user plane will permit full coverage while seamlessly achieving very high data rates in the vicinity of mm-wave small cells.**

Index Terms—**5G, Millimeter-wave, 60 GHz, Centralized-RAN, HetNet, Backhaul, Fronthaul, Millimeter-wave radio channel, Overlay, Small Cell, C/U plane split**

I. INTRODUCTION

WITHIN the evolution of the fifth generation mobile networks (5G) several radio technologies are targeted for improvement and millimeter-wave communication is seen as one of the key technologies [1]. In this paper we present the joint European-Japanese research project MiWEBA [2] that is part of the European initiative for the development of 5G, e.g. METIS and 5GNOW. Especially the license free 60 GHz band is under focus in MiWEBA as it delivers up to 9 GHz of continuous spectrum available almost everywhere in the world. Furthermore the high propagation loss in free space due to oxygen absorption helps in reducing interference between neighboring connections. Additionally, monolithic microwave integrated circuits are expected to be available on a large scale basis soon with the advent of the 60 GHz extension of Wi-Fi in IEEE 802.11ad.

MiWEBA proposes research and proof of concept of a millimeter-wave overlay in densely populated heterogeneous networks (HetNet) where millimeter-wave small cell base stations are integrated into conventional cellular networks. The project aims to extend the network capacity massively at reasonable cost and without loss of convenience to users. The envisioned HetNet consists of the mm-wave backhaul/fronthaul integrating small cells in the cellular network. The small cell can have an access link compromising both conventional cellular access such as LTE and a novel millimeter-wave link utilizing a centralized radio access network (C-RAN). The architecture and technical solution proposed by MiWEBA introduces for the first time a holistic approach for enabling data and control plane splitting to overcome the restricted coverage problem of mm-wave links. Multi-Technology HetNet and network densification composed of independent technologies for small and macro-cells respectively will be optimized along green criteria owing to novel link adaptation metrics implemented in the centralized architecture.

The paper is organized as follows: First the detailed concepts and the defined scenarios are presented. In section III a summary of the conditions of mm-wave propagation is given. Section IV details the technical challenges and the approaches to solving them.

II. CONCEPTS AND SCENARIOS

A. System overview

The different elements and connections that we address are shown in figure 1. Traditional macro base stations are placed on rooftops and give full network coverage in the traditional frequency bands. Smaller base stations (small cells) are placed within their footprint to give increased data rates or coverage where needed. In this concept there is no further differentiation between different sizes of the small cells.

The base stations are connected to the core network through backhaul links that transport the payload data. These links can be either wired (fibre) or wireless and can also be routed through other base stations in a multi-hop scheme. For the wireless links millimeter-wave technology might be needed to support the high data rates of future systems. Some of the functionality of the base stations can be moved to a more central position in the network. This enables advanced optimizations of the network such as interference control, topology reconfiguration, power saving, etc. This is referred to as centralized radio access network (C-RAN) and is explained later in this section. The requirements for the connection of these C-RAN base stations to the core network are different and to reflect the different logical split they are called fronthaul.

The user terminals (UE) are directly connected to one or multiple base stations via the access link. This link can be on 3G/4G technology or on millimeter-wave as is explained in the next section.

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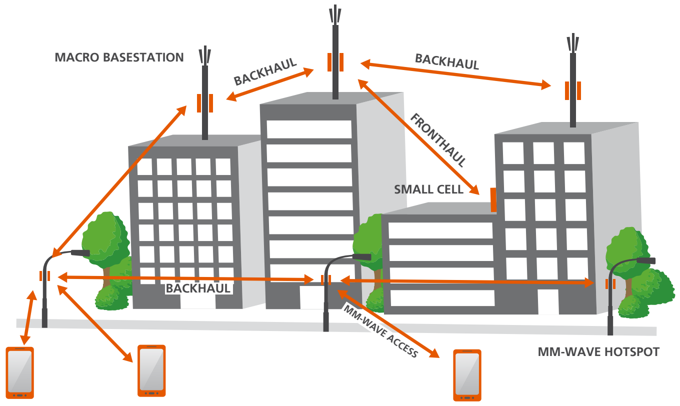

