5G-MiEdge

Millimeter-wave Edge Cloud as an Enabler for 5G Ecosystem

EU Contract No. EUJ-01-2016-723171

Abstract

This deliverable reports second year results of WP2, mmWave ultra broadband access for highest capacity 5G scenarios.

Keywords

millimeter-wave, millimeter-wave access, millimeter-wave backhaul, edge cloud, mobile edge computing, MU-MIMO, hybrid beamforming

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<th>Description</th>
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<tbody>
<tr>
<td>ABF</td>
<td>Analogue beamforming</td>
</tr>
<tr>
<td>ADC</td>
<td>Analogue-to-digital convertor</td>
</tr>
<tr>
<td>AoA</td>
<td>Angle of Arrival</td>
</tr>
<tr>
<td>AoD</td>
<td>Angles of departure</td>
</tr>
<tr>
<td>AP</td>
<td>Access point</td>
</tr>
<tr>
<td>Beam RR</td>
<td>Beam round robin</td>
</tr>
<tr>
<td>BO</td>
<td>Back-off</td>
</tr>
<tr>
<td>CDF</td>
<td>Cumulative distribution function</td>
</tr>
<tr>
<td>CDN</td>
<td>Content delivery network</td>
</tr>
<tr>
<td>CPE</td>
<td>Common-phase-error</td>
</tr>
<tr>
<td>CSI</td>
<td>Channel state information</td>
</tr>
<tr>
<td>CSMA/CA</td>
<td>Carrier sense multiple access with collision avoidance</td>
</tr>
<tr>
<td>DAC</td>
<td>Digital-to-analogue convertor</td>
</tr>
<tr>
<td>DBF</td>
<td>Digital beamforming</td>
</tr>
<tr>
<td>DL</td>
<td>Down-link</td>
</tr>
<tr>
<td>DPD</td>
<td>Digital pre-distortion</td>
</tr>
<tr>
<td>EVM</td>
<td>Error vector magnitudes</td>
</tr>
<tr>
<td>GI</td>
<td>Guard interval</td>
</tr>
<tr>
<td>HBF</td>
<td>Hybrid beamforming</td>
</tr>
<tr>
<td>ICI</td>
<td>Inter-carrier interference</td>
</tr>
<tr>
<td>IFE</td>
<td>In-flight entertainment</td>
</tr>
<tr>
<td>IMD</td>
<td>Inter-modulation distortion</td>
</tr>
<tr>
<td>IUI</td>
<td>Inter-user interference</td>
</tr>
<tr>
<td>LDPC</td>
<td>low-density parity-check</td>
</tr>
<tr>
<td>LOS</td>
<td>Line of sight</td>
</tr>
<tr>
<td>MEC</td>
<td>Mobile edge computing/multi access edge computing</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multiple-input and multiple-output</td>
</tr>
<tr>
<td>mmWave</td>
<td>Millimeter-wave</td>
</tr>
<tr>
<td>MSE</td>
<td>Mean squared error</td>
</tr>
<tr>
<td>MU-MIMO</td>
<td>Multi-user multiple-input and multiple-output</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>--------------------------------------------</td>
</tr>
<tr>
<td>NLOS</td>
<td>Non-line of sight</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal frequency division multiplexing</td>
</tr>
<tr>
<td>PA</td>
<td>Power amplifiers</td>
</tr>
<tr>
<td>PAPR</td>
<td>Peak-to-average power ratio</td>
</tr>
<tr>
<td>PER</td>
<td>Packet error rate</td>
</tr>
<tr>
<td>PNC</td>
<td>Phase noise compensation</td>
</tr>
<tr>
<td>PN-robust</td>
<td>Phase-noise-robust</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of service</td>
</tr>
<tr>
<td>RF</td>
<td>Radio frequency</td>
</tr>
<tr>
<td>RR</td>
<td>Round robin</td>
</tr>
<tr>
<td>Rx</td>
<td>Receiver</td>
</tr>
<tr>
<td>SIC</td>
<td>Successive interference cancellation</td>
</tr>
<tr>
<td>SISO</td>
<td>Single-input and single-output</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal-to-noise power ratio</td>
</tr>
<tr>
<td>STA</td>
<td>Station</td>
</tr>
<tr>
<td>TDI</td>
<td>Time domain interpolation</td>
</tr>
<tr>
<td>Tx</td>
<td>Transmitter</td>
</tr>
<tr>
<td>UE</td>
<td>User equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Up-link</td>
</tr>
<tr>
<td>WP</td>
<td>Work Package</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero forcing</td>
</tr>
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Executive Summary

This deliverable reports details of the work done in Task 2.1, which focuses on design of millimeter-wave (mmWave) ultra broadband access for 5G. 5G-MiEdge specified five use cases, each of which requires significant improvements in mmWave access in order to achieve multi-gigabit throughput under high user density, signal blockage, etc. To satisfy such stringent requirements, Task 2.1 aims to develop four innovative technologies, whose highlights are summarized as follows.

(1) Spatial multiplexing (MIMO, massive MIMO) for mmWave

The mmWave multi-user MIMO systems has been investigated, targeting for the stadium scenario with high density user stations. The performance was evaluated using hybrid beamforming with a line of sight component-only channel model, employing user scheduling algorithm. The proposed beam round Robin algorithm that considers the joint beam and user selection can reduce the inter user interference between the selected stations. The evaluation results show that the average system capacity is larger than 16 bps/Hz, when the maximum number of selected STAs is 4, and both the analogue beamforming and digital beamforming (zero forcing) are adapted.

(2) Multi-link coordination of mmWave access to control interference and blocking

This technology aims to develop an efficient method for handling users’ mutual interferences in case of spatial division multiple access in the uplink direction, when users are served in the same frequency band at the same time. The convenience of exploiting multi-link communications by coordinating multiple access points is shown by numerical results. The presented algorithms aim at finding the optimal users’ precoding matrices in order to minimize the transmit power under QoS constraints, taking into account interferences.

(3) Channel bonding and higher order modulation for super high speed mmWave access including phase noise compensation and pre-distortion

A phase-noise-robust channel estimation for mmWave MU-MIMO OFDM systems is proposed and evaluated. The packet error rate (PER) results of a simple frequency-domain phase noise compensation (PNC) scheme using the proposed channel estimation method are shown. Comparing with the system with perfect channel state information (CSI), the degradation of PER performance of the proposed simple PNC scheme with the estimated CSI is around 3 dB in signal-to-noise power ratio (SNR); however, it still outperforms the conventional common-phase-error (CPE)-only compensation scheme, when the total phase noise level is −88 dBc/Hz @ 1MHz offset. And the maximum throughput is around 27 Gbps, when the number of STAs is 4, the bandwidth is 1.815 GHz, and the secondary modulation schemes are 64QAM.

(4) Ultra lean signaling/control plane for mmWave

The cooperative WiGig/Wi-Fi connection management scheme is proposed to minimize latency due to WiGig connection while reducing overhead of mmWave control signals. Measurement shows that the WiGig connection can be established before the download request from stations with about 90% probability, validating the effectiveness of the proposed scheme.
1. Introduction

This deliverable belongs to WP2 (Millimeter-wave edge cloud for 5G RAN deployment paradigm), which focuses on the development of the millimeter wave technologies required for the mmWave edge cloud, one of the key technology concepts in 5G-MiEdge. The mmWave edge cloud comprises mmWave access and mobile edge computing/multi access edge computing (MEC) to bring cloud-computing capabilities, including computing and caching, at the edge of the mobile network.