Figure 1. MiWEBA system physical topology

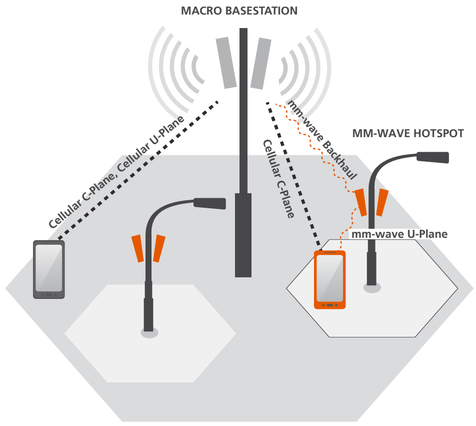

Figure 2. Control/user plane physical links

B. *Control/user plane splitting*

The basic idea of control/user plane (C/U plane) splitting is to enable mobile terminals to receive system information, issue access requests to a base station and getting assigned radio resources for high-rate data transmission at a different base station, see fig. 2. Signaling and data services can be provided by specialized base stations or implemented as separated and independent services into the same physical equipment. In the case of HetNets a possible approach is to have the macro base station providing the signaling service for the whole area and the small cells specialized in data resources for high-rate transmission with a light control overhead and appropriate air interface.

The main advantage of separation is the removal of the constraint for which radio resources for data transmission are assigned by the same base station used for accessing the service, which is autonomously selected by user terminals. In terms of energy efficiency, this is a big advantage since it allows to activate small cells only when needed, with "on demand" data coverage, while providing everywhere and anytime service accessibility through the full coverage signaling function. More in general, the additional flexibility in resource assignment allows to shift the control of access selection from mobile terminals to a logical Network Access Entity (NAE) and to optimize the resource assignment with a larger view on several parameters, at both user and network side. The NAE can be implemented as a network virtual function that can be migrated throughout the network. On a longer-term perspective, the separation enables new approaches for sharing infrastructures owned by different operators that can be managed by the control plane according to the specific commercial policies they agreed upon, as well as on the network status and the user characteristics and preferences.

C. *Centralized-RAN*

Recently, the "C-RAN" approach has been proposed by different vendors and operators [3], [4]. The main idea of C-RAN is to shift the baseband processing from the cell to a central location where coordinated processing and resource management is performed while the remaining functions are executed at the antenna location, see fig. 3. This paradigm enables to increase the spectral resource usage as well as the overall energy and computational costs by exploiting multi-user, traffic, and computational diversity. Nevertheless, these gains come at the price of high-capacity links, which usually implies the deployment of optical fiber links. Small cells will likely be deployed at about 3-6m above street level (on street furniture and building facades) to improve the system coverage [5]. However, at these locations, installing fixed broadband access (such as fiber links) for backhaul or Line-Of-Sight (LOS) based microwave links may be too expensive. Hence, in a given area, different small cells will be characterized by heterogeneous backhaul connections, with regard to physical design (wired/wireless), capacity, latency, and topology.

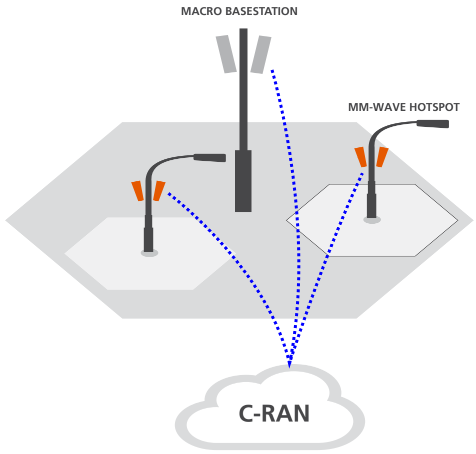

Figure 3. C-RAN logical architecture

To cope with this challenge, depending on the momentary backhaul characteristics (in terms of capacity and latency), service requirements, and network conditions (i.e., load, interference) only a part of the RAN functionalities can be actually be implemented at the central coordinator. In particular, we can envisage three principal functional split options: at the PHY layer, at the MAC layer, and at the Radio Resource Control (RRC).

Functional split on PHY layer enables to fully exploit spatial and computational diversity and by implementing advanced signal processing mechanisms, inter-cell interference can be mitigated or even exploited to enhance the overall spectral efficiency. Functional split can also be implemented at the MAC layer, which enables coordinated radio resource management (RRM) and centralized scheduler. This solution increases the network throughput by mitigating inter-cell interference and exploiting multiplexing gains. A full centralized RRM approach still requires high-capacity backhaul links, since sharing channel state information (CSI) is necessary to correctly implement i.e., multi-cell scheduler. Furthermore, performance relies also on the backhaul latency, since outdated CSI strongly affects the achievable gains.

Third, coordinated RRC enables to optimize the mobility management process, to implement global load balancing mechanisms, and to realize mid-term cell activation/deactivation schemes for energy saving purposes. Although the PHY/MAC adapting mechanisms are implemented in short-time scale to reply to fast changes due to i.e., the channel conditions, coordinated RRC operates in a second basis, which results on less stringent constraints in terms of latency and bandwidth.

D. Multi-Technology HetNet deployment

The Multi-Technology HetNet (MT-HetNets) concept resorts from two fundamental technical challenges: offering high QoS seamless connectivity everywhere with interference limitations and efficient radio resource management and designing Energy Efficient networks by considering MT HetNet architectures able to dynamically select the most green oriented technology to be deployed in a local zone. For that purpose, three research topics are addressed in the MiWEBA project: Multi-Technology (MT) link adaptation techniques are investigated using novel channel quality indicator (CQI) metrics able to limit transmit power whilst ensuring QoS and desired radio coverage of mobile access and backhaul scenarios. The second research topic points at the implementation of such metrics upon cross layer mechanisms that overcome latency, ensure backward compatibility with PHY and MAC in MT base stations, signaling protocols of implemented systems in MT base stations and terminals. Depending on radio link profiles, several solutions are envisioned as the Fast Session Transfer to switch between Wi-Fi label standards (typically IEEE802.11ac and IEE802.11ad), the integration of a new L2.5 layer for Multiple Interface Management as developed in the ICT-FP7 OMEGA project ([6], Deliverable 5.5) and evolved green oriented access network discovery and selection function (ANDSF) discovery protocols currently considered in the 3GPP/Wi-Fi convergence work items. The third research topic deals with the network densification and inter-cell distance (ICD) optimization in MT-HetNets in extending radio engineering functionalities that integrate link adaptation metrics. The CQI metrics previously designed for energy efficient (EE) air interface selection will be mapped into radio planification tools in order to optimize MT-HetNet infrastructure deployments encountering Line-Of-Sight / Non-Line-Of-Sight (LOS/NLOS) critera, base station position and environment topologies under green radio criteria. This new functionality will support active and sleep modes of transmitters, thus ensuring radio coverage with a transmit power minimization.

E. Scenarios

A set of scenarios is defined that serves as a common baseline for all research aspects. The scenarios can be differentiated in indoor and outdoor with the focus being on outdoor environments. The first outdoor scenario are large public areas that are covered with traditional cellular technology and a large number of mm-wave small cells that also provide full coverage of the space. This also includes a mixture of open spaces and adjacent rooms. Typical situations described by this could be e.g. shopping malls. The second outdoor scenario are ultra high-rate hot-spots. In this case, the area is also fully covered by traditional cellular technology and supplemented by mm-wave small cells only on non overlapping spots. The third outdoor scenario are high-rate areas. This is an extension of the second case with a denser distribution of small-cells that can also overlap.

III. MILLIMETER-WAVE PROPAGATION

Radio wave propagation is affected by diverse physical mechanisms. To what extend each mechanism contributes to the overall signal attenuation and distortion highly depends on the scenario and radio frequency. Millimeter-wave mobile communication will take place at frequencies far above the classical bands – a fact which necessitates a closer look at the principles of propagation.