In order to carry out technology development efficiently, WP2 comprises of three tasks (Task2.1, Task2.2 and Task2.3) as shown in Figure 1-1. They have been jointly studied by European partners (Fraunhofer-HHI, CEA-LETI, Sapienza University, Telecom Italia) and Japanese partners (Panasonic, Tokyo Institute of Technology).

At the end of the 1st year, D2.1 described basic concepts of overall technologies as an interim report. Then, in D2.3 and D2.4 we have reported the work done in Task 2.2 and Task 2.3, respectively. Following that, this work focuses on Task2.1 (Design of mmWave ultra broadband access for 5G) and describes details of the work done during 2nd year and 3rd year.

D2.1: (M12) Requirement and scenario definition for mmWave access, antenna and area planning for mmWave edge cloud
Deliver midterm report on Task 2.1, Task 2.2 and Task 2.3 activities.

D2.2: (M30) Design of mmWave ultra broadband access for 5G
Report on variety of techniques developed for realizing mmWave ultra broadband access, including mmWave MU-MIMO scheduling and protocols, RF impairments calibrations and ultra lean signaling/control plane mechanisms.

D2.3: (M24) Design of mmWave antennas for 5G enabled stadium
Provide antenna prototypes along with report of their design, analysis and experimental results.

D2.4: (M26) Method of site specific deployment of mmWave edge cloud
Report on algorithm and control protocols as well as overall architecture for mmWave edge cloud

Figure 1-1 WP2 deliverable plan
2. Overview of target use cases and requirements

5G-MiEdge defines five use cases as shown Figure 2-1, which requires significant innovation in mmWave access and backhaul, including MEC, in order to achieve multi-gigabit throughput while dealing with dense environment, signal blockage, etc.

To this end, Task 2.1 investigates several key technologies, which include spatial multiplexing, multi-link coordination, channel bonding/higher order modulation and ultra lean signaling/control plane. Table 2-1 summarizes relationships between system requirements of five use cases and key technologies. In principle, each technology can be applied to all the use cases, but highlighted cells indicate most stringent requirements which can be achieved by introducing the key technology listed in the right column. In the following sections, details of these key technologies are described.

![Figure 2-1 Five use cases defined in 5G-MiEdge](image-url)
<table>
<thead>
<tr>
<th>No.</th>
<th>Use Cases</th>
<th>Key technologies</th>
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<tr>
<td>1</td>
<td>System rate</td>
<td>Spatial multiplexing</td>
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<tr>
<td></td>
<td>Omotenashi services</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Moving hotspot</td>
<td></td>
</tr>
<tr>
<td></td>
<td>2020 Tokyo Olympic</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Dynamic crowd</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Automated driving</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 6.6 Gbps</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Area/ distance (km²)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 10 m</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 1000 m²</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Blocking</td>
<td>Multi-link coordination</td>
</tr>
<tr>
<td></td>
<td>Severe in vehicle</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Severe in viewing area</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Severe in V2I</td>
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</tr>
<tr>
<td>3</td>
<td>Mobility</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 km/h (backhaul on train)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>120 km/h</td>
<td></td>
</tr>
<tr>
<td></td>
<td>4 km/h</td>
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<tr>
<td>4</td>
<td>Peak user rate</td>
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<tr>
<td></td>
<td>&gt; 2 Gbps</td>
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</tr>
<tr>
<td></td>
<td>&gt; 2.15/0.54 Gbps (DL/UL)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>&gt; 4.2 Gbps (Gates)</td>
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<tr>
<td></td>
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</tr>
<tr>
<td></td>
<td>1 Gbps</td>
<td></td>
</tr>
<tr>
<td>5</td>
<td>User density</td>
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</tr>
<tr>
<td></td>
<td>0.4 users/m² (Train station)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 users/m² (Viewing area)</td>
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<td></td>
<td>0.2 vehicles/m²/ 0.18 users/m²</td>
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</tr>
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**TABLE 2-1 Mapping between requirements and key technologies**
3. **Ultra broadband access technologies**

This section describes details of four key technologies developed in Task 2.1.

3.1 **Spatial multiplexing (MIMO, massive MIMO) for mmWave**

Hybrid beamforming (HBF) is considered in the spatial multiplexing for the mmWave to reduce the hardware complexity of the multiple-antenna systems and to enlarge the coverage of the access point (AP). In the previous works, the evaluations almost focus on more general cases, or focus on complex optimization methods [IEEE18]. However, we have a very clear use case and scenario; thus, in this work we focus on the sport stadium use case, which have very high density user stations (STAs) in the band-like stands area. We try to provide quantitative evaluations for this specific scenario with the specific purposes. Figure 3.1-1 shows an example of the mmWave multi-user MIMO (MU-MIMO) systems, where there are a lot of antennas elements equipped in the AP side, and there are also several STAs in this MU-MIMO system. It is not economic to employ a radio frequency (RF) chain for each antenna element due to the huge number of the elements of the massive MIMO systems. In the transmitter (Tx) of a HBF system the signal output from each RF chain is power divided into several routs, and phase shifted by the phase shifters, then transmitted by the antenna elements (antenna array), which is called the analogue beamforming (ABF) that can compensate the limited coverage due to the large path loss of the mmWave system with lower hardware complexity. The same concept also can be used in the receiver (Rx), where the power dividers are changed by the power combiners. The power combiner/divider can be implemented with the directional couplers. With ABF the AP can control the directivity of each antenna array at the AP toward each STA, and the STAs also can control the directivities of their arrays toward the AP. By properly selecting the simultaneously transmitted STAs from the active STAs, the ABF can enlarge the power of the diagonal entries of the effective channel matrix including the ABFs and suppress that of the non-diagonal entries. In down-link (DL) systems, the simple precoding (or post-coding in up-link systems) likes zero forcing (ZF) can be employed to pre-code the signal inputted into each RF chain as the digital beamforming (DBF) to cancel the remained inter-user interference (IUI) between the STAs.

![Figure 3.1-1 An example of spatial multiplexing for mmWave MU-MIMO systems](image_url)
3.1.1 System model

We consider a DL scenario with the line of sight (LOS)-components-only channel model. When the number of STAs is equal to (or smaller than) the number of the RF chains in the AP, the channel matrix between the AP and the STAs becomes

\[
H = \begin{bmatrix}
H_{1,1} & H_{1,2} & \ldots & H_{1,K} \\ H_{2,1} & H_{2,2} & \ldots & H_{2,K} \\ \vdots & \vdots & \ddots & \vdots \\ H_{K,1} & H_{K,2} & \ldots & H_{K,K}
\end{bmatrix},
\]

where \( K \) is the number of simultaneously communicated STAs, and \( H_{p,q}, p, q = 1, 2, \ldots, K \), is the channel matrix between the \( p \)-th STA and the \( q \)-th antenna array in the AP that is defined as

\[
H_{p,q} = \sqrt{P_{\text{Free}}} \cdot a_p(\Phi_p^{\text{AoA}})a_q^T(\Phi_p^{\text{AoD}}),
\]

where \( P_{\text{Free}} \) denotes the path gain calculated from the free space path loss, \( a_p(\cdot) \) and \( a_q(\cdot) \) are the array response vectors of the \( p \)-th STA and the \( q \)-th array in the AP, respectively, and are the functions of the information of angles. \( \Phi_p^{\text{AoA}} \) and \( \Phi_p^{\text{AoD}} \) are the angles of arrival (AoA) to the STA and the angles of departure (AoD) from the AP, respectively, of the \( p \)-th STA that including the elevation and azimuth angles. The received baseband signal vector then becomes

\[
y = [y_1 \quad y_2 \quad \ldots \quad y_K]^T = MHFx + Mn = \tilde{H}x + \tilde{n},
\]

where \( y_p \) is the received signal of the \( p \)-th STA, and \( x = [x_1 \quad x_2 \quad \ldots \quad x_K]^T \) is the Tx signal vector transmitted by each element of the STAs respectively. \( n \) is the received noises of the elements in every array of the STA, and \( \tilde{n} \) is the vector of received noise in the baseband. Matrix \( \tilde{H} = MHF \) is the effective channel matrix that will be diagonalized by the ZF precoding and the design will be discussed later.

3.1.2 Analogue beamforming

\( F \) and \( M \) are the precoding and post-coding matrices for ABF that are defined as

\[\text{For the considered mmWave system has very high directivity of antenna arrays, which is the benefit from the ABF, the LOS components of the channel are more dominant than the others.}\]

\[\text{However, here we only consider the case of the number of STAs is equal to the number of the RF trains in the AP for simplicity.}\]
where $N_{AP}$ is the number of elements in each array of AP, and the total Tx power of each array is normalized to $P_t$. The vectors $f_q$ and $m_p$ are implemented by the phase shifters and can be designed as $f_q = a_q(\Phi_q^{AoD})$ and $m_p = a_p(\Phi_p^{AoA})$, when the information of angles is known. However, it is difficult to estimate the accurate angles under this system configuration with the ABF matrices. A simple approach is to pre-define the precoding and post-coding vectors with the corresponding angles as the ABF beam patterns, and each STA can select a precoding vector and a post-coding vector from the pre-defined ABF beam candidates, with which the STA can obtain the maximum receive power level. The sets of the ABF beam patterns are defined as

$$\mathcal{F} = \{\hat{f}_1, \hat{f}_2, ..., \hat{f}_M\},$$

and

$$\mathcal{M} = \{\hat{m}_1, \hat{m}_2, ..., \hat{m}_N\},$$

where $M$ and $N$ are the numbers of ABF beam patterns of the AP and each STA, respectively; $\hat{f}_m = a_{AP}(\Phi_m^{AoD})$ and $\hat{m}_n = a_{STA}(\Phi_n^{AoA})$ are the ABF candidates for the AP and each STA. The corresponding angles are

$$\Psi_{AoD} = \{\Phi_1^{AoD}, \Phi_2^{AoD}, ..., \Phi_M^{AoD}\},$$

and

$$\Psi_{AoA} = \{\Phi_1^{AoA}, \Phi_2^{AoA}, ..., \Phi_N^{AoA}\},$$

The beam patterns for each array in the AP and the assigned STA (the $p$-th STA) are selected with the criterion that maximize the received signal power at the STA

$$\{\hat{f}_p, \hat{m}_p\} = \arg \max_{\{f \in \mathcal{F}, m \in \mathcal{M}\}} |f H_{p,p} m^T|^2, \forall p \in \{1,2, ..., K\}.$$ (3.1.1)
In this system configuration, only one STA is assigned to one array (RF chain) in the AP; and the angles in $\Psi_{\text{AoD}}$ are designed to let the beam patterns can cover all over the coverage area of this AP, and the angles in $\Psi_{\text{AoA}}$ are designed to let the STA can direct to the proper AP, whose coverage area covers this STA.

Note that $m_p$ may increase the received baseband noise $N_{\text{STA}}$ times for it combines several Rx noises in the RF, and $N_{\text{STA}}$ is the number of elements in the array of each STA. With ZF precoding, the Tx signal becomes

$$x = \mathbf{W}s = \frac{\sqrt{K}}{\beta} \mathbf{H}^{-1}s,$$

where $s$ is the information vector for the STAs, and $\mathbf{W}$ is the digital precoding matrix for cancelling the IUI. The factor $\beta = \text{trace}\left[\mathbf{H}^{-1}(\mathbf{H}^{-1})^H\right]$ is for the power normalization. Then the Rx signal-to-noise power ratio (SNR) of each STA becomes $KP_t/(\beta N_{\text{STA}}P_n)$, where $P_n$ is the Rx noise power of each element in the array of each STA.

3.1.3 User scheduling algorithms

When the number of STAs is larger than that of the RF chains in the AP, as mentioned earlier, it is necessary to select numbers of STAs from the active STAs with the user selection algorithm. Two kinds of user scheduling algorithms at the AP side are considered in the evaluation: 1) Round Robin (RR) algorithm: that selects the STAs in turn, which may induce large level of IUI between the selected STAs. 2) Beam RR algorithm: that first selects the ABF beams in turn, then selects one STA in turn during the group of STAs in the coverage of each selected ABF beam. The detail of Beam RR is described as follow: i) In the initialization phase of Beam RR, the AP has to group the STAs into the group of each ABF beam pattern. In each Tx timing, ii) the AP selects the ABF beam patterns in turn for each RF chain, which has a non-null STA group, and then iii) for each ABF beam, the AP selects one STA in turn from the group of this ABF beam. The RR algorithm and Beam RR algorithm are summarized in the next page.
Algorithm I: Round Robin (RR)

1. Select $K$ STAs from the active STAs in turn:
   The set of the selected STAs is $\mathcal{S} = \{\hat{k}_1, \hat{k}_2, ..., \hat{k}_K\}$, where $\hat{k}_k$ is the index of each selected STA. In this case, the indices are contiguous.
2. Assign each selected STA to each array (RF chain) of the AP:
   The analogue precoding vector of the $q$-th array in AP is $\mathbf{f}_q = \mathbf{f}_{\hat{k}_q}$.
3. Conduct the transmission:
   The information for the STAs are transmitted with the ABF vectors $\mathbf{f}_q (q = 1, 2, ..., K)$ and the digital precoding matrix $\mathbf{W}$ that is calculated based on the estimated channel information including the ABF vectors $\mathbf{f}_q , \mathbf{m}_q , (q = 1, 2, ..., K)$. And the $q$-th selected STA receive the information with ABF vector $\mathbf{m}_q = \mathbf{m}_{\hat{k}_q}$.

Algorithm II: Beam RR

Initial phase: grouping the active STAs that belong to each beam pattern $\mathbf{f}_m, \forall m \in \{1, 2, ..., M\}$.

1. The set of the STAs belonging to the $m$-th beam pattern becomes $\mathcal{S}_m = \{\hat{k}_1^{(m)}, \hat{k}_2^{(m)}, ... \}$, where $\hat{k}_k^{(m)}$ is the index of the STA belonging to the group of $\mathbf{f}_m$, i.e., the STA, $\hat{k}_k^{(m)}$, has select $\mathbf{f}_m$ as its best beam pattern in (3.1.1).
2. Select the non-null groups, i.e. $\mathcal{S}_m \neq \emptyset$, and sort the non-null groups. The set of the sorted non-null groups becomes $\mathcal{G} = \{\mathcal{S}_1, \mathcal{S}_2, ...\}$, where $\mathcal{S}_m$ is the non-null group in the set with the corresponding beam pattern $\mathbf{f}_m$ that is the sorted $\mathbf{f}_m$ in the order of $\mathcal{S}_m$.