The free-space path loss scales with the square of link distance and carrier frequency. Hence a signal at 60 GHz undergoes an almost 36 dB higher attenuation on the same way to the receiver compared to a signal at 1 GHz. Atmospheric effects mainly involve oxygen absorption (peak at 60 GHz) and water vapor absorption (peak at 183 GHz) as well as fog and precipitation. They scale exponentially with the link distance. They become relevant for millimeter-wave links exceeding 100 m and crucial for longer distances like 1 km. Furthermore, penetration losses drastically increase with frequency. Whereas up to several GHz, it is possible to achieve good coverage inside buildings from a base station outside, solid walls are practically impenetrable for millimeter-waves.

The frequency dependence of reflections, which are the main reason for multipath propagation, is mainly related to surface roughness. The roughness of typical exterior building materials only moderately affects propagation in the lower GHz range. However, in the millimeter-wave band it may decide between receiving a beneficial near-specular reflection path and none at all. Diffraction effects decrease rapidly as frequency increases. In the millimeter-wave band they are typically only relevant if the size of the obstacle is quite small like in the order of tens of cm. As a result even human body shadowing can cause severe losses exceeding 30 dB [7].

Recently, characterization of millimeter-wave outdoor channels has been emerging as important research topic [8], [9]. The most important finding of previous studies is that multipath propagation is an issue for outdoor scenarios as it is for indoor propagation. Buildings, the ground, cars and also small objects like trash cans or signs act as reflectors. Measurements consistently confirm that the path loss exponent is close to two for LOS propagation.

Though mainly LOS scenarios are focused for millimeter-wave mobile communication, the presence of specular reflections with significant power in relation with highly directional steerable antennas also motivates the investigation of millimeter-wave usage under obstructed LOS (OLOS) or NLOS conditions. NLOS path loss behavior was found to be similar to that at lower frequencies, but keeping in mind that the results are related to much smaller cell sizes [8], [9].

Time dispersion under LOS conditions is typically small (RMS delay spreads below 20 ns) but highly dependent on the environment as well as on the antennas [10], [11]. Very low delay spreads (only up to 1.4 ns) were observed for the peer-to-peer and cellular scenario with 25 dBi antennas in [8]. Under NLOS conditions the spread increases. Though average values are still moderate (7–24 ns), maximum values exceeding 100 ns are reported in [8]. The results indicate that the RMS delay spread of millimeter-wave outdoor channels are of the same order as for indoor and in-cabin propagation, where values between 10–100 ns have been found [10], [12]. It stays one order below the spread occurring at classical cellular frequencies.

IV. CHALLENGES AND ENVISIONED SOLUTIONS

A. *Channel characterization & modeling*

The requirements for an outdoor millimeter-wave channel model are expected to be very similar to the indoor case which is well-described in IEEE 802.11ad documents [13]. The channel model should provide accurate space-time characteristics of the propagation channel (basic requirement) for main usage models of interest, support beamforming with steerable directional antennas on both TX and RX sides with no limitation on the antenna technology, take into account polarization characteristics of antennas and signals and support non-stationary characteristics of the propagation channel. This can be achieved by using a dynamic space-time clustered channel model approach.

The investigated channel model adopts the clustering approach with each cluster consisting of several rays closely spaced in time and angular domains. In a real environment, time and angular parameters of different clusters and rays are time varying functions due to a non-stationary setup. However, the rate of these variations is expected to be relatively slow. Within MiWEBA measurements as well as ray tracing simulations based on the defined scenarios will be done and combined into the channel model.

B. *PHY and MAC layer*

The design space for the physical layer and the wave forms of a new system in the millimetre-wave region is very large. Unlike in lower frequencies the bandwidth available is not dictated by available spectrum. As part of MiWEBA this design space will be evaluated under technical constraints such as phase noise, channel length, fading characteristics etc. Existing approaches such as the recently standardized IEEE 802.11ad will serve as a starting point. Time reversal processing, foreseen as a green PHY/MAC technique [14], will be investigated for millimeter-wave hotspot transmissions benefiting from multipath diversity and small scale multi-antennas. The MiWEBA project will focus on Link level performance as well as efficient channel sounding techniques for access and backhaul scenarios.

For the MAC layer the focus will lie on seamless integration with the legacy cellular systems in the context of the splitting between control and user plane.