Transmission phase:

1. Select $K$ groups from $\mathcal{G}$ in turn:
   Where we assume the length of $\mathcal{G}$ is larger than $K$, when the number of active user is large enough; and the set of selected groups becomes $\tilde{\mathcal{G}} = \{\tilde{\mathcal{S}}_1, \tilde{\mathcal{S}}_2, ..., \tilde{\mathcal{S}}_K\}$, where $\tilde{\mathcal{S}}_k$ is the selected group of STAs.
2. Select one STA in each selected group $\tilde{\mathcal{S}}_k$ in turn:
   The set of the selected STAs becomes $\tilde{\mathcal{S}} = \{\tilde{k}_1, \tilde{k}_2, ..., \tilde{k}_K\}$, and the corresponding beam pattern $\mathbf{f}'_k$ of each $\tilde{k}_k$ is guaranteed to be different from the others.
3. Conduct the transmission:
   The information for the STAs are transmitted with the ABF vectors $\mathbf{f}'_q (q = 1, 2, ..., K)$ and the digital precoding matrix $\mathbf{W}$ that is calculated based on the estimated channel information including the ABF vectors $\mathbf{f}_q', \mathbf{m}_q' , (q = 1, 2, ..., K)$. And the $q$-th selected STA receive the information with ABF vector $\mathbf{m}_q' = \mathbf{m}_{\hat{k}_q}$.
3.1.4 Computer simulation

Computer simulation is conducted to show the performance of HBF MU-MIMO system with the user scheduling algorithms over the LOS-components-only channel model. The simulation condition is shown in Table 3.1-1 that is a DL scenario with one AP and several (10-50) STAs. Each STA has one antenna array, and the AP has 4 antenna arrays. Each array in the AP has 16 antenna elements that are constructed on a square uniformly. The array of each STA has 4 antenna elements that are linearly and uniformly constructed (as the example shown in Figure 3.1-1). The coverage area is shown in Figure 3.1-2, where there is an AP with height $h_{AP}$ and a square coverage area of the STAs with side length $L_{STA}$, and the minimum horizontal distance between the AP and the area is $d_{AP}$. The STAs are uniformly distributed in this area. Because the number of RF chains of the AP is 4, the user scheduler has to always select 4 STAs (as mentioned above, here we only consider the case of 4 STAs for simplicity) to transmit. There are 10 (as shown in Figure 3.1-3) and 5 predesigned ABF beam patterns for the AP and the STAs, respectively, where the beam patterns of the STAs is the same with the azimuth pattern of the AP [as shown in Figure 3.1-3(a)]. The ABF beams in the AP are designed to cover the aforesaid coverage area. Figure 3.1-4 shows the simulation results, where “w/ ZF” denotes the results with not only ABF but also DBF (here ZF is employed), while “ABF only” denotes the results without DBF thus the IUI is remained. We can see, with ZF the system capacities are improved to larger than twice. And the results of Beam RR are better than the normal RR; especially, when ZF is employed the improvement is larger than 20%. With Beam RR and ZF the system capacity of more than 17 bps/Hz can be achieved when the number of STAs is fewer than 50. Note that the system capacities do not increase with the total number of STAs, for the scheduling algorithms are all RR-based algorithms that cannot obtain the benefit of multiuser diversity. When the number of STAs is smaller, the system capacity becomes larger, because of the higher probability to select the STAs with lower IUI levels.

<table>
<thead>
<tr>
<th>TABLE 3.1-1 Parameters of the evaluated hybrid beamforming MU-MIMO</th>
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<tbody>
<tr>
<td>Height of AP, $h_{AP}$</td>
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<tr>
<td>Min. distance from AP, $d_{AP}$</td>
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<tr>
<td>Length of the side of coverage area, $L_{STA}$</td>
</tr>
<tr>
<td>No. of RF chains of AP, $K$</td>
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<tr>
<td>Tx power of each RF chain, $P_t$</td>
</tr>
<tr>
<td>No. of elements of each ABF array in the AP, $N_{AP}$</td>
</tr>
<tr>
<td>No. of STAs, $K$</td>
</tr>
<tr>
<td>No. of RF chains of each STA</td>
</tr>
<tr>
<td>No. of elements of ABF array in each STA, $N_{STA}$</td>
</tr>
<tr>
<td>Rx noise power of each element</td>
</tr>
<tr>
<td>No. of ABF beam patterns of AP</td>
</tr>
<tr>
<td>No. of ABF beam patterns of STA</td>
</tr>
<tr>
<td>User scheduling methods</td>
</tr>
</tbody>
</table>
It is expected that there is fewer multiuser diversity in the mmWave MU-MIMO systems with ABF that will harden the wireless channels, and reduces the fluctuation level of fading, which also reduces the user selection diversity (multiuser diversity) gain. RR-based user scheduling algorithms have the best fairness between the STAs, and Beam RR algorithm can guarantee the reduction of the IUI level between the selected STAs.

3.1.5 Conclusion and future works

In this section, we evaluated the performance of the mmWave MU-MIMO systems using hybrid beamforming with a LOS-component-only channel model over the stadium scenario with high density STAs employing user scheduling algorithm. The proposed user scheduling algorithm called beam RR that considered the joint beam and user selection and can reduce the IUI between the selected STAs. The evaluation results show that the average system throughput is larger than 16 bps/Hz, when both the analogue beamforming and digital beamforming (ZF) are adapted. In the previous works, again, the evaluations almost focus on more general cases, or focus on complex optimization methods [IEEE18]. The contribution of this work is that we focus on the more practical scenario of sport stadium, in where there are higher density STAs in the band-like stands area. We provided the quantitative evaluation for this specific scenario with the specific purposes. In future works, we are going to evaluate the scenarios of mmWave MU-MIMO with multi-AP (as shown in Figure 3.1-5, where the colours are just used to show the different areas of the different APs), in where we also have to consider the cooperation between the APs to suppress the inter-cell interference (ICI) between the APs.
Figure 3.1-3 ABF beam patterns of AP
Figure 3.1-4 Average system capacity vs. number of users

Figure 3.1-5 The coverage areas of mmWave MU-MIMO system with multiple AP
3.2 Multi-link coordination of mmWave access to control interference and blocking

The scope of this section is to present a radio resource allocation strategy for the uplink transmission, exploiting multi-link communications to reduce power consumption and counteract blocking events, while avoiding interference among neighbouring cells. One of the major drawbacks of mmWave communications is their vulnerability to blocking events, due to obstacles in the communication path or high interferences caused by beam collisions. In previous investigations mainly presented in [D2.1], we introduced the concept of multi-link communications to reduce the power consumption, especially in the case of blocking events. However, in those evaluations we did not deal with the problem of optimizing the precoding matrices to avoid interferences among user equipments (UEs). In this deliverable we deal with this problem, introducing the interference among users. Two different sources of interference can be considered: inter-cell interference, caused by users in other cells, and intra-cell interference, caused by users in the same cell considering that they can communicate on the same frequency band at the same time. In general, users’ orthogonality within the same call can be achieved by splitting frequency and/or time resources. However, if there is a shortage or a high demand of resources, spatial division multiple access among users is a helpful solution to guarantee a certain quality of service, for instance in terms of minimum data rate. Even in the cases in which users in the same cell are divided in time and/or frequency, the method we propose is useful to avoid inter-cell interference. The possibility to separate users across space is possible thanks to multiple antenna systems, introduced in mobile networks by mmWave communications. We consider a scenario in which UE’s wish to upload data through mmWave links for, e.g. running an application in the edge cloud. We do not explicitly introduce computation aspects, formulating the problem in such a way that a minimum data rate is maintained. Thus, this framework is general and can include other particular cases such as computation offloading problems, caching etc.

3.2.3 Scenario and problem description

In the following, we will consider a system with $K$ users and $N$ Aps, both endowed with multiple antennas and thus capable of performing beamforming. Thus, we consider a MIMO system, with $n_R$ antennas at the AP side and $n_T$ antennas at the UE side. Beamforming at both the transmit and the receive side helps in compensating the high path loss of mmWave propagation. The aim is to minimize the power consumption of the mobile device with the constraint of maintaining a minimum data rate $R_{\text{min}}$ required to meet a desired quality of service (QoS). We build on the results presented in [SAR14], introducing the possibility for the user to communicate with two APs at the same time to further reduce the power consumption. As described later on, the problem is non-convex due to mutual interference, so that we propose an iterative algorithm based on Successive Convex Approximation [SCU17], [SCU217], converging very efficiently to a local optimal solution. First, a closed form solution is derived for the single-user case, where we will show the gain of exploiting multi-link communications in terms of power consumption. Then, we will present the multi-user case, in which the coordination among different mmWave APs is necessary to avoid interferences due to beam alignments. In general, as shown in Figure 3.2-1, the scenario is composed by $N$ APs and $K$ users, each one connected to its two closest APs.
3.2.4 Radio resources and notation

To build the channel matrix of a generic user $k$, we denote by $\mathbf{a}_{t,k,i}(\theta_{t,k,i}, \phi_{t,k,i})$ and $\mathbf{a}_{r,k,i}(\theta_{r,k,i}, \phi_{r,k,i})$ the steering vectors (column vectors) between user $k$ and AP $i$, where $(\theta_{T,k,i}, \phi_{T,k,i})$ and $(\theta_{R,k,i}, \phi_{R,k,i})$ are the direction of arrivals (azimuth and elevation) at the transmit and the receive side, respectively. Then, the channel matrix $\mathbf{H}_{k,i} \in \mathbb{C}^{n_r \times n_t}$ between UE $k$ and AP $i$ is given by

$$\mathbf{H}_{k,i} = \sqrt{\gamma_{k,i}} \mathbf{a}_{R,k,i}(\theta_{R,k,i}, \phi_{R,k,i})^T \cdot \mathbf{a}_{T,k,i}(\theta_{T,k,i}, \phi_{T,k,i})$$

where $\gamma_{k,i}$ is the channel gain between UE $k$ and AP $i$. Since each user communicates with two APs simultaneously, the overall channel matrix $\mathbf{H}_k \in \mathbb{C}^{2n_r \times n_t}$ is given by

$$\mathbf{H}_k = \begin{pmatrix} \mathbf{H}_{k,1} \\ \mathbf{H}_{k,2} \end{pmatrix}$$

Denoting by $\mathbf{Q} = (\mathbf{Q}_k)_{k \in \mathcal{K}}$ the users’ covariance matrices, we can write:

$$\mathcal{Q}_k = \{ (\mathbf{Q}_k) \in \mathbb{C}^{n_t \times n_t} : \mathbf{Q}_k \succeq 0, \text{tr}(\mathbf{Q}_k) \leq P_k \}$$

where $P_k$ is the maximum power budget of user $k$. Then, we can denote by $\mathcal{Q}$ the joint set $\mathcal{Q} = \prod_{k \in \mathcal{K}} \mathcal{Q}_k$. For any given profile $\mathbf{Q} = (\mathbf{Q}_k)_{k \in \mathcal{K}}$, the maximum achievable data rate of UE $k$ is given by

$$r_k(\mathbf{Q}) = B \log_2 |\mathbf{I} + \mathbf{H}_k^H \mathbf{R}_k(\mathbf{Q}_{-k})^{-1} \mathbf{H}_k \mathbf{Q}_k|$$

where
\[
\mathbf{R}(\mathbf{Q}_{-k}) \triangleq \mathbf{R}_w + \sum_{j \neq k} \mathbf{H}_j \mathbf{Q}_j \mathbf{H}_j^H
\]

is the covariance matrix of the noise \(\mathbf{R}_w \triangleq \sigma_w^2 \mathbf{I}\) (assumed to be diagonal) plus the interference caused by other UEs. \(\mathbf{H}_j\) and \(\mathbf{Q}_j\) are the channel and the covariance matrices of other users and \(B\) is the available bandwidth.

### 3.2.5 Single-user case

In the single-user case, there is only one active UE wishing to upload some content or task. This is clearly an interference-free scenario, and the maximum achievable rate is given by

\[
\mathcal{R}^{\star} = B \log_2 |\mathbf{I} + \mathbf{H}^H \mathbf{Q} \mathbf{H}^{-1}_w|
\]

where \(\mathbf{Q}\) denoted now the covariance matrix of the UE. We can formulate the problem as the minimization of the UE power consumption subject to the constraint of achieving a minimum rate \(R^\text{min}\) and a maximum power budget constraint. Formally, the problem is

\[
\begin{array}{l}
\min_{\mathbf{Q}} \quad \text{tr}(\mathbf{Q}) \\
\text{s.t.} \quad (a) \mathcal{R}(\mathbf{Q}) \geq R^\text{min} \\
\quad (b) \text{tr}(\mathbf{Q}) \leq P_T, \quad \mathbf{Q} \succeq 0
\end{array}
\]

In its simplicity, problem \(\mathcal{P}\) is interesting due to the possibility of finding a closed form solution. Let \(\mathbf{H}^H \mathbf{R}_w^{-1} \mathbf{H} = \mathbf{U} \mathbf{D} \mathbf{U}^H\) be eigenvalue decomposition of \(\mathbf{H}^H \mathbf{R}_w^{-1} \mathbf{H}\), with rank \(r \triangleq \text{rank}(\mathbf{H}^H \mathbf{R}_w^{-1} \mathbf{H}) = \text{rank}(\mathbf{H})\), where \(\mathbf{U} \in \mathbb{C}^{n_k \times r}\) is the (semi-)unitary matrix whose columns are the eigenvectors associated with the \(r\) positive eigenvalues of \(\mathbf{H}^H \mathbf{R}_w^{-1} \mathbf{H}\) and \(\mathbb{R}_{++}^r \ni \mathbf{D} \triangleq \text{diag}(\{d_i\}_{i=1}^r)\) is the diagonal matrix, whose diagonal entries are the eigenvalues arranged in decreasing order. Note that, in our special case of steered beams, the rank of matrix \(\mathbf{H}\) is at most 2, since we are not considering multipath. After having formulated the problem, we can now present the solution as follows:

\[
\mathbf{Q}^{\star} = \mathbf{U}(\alpha \mathbf{I} - \mathbf{D}^{-1})^+ \mathbf{U}^H
\]