C. *Antenna technology and Beamforming*

Insertion losses at millimeter-wave frequencies are much higher than in the sub 6 GHz band. To enable connections with sufficient SNR, antennas with high directionality are a necessity. While backhaul and fronthaul connections are generally static, the channel and direction of access links is constantly changing due to movement of the UE and changing environments. High gain beamforming antennas are therefore needed at the small cell base station as well as the user terminal. The most straightforward solution that qualifies for all requirements is the millimeter-wave phased array antenna, that is successfully used for prototypes [15]. However, creation of such large-aperture antenna arrays may pose a problem due to production cost, heat dissipation and feed circuitry complexity.

A solution that helps to overcome mentioned difficulties is the concept of large aperture modular antenna arrays (MAA) recently proposed. The large antenna array is constructed from a number of smaller array modules, each with its own on-chip RF part and common baseband. Another option that may be used in low-cost devices is chip-lens antennas [16] that have great directionality but limited beamsteering ability and will not be able to create several beams simultaneously.

Robust beamforming algorithms that enable fast tracking the beams are also necessary to maximize the link performance. A thorough analysis of the available link budgets under the channel conditions in the defined scenarios will serve as a basis for this research.

D. *Small cell discovery*

The discovery of millimeter-wave small cells is tightly connected to the above mentioned problem of high gain directional access links and the concept of split planes. The end user terminal must be enabled to detect whether it is under coverage of a small cell quickly in order to profit of the higher data rated of that cell. The design space for such detection mechanisms is dictated by the beamforming antennas and algorithms but also includes side channel information such as the geographical position of the device and small cells in its vicinity.

E. *Control/User plane splitting*

The most crucial aspects brought in by the C/U splitting is that of providing the information necessary for performing the radio resource assignment and management in an optimized way to the logical network entity. This constitutes the context characterizing service requests and its management represents one of the main differences between the new architecture and the traditional ones. The control plane separation facilitates the coexistence of different radio access technologies within the same network, that are piloted by a common control infrastructure to serve "on-demand" user requests. The heterogeneity can be extended to legacy technologies, like 4G, as well.

We envision a common control channel architecture where the signaling function can be jointly provided by legacy 4G BSs and new generation ones. Service requests issued through the signaling function can be served according to a resource allocation algorithm that can assign the service to the same 4G BS or alternative BSs according to device capabilities. The architecture can be centralized, where a macro BS controls the data service of small base stations under its coverage umbrella, or distributed, where control entities of peer BSs cooperate to provide a logical network entity to the users. A further architectural choice is between the implementation of the control entity as a different and independent type of BS or as a separated function within a device that hosts both user and control plane interfaces. The selection of the best paradigm will be driven by the deployment scenario.

The investigations related to this challenge will design the best solution according to several key performance indicators, like data channel acquisition delay, data session retainability during mobility, network load increase due to a larger amount of exchanged information, and network capacity and energy consumption trade-offs.

F. Centralized-RAN

The joint implementation of the C/U splitting with the dual connectivity enables reliable radio resource control at a central location. This allows for coordinating the mobility management, the network discovery, the small cell activation/deactivation, the load balancing and inter-cell interference coordination. Finally, coverage areas become dynamic, and virtual cells can be created through the cooperation of multiple neighboring millimeter-wave small cells. Coordinated Multi Point clusters and distributed Massive MIMO can further enhance the performance perceived at the end user.

The C/U splitting will reduce signaling overhead to the small cells. Nevertheless, while being active, small cells will have to transmit to their serving UEs other signals to i.e., indicate the resource allocation, to acquire channel state information, and local synchronization. This approach can be easily integrated in our architecture; however, the transmission of these signals has to be coordinated with the management of the antenna steering. Neighboring small cell cooperation can be required to manage the UE tracking and prevent outage events, i.e., by proactive handover.

Another approach consists in optimizing the beam angle of a dynamic set of neighboring small cells to perform joint transmission towards the nearby user and avoid connection loss due to radio environments. In this way, the average spectral efficiency can be notably improved and coverage holes avoided [17].