with \(\alpha > 0\) must be chosen so that the constraint on the minimum rate is satisfied with equality at \(\mathbf{Q}^{\star}\). Note that \(\mathbf{Q}^{\star}\) has a water-filling-like structure [COV91]: the optimal transmit “directions” are aligned with the eigenvectors \(\mathbf{U}\) of the equivalent channel \(\mathbf{H}^H \mathbf{R}_w^{-1} \mathbf{H}\). The water-level \(\alpha > 0\) can be efficiently computed using the hypothesis-testing-based algorithm described in the following algorithm.
Differently from the classical water-filling solution $Q^{\text{wf}}$, the water-level $\alpha$ is now computed to meet the rate constraint with equality sign. This means that a transmit strategy using the full power $P_T$ (like $Q^{\text{wf}}$) is no longer optimal. In Figure 3.2-2 we present numerical results for the single-user case, comparing the performance of the double-link communication with respect to the baseline single-link communication, in which the UE communicates only with the closest AP. In its simplicity, the single-user scenario shows that double link communications provide a non-negligible gain in terms of power consumption. Moreover, the gain increases as $R_{\text{min}}$ increases, so that for low data rate double link communications can be not necessary. However, it can be necessary to avoid losses due to blocking events. For the performance evaluation of the proposed method we considered a UE and two APs with 4 and 16 antenna elements, respectively. Users and AP are randomly located in a square area of $50 \times 50$ m, and the available bandwidth is set to 10 MHz. The channels are generated with a path loss as given in [SAK14] and results are averaged over realizations of APs positions.

**Figure 3.2-2** Transmit power vs. minimum data rate, averaged over different realizations of APs positions

\[
\begin{align*}
\text{Data: } & \quad (d_i)^r_{i=1} > 0 \text{ (arranged in decreasing order), } r = \text{rank}(H^T R^{-1} w H), \\
\text{and } & \quad R_{\text{min}}; \\
(8.0): & \quad \text{Set } r_e = r; \\
(8.1): & \quad \text{Repeat} \\
& \quad \text{a): Set } \alpha = 2 \frac{R_{\text{min}}}{r_e} - \frac{1}{r_e} \sum_{i=1}^{r_e} \log_2(d_i), \\
& \quad \text{b): If } p_i = (\alpha - 1/d_i) \geq 0, \forall i = 1, \ldots, r_e, \\
& \quad \text{and } \sum_{i=1}^{r_e} p_i \leq P_T, \\
& \quad \text{then STOP;} \\
& \quad \text{else } r_e = r_e - 1; \\
\text{until } & \quad r_e \geq 1.
\end{align*}
\]
3.2.6 Multi-user case

In the multi-user scenario, the convexity of the single-user case is not maintained due to the interference term. In this case, we can formulate the problem as follows

\[
\begin{align*}
\min_Q & \quad tr(Q) \\
\text{s.t.} & \quad a) \ r_k(Q) \geq R_k^\text{min}, \quad \forall k \in \mathcal{K}, \\
& \quad b) \ Q_k \in \mathcal{Q}_k, \quad \forall k \in \mathcal{K}, \quad \triangleq \mathcal{X} \\
\end{align*}
\]

(\mathcal{P}_1)

The non-convexity of \(\mathcal{P}_1\) is due to the first constraint, since the rate of user \(k\) is affected by the interferences of other users. Note that we can write this constraint as

\[ g_k(Q) = -r_k(Q) + R_k^\text{min} \leq 0 \]

To deal with this non-convexity, we build on the tools of SCA, devising an iterative algorithm proved to converge to local minima very efficiently. Denoting by \(Q^\nu\) the current feasible solution at iterate index \(\nu\), we used an inner convex approximation \(\tilde{g}_k(Q, Q^\nu)\) of \(g_k(Q)\) around \(Q^\nu \in \mathcal{X}\). Without going into the details, it can be easily noticed that \(r_k(Q)\) can be written as

\[ r_k(Q) = r_k^+(Q) + r_k^-(Q) \]

where

\[ r_k^+(Q) = B \log_2 |R_k(Q^-) + H_k^T Q_k H_k| \]

and

\[ r_k^-(Q) = -B \log_2 |R_k(Q^-)| \]

so that the constraint can be rewritten as

\[ g_k(Q) = -r_k^+(Q) - r_k^-(Q) + R_k^\text{min} \leq 0 \]

Then, \(g_k(Q)\) is composed by a convex part (first term) and a concave part (second term) that can be linearized to obtain a convex approximation \(\tilde{g}_k(Q, Q^\nu)\) of the overall constraint. Then, the problem can be iteratively solved using the constraint

\[ \tilde{g}_k(Q, Q^\nu) + R_k^\text{min} \leq 0, \quad \forall k \]
Then, starting from a non-convex problem, it is possible to iteratively solve a strongly convex problem, converging very efficiently to local minima. More specifically, given a feasible point $Q^\nu$, the problem can be formulated at each iteration as follows

$$
\hat{Q}(Q^\nu) \triangleq \arg \min_{Q} \ \text{tr}(Q) \\
\text{s.t.} \quad \begin{align*}
& \text{a}) \ g(Q, Q^\nu) + R_k^{\min} \leq 0, \quad \forall k \in \mathcal{K}, \quad (P^\nu) \\
& \text{b}) \ Q_k \in \mathcal{Q}_k, \quad \forall k \in \mathcal{K}.
\end{align*}
$$

Then, the algorithm consists in solving the sequence of problems $P^\nu$, starting from a feasible point $Q^0$. The formal description of the algorithm is the following

**Initial data:** $Q^0 \in \mathcal{X}; \ \{\gamma^\nu\}_\nu \in (0, 1]$;  
(S.1): If $Q^\nu$ satisfies a suitable termination criterion, STOP  
(S.2): Compute $\hat{Q}(Q^\nu) \triangleq (\hat{Q}(Q^\nu),)$ [cf. $P^\nu$];  
(S.3): Set $Q^{\nu+1} = Q^\nu + \gamma^\nu \left(\hat{Q}(Q^\nu) - Q^\nu\right)$;  
(S.4): $\nu \leftarrow \nu + 1$ and go to (S.1).

In Figure 3.2-3, we show the performance of the proposed algorithm, in case of double link communications, compared with the single link case in terms of transmit power, for different data rates $R_k^{\min}$. A simple scenario with 3 users and 2 APs is used for the evaluation of the performance of the proposed algorithm. We can see how the double link case yields significant gains, especially for higher required data rates. In particular, in this example, for a required data rate of 60 Mbps the single link case does not provide a feasible solution for the problem, while the double link case (dark blue curve) guarantees the required QoS with a transmit power that meet the constraints of the problem.
Figure 3.2-3 Total transmit power vs. iteration index for different values of data rate, averaged over different realizations of APs positions

3.2.7 Conclusion

To conclude, in this section we presented the problem of multi-link communications to reduce power consumption while maintaining a minimum data rate, handling the interference among different users. We exploited multi-antenna systems to separate users across space, serving them in the same frequency band at the same time, and to avoid inter-cell interference. Although the problem is non-convex, the tools of Successive Convex Approximation are used to efficiently solve the problem converging in a very few steps. This efficiency is given by the particular structure of the problem, which can be split into a convex part and the linearization of the non-convex part. Numerical results show the effectiveness of the proposed method, compared to the case of single-link communications, in which every user communicate only with its closest AP.
3.3 Channel bonding and higher order modulation for super high speed mmWave access including phase noise compensation and pre-distortion

In this section we discuss the issues of digital pre-distortion (DPD) and phase noise compensation for the channel bonding and higher order modulation. The digital pre-distortion aims to reduce the effects of the non-linearity in the power amplifier at the transmitter due to the high peak-to-average power ratio. And the phase noise compensation aims to reduce the effects of the phase noise occurs both at the oscillators in the transmitter and the receiver.