V. CONCLUSION

A concept that uses millimeter-wave links for backhaul, fronthaul and access with a novel control/user plane split is presented as a candidate for 5G system evolution. This concept will enable high data rate densities and other innovative approaches such as centralized RAN (C-RAN) architectures. Technical challenges associated with this concept, such as the need for coordinated centralized resource management and adaptive beamforming and beam tracking were outlined.

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REFERENCES

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

[2] MiWEBA Website. [Online]. Available: http://www.miweba.eu/

[3] China Mobile Research Institute, "C-RAN - Road Towards Green Radio Access Network," in *Wireless World Research Forum, Meeting 27 (WWRF 27), Düsseldorf*, 2011, pp. pp. 73–80.

[4] NGMN. (2013, Jan.) Suggestions on Potential Solutions to C-RAN by NGMN Alliance.

[5] Next Generation Mobile Networks (NGMN) Alliance, "Small cell backhaul requirements," *Backhaul Evolution*, June 2012.

[6] Omega Website. [Online]. Available: http://www.ict-omega.eu/

[7] M. Peter, M. Wisotzki, M. Raceala-Motoc, W. Keusgen, R. Felbecker, M. Jacob, S. Priebe, and T. Kurner, "Analyzing human body shadowing at 60 GHz: Systematic wideband MIMO measurements and modeling approaches," in *Antennas and Propagation (EUCAP), 2012 6th European Conference on*. IEEE, 2012, pp. 468–472.

[8] T. S. Rappaport, E. Ben-Dor, J. N. Murdock, and Y. Qiao, "38 GHz and 60 GHz angle-dependent propagation for cellular & peer-to-peer wireless communications," in *Communications (ICC), 2012 IEEE International Conference on*. IEEE, 2012, pp. 4568–4573.

[9] S. Rajagopal, S. Abu-Surra, and M. Malmirchegini, "Channel Feasibility for Outdoor Non-Line-of-Sight mmWave Mobile Communication," in *Vehicular Technology Conference (VTC Fall), 2012 IEEE*. IEEE, 2012, pp. 1–6.

[10] P. Smulders and L. Correia, "Characterisation of propagation in 60 GHz radio channels," *Electronics & communication engineering journal*, vol. 9, no. 2, pp. 73–80, 1997.

[11] L. M. Correia and J. R. Reis, "Wideband characterisation of the propagation channel for outdoors at 60 GHz," in *Personal, Indoor and Mobile Radio Communications, 1996. PIMRC'96., Seventh IEEE International Symposium on*, vol. 2. IEEE, 1996, pp. 752–755.

[12] M. Peter, W. Keusgen, A. Kortke, and M. Schirrmacher, "Measurement and analysis of the 60 GHz in-vehicular broadband radio channel," in *Vehicular Technology Conference, 2007. VTC-2007 Fall. 2007 IEEE 66th*. IEEE, 2007, pp. 834–838.

[13] IEEE doc. 802.11-09/0334r8, "Channel Models for 60 GHz WLAN Systems," Tech. Rep., 2010.

[14] M.-A. Bouzigues, I. Siaud, A.-M. Ulmer-Moll, and M. Hélard, "On the use of time-reversal for packet switching in green communications," in *Wireless and Mobile Computing, Networking and Communications (WiMob), 2013 IEEE 9th International Conference on*. IEEE, 2013, pp. 22–27.

[15] 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," *Communications Magazine, IEEE*, vol. 52, no. 2, pp. 106–113, February 2014.

[16] A. Artemenko, A. Maltsev, A. Mozharovskiy, A. Sevastyanov, V. Ssorin, and R. Maslennikov, "Millimeter-wave electronically steerable integrated lens antennas for WLAN/WPAN applications," *Antennas and Propagation, IEEE Transactions on*, vol. 61, no. 4, pp. 1665–1671, 2013.

[17] K. Sakaguchi, S. Sampei, H. Shimodaira, R. Rezagah, G. K. Tran, and K. Araki, "Cloud cooperated heterogeneous cellular networks," in *Intelligent Signal Processing and Communications Systems (ISPACS), 2013 International Symposium on*. IEEE, 2013, pp. 787–791.