3.3.1 Channel bonding and digital pre-distortion for PAPR reducing

Channel bonding for more than two mmWave channels is also considered in standards like IEEE 802.11ay to provide super high speed access. However, due to the limited sampling frequency of the digital-to-analogue convertor (DAC) and analogue-to-digital convertor (ADC), one signal chain including DAC (or ADC) and RF circuit is difficult to handle the multiple channels of mmWave system simultaneously. Each channel must be handled by individual signal chain both in the transmitter and the receiver.

On the other hand, orthogonal frequency division multiplexing (OFDM) scheme is also employed in the mmWave standards, for its high spectral efficiency. However, OFDM signals always have high peak-to-average power ratio (PAPR), which require larger dynamic range power amplifiers (PA) with higher linearity, and the power efficiency of PA is reduced due to the large power back-off (BO). DPD methods for baseband input signals were proposed to pre-compensate the nonlinearity of PA that can improve the power efficiency of PA. For simplifying the RF circuits of the transmitter, multi-band PA and concurrent dual-band DPD have been proposed in some literatures. However, it becomes a difficult task due to the low oversampling rate of the baseband for the mmWave channels.

![Figure 3.3-1 Architecture of the dual-channel mmWave DPD](image-url)

* LO: local oscillator.
* BPF: band pass filter.
A dual-channel DPD scheme is evaluated with a 3-box nonlinear PA model that represent the memory effects in [IWS16]. Figure 3.3-1 shows the architecture of the dual-channel DPD scheme. The DPD scheme includes 2 DAC for the baseband signals of the channels and 2 ADC to observe the distorted signals of the channels in baseband. Each order of the inter-modulation distortion (IMD) can be calculated by the digital processing with the up-sampled baseband signals of the channels, and the calculated IMD signals are used in the coefficient training and the digital pre-distortion phases of this DPD scheme.

The simulation shows the error vector magnitudes (EVM) of the channels are improved more than 9 dB and 11 dB in the pass bands of channels with DPD compensation up to the 3rd and 5th order, respectively, when the back-off is 6 dB. In additionally, for achieving the same EVM without DPD, it needs 15 dB back-off, i.e., with DPD it is expected to obtain more than 8 times power efficiency with the same PA. Because the numerical complexity of the proposed scheme will increase with the up-sampling rate, and the scheme needs the characteristics of the BPFs in the IF circuit; we are going to analyse and reduce the numerical complexity of this method in the future works. The nonlinear distortion is also possible to be cancelled in the Rx side with iterative successive interference cancellation (SIC) technique. However, due to the necessity of compensation for the hardware impairment likes phase noise, the complexity of the Rx process will become extremely high. So it is recommended to conduct the DPD at the Tx side, and leave the other compensation process at the Rx side.

### 3.3.2 Phase noise compensation and the channel estimation

In [IEICE16], a simple frequency domain phase noise compensation (PNC) scheme is proposed for the single-input and single-output (SISO) mmWave systems, which is expected to have much lower numerical complexity. The channel estimation methods are also evaluated, and a phase-noise-robust channel estimation method for the frequency domain scheme is also proposed. The proposed scheme compensates the phase noise with a 3-tap frequency domain equalizer that can simultaneously cancel the common phase error (CPE) of all the subcarriers and the inter-carrier interference (ICI) from the adjacent subcarriers, and the weights of the equalizer can be estimated by using the pilot subcarriers. The channel estimation preamble with comb-type pilots is also proposed that can reduce the effects from the high level phase noise to improve the channel estimation accuracy. With time domain interpolation (TDI), the proposed channel estimation method can keep lower interpolation error in the environment with Rician factor ($K$) is 10 dB. We extend the proposed phase noise compensation into mmWave MU-MIMO OFDM systems; however, the channel estimation considering the multiplexing of the multiple Tx antennas, as well as the phase noise becomes a difficult challenge [SmartCom17], [SmartCom18]. In this document, we evaluate the performance a PN-robust channel estimation scheme for the mmWave MU-MIMO OFDM systems. Four comb-type preambles are used in the channel estimation, and estimation results are averaged to reduce the effects of ICI. As the preambles, 2 types of pilot arrangements, continue and scattered pilots, are compared, which shows that the scattered pilots outperform the continue pilots. The packet error rate (PER) performance of the proposed scheme with channel estimation is also evaluated.
3.3.2.1 System model and frequency-domain phase noise compensation scheme

We consider the up-link (UL) a mmWave MU-MIMO OFDM system with one access point (AP) and $K$ single antenna user stations (STAs). The number of antenna equipped in the AP is $N_r \geq K$, then the FFT transformed received (Rx) signal at the $i$-th antenna becomes

$$ Y_i(m) \approx \sum_{k=1}^{K} [H_{i,k}(m) \Phi_k(0)X_k(m)] + \sum_{k=1}^{K} [H_{i,k}(m + 1) \Phi_k(1)X_k(m + 1) + H_{i,k}(m - 1) \Phi_k(-1)X_k(m - 1)] + Z_i(m) + V_i(m), $$

where $m$ is the index of subcarrier, $X_k(m)$ is the transmitted (Tx) signal of the $k$-th STA, $H_{i,k}(m)$ is the channel response from the $k$-th STA to the $i$-th Rx antenna. In the right hand side of this equation, the first term is the desired signal with CPE, $\Phi_k(0)$, the second term is the ICI from the adjacent subcarriers, and the third term includes the other ICI, $Z_i(m)$, and the Rx noise, $V_i(m)$. And the vector of the Rx signal becomes

$$ y(m) \approx H(m)\Phi(0)x(m) + H(m + 1)\Phi(+1)x(m + 1) + H(m - 1)\Phi(-1)x(m - 1) + z(m) + v(m), $$

where the matrices $\Phi(0)$, $\Phi(+1)$, and $\Phi(-1)$ are diagonal matrices with the diagonal elements are the CPE, and adjacent ICI coefficients, respectively; and $H(m)$ is the channel matrix of the $m$-th subcarrier. Note that the approximation holds, because we assume the channel matrix of the adjacent subcarriers are similar to each other. $y(m)$ is the vector of the Rx signal at the $i$-th antenna.

After MIMO channel equalization, e.g., ZF, the separated signals become

$$ x'(m) = H^\dagger(m)y(m) \approx \Phi(0)x(m) + H^\dagger(m)H(m + 1)\Phi(+1)x(m + 1) + H^\dagger(m)H(m - 1)\Phi(-1)x(m - 1) + z'(m) + v'(m), $$

where $A^\dagger$ denotes the pseudo inverse of a matrix $A$; and the second approximation holds, because we assume the channel matrix of the adjacent subcarriers are similar to each other. $x'(m)$ is the vector of the separated signal with elements are $X'_k(m), k = 1, 2, ..., K$. Then $X'_k(m)$ is input into the 3-tap equalizer (as shown in Figure 3.3-2) to cancel the CPE and ICI simultaneously, where the weights of the 3-tap equalizer can be estimated by using the pilots inserted in the data OFDM symbols, which’s process is just like that of the mmWave SISO OFDM systems [IEICE16]. However, the
channel state information (CSI) is necessary, the estimation of which can be degraded by the phase noise. In [IEICE16], the comb-type pilot configuration is adapted to avoid ICI from the adjacent subcarriers in SISO systems; however, in MIMO system, the comb-type pilot should be used to multiplex the pilots for the different STAs. In this evaluation, we use the packet construction, shown in Figure 3.3-3, that has 4 preambles for the channel estimation. There are several data symbols following the preambles that have several pilots inserted for the CPE estimation in the data symbols. In the preambles, 2 types of pilot constructions, continue and scattered pilots\(^3\), are evaluated (as shown in Figure 3.3-4, which is an example for that of STA 1). The measured CSI of different preambles is firstly interpolated with TDI, then the interpolated CSIs of different preambles are averaged to reduce the effects of the interpolation error, the ICI, as well as the Rx noise.

\[^3\text{That are denoted by type I and type II, respectively.}\]

---

**Figure 3.3-2** 3-tap frequency domain CPE and ICI canceller

**Figure 3.3-3** Packet construction of the mmWave MU-MIMO OFDM system
Figure 3.3-4 Types of the configuration of pilots. (a) type I; (b) type II
3.3.2.2 Computer simulation

Computer simulations are conducted to evaluate the channel estimation schemes and the phase noise compensation scheme including the channel estimation for the mmWave MU-MIMO OFDM systems. The simulation conditions are shown in Table 3.3-1, where the secondary modulation is 64QAM. The number of the pilot subcarriers is 368, that is multiplexed to the 4 STAs, so the number of pilot subcarriers for each STA is 96; then the space between the pilots becomes 4. The number of preambles is 4 and the number of data symbols is 24, while the case with only one preamble is also evaluated in the simulation for the channel estimation evaluation. The channel coding is low-density parity-check (LDPC) with code rate 13/16, then the maximum total system throughput is about 27 Gbps that is also considering the guard interval (GI) of the 1/4 FFT points. The channel model is Rician channel with the K factor is 30 dB; and in the channel estimation evaluation the results with K =100 dB are also shown.

3.3.2.2.1 Mean squared error of the channel estimation

Figure 3.3-5 shows the mean squared error (MSE) results of the channel estimation schemes with or without phase noise, and with the Rician factor is 30 dB or 100 dB. The error of the estimated channel matrix is defined as below

\[ E(m) = H^\dagger(m)\tilde{H}(m) - D, \]

where \( \tilde{H}(m) \) is the estimated version of the channel matrix \( H(m) \); and \( D \) is a diagonal matrix with the diagonal elements are the estimated CPEs of the separated signals, for the remained CPE in the channel estimation phase can be compensated simultaneously with that of the data symbols. In the case of no phase noise and no channel estimation error, the terms in the right hand side become unit matrix, and the error also become 0 matrix.

Then the MSE is defined as follow

\[ \frac{1}{KN_{active}} \sum_m \text{tr}\{E^H(m)E(m)\}, \]

where \( \text{tr}\{\cdot\} \) denotes the trace of a matrix, and \( A^H \) denotes the Hermitian transpose of a matrix \( A \); and the summation is over all \( m \) belonging to the set of the active pilot subcarriers in the preambles.

\[ \text{TABLE 3.3-1 Simulation parameters} \]

<table>
<thead>
<tr>
<th>Transmission Scheme</th>
<th>OFDM/64QAM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sampling rate</td>
<td>2.640 GHz</td>
</tr>
<tr>
<td>Parameter</td>
<td>Value</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>----------------------------------------------------------------------</td>
</tr>
<tr>
<td>No. FFT/GI points</td>
<td>512/128</td>
</tr>
<tr>
<td>No. of active subcarriers in preambles, $N_{active}$</td>
<td>368</td>
</tr>
<tr>
<td>No. of pilot subcarriers per Tx</td>
<td>96 ($N_s$: 4)</td>
</tr>
<tr>
<td>No. of active subcarriers in data symbols</td>
<td>Data: 336, Pilot: 16</td>
</tr>
<tr>
<td>Packet construction</td>
<td>Preamble: 4, Data: 24</td>
</tr>
<tr>
<td>No. of Rx antennas in AP</td>
<td>4</td>
</tr>
<tr>
<td>No. of single-antenna STAs</td>
<td>4</td>
</tr>
<tr>
<td>Channel coding</td>
<td>LDPC (672, 546)</td>
</tr>
<tr>
<td>Channel decoding</td>
<td>Sum-product algorithm (max. 8 iterations)</td>
</tr>
<tr>
<td>Max. system throughput</td>
<td>27.03 Gbps (4 STAs)</td>
</tr>
<tr>
<td>Channel mode</td>
<td>32-tap Rician channel (K: 30, 100 dB)</td>
</tr>
<tr>
<td>PN level (Tx + Rx)</td>
<td>$-88$ dBc/Hz @ 1MHz offset, generated by AR model [IEEE09]</td>
</tr>
</tbody>
</table>

When $K = 100$ dB, the channel estimations with 1 and 4 preambles are evaluated without phase noise. Because the value of $K$ is very large, the channels can be considered as frequency flat fading, and the error due to the interpolation approaches to 0. Average over 4 preambles provides 6 dB SNR gain from the case of 1 preamble. When $K = 30$ dB and there is not phase noise, the schemes with 4 preambles is much better than that with 1 preamble in the low SNR region; however, in high SNR region, the MSE of type I preambles approaches to that of only one preamble, while type II preambles have the best performance. When $K = 30$ dB and the phase noises both in the Tx and the Rx arise, the preambles of type II also have the best performance than other schemes.
Figure 3.3-5 MSE performances of the channel estimation schemes

Figure 3.3-6 PER performances of the PN-compensation scheme with different CSIs

3.3.2.2.2 Packet error rate performance

Figure 3.3-6 shows the PER of the mmWave MU-MIMO OFDM systems with or without phase noise and with the perfect CSI or the estimated CSI obtained by type II preambles, in where the Rician factor is 30 dB. When the CSI is perfect and without phase noise, the PER performance is just like the normal OFDM system. When the phase noises arise, with the proposed PNC scheme using the perfect CSI, the SNR degradation is only 2 dB from that without phase noise, while the scheme that only compensate CPE has more than 5 dB degradation with the error floor in the high SNR region. When the estimated CSI is utilized, the performance of the proposed PNC has further 3 dB degradation from that with perfect CSI at PER = 10^{-1}, and the error floor occurs in the high SNR region. However, the performance of the proposed PNC still
has the better PER performance than the CPE compensation only scheme that also uses the estimated CSI. In the future works, we are going to refine and improve the channel estimation accuracy to improve the performance of the proposed PNC scheme.

3.3.3 Conclusion

In this section we discuss the issues of digital pre-distortion that can be conducted in the transmitter side, and phase noise compensation that can be conducted in the receiver side. Especially, we extended a simple frequency-domain phase noise compensation method from SISO into MU-MIMO OFDM systems. The PN-robust channel estimation approach was also evaluated for the proposed phase noise compensation.
3.4 Ultra lean signaling/control plane for mmWave

Omotenashi services aim to deliver ultra-high-speed wireless access in high user density environments. Figure 3.4-1 shows selected three locations (airport, train station and food court) as typical scenarios where many people are waiting in a dedicated area. One of the typical application examples is ultra-high-speed content download, which is very challenging due to high user density that reaches 2 users/m² as listed in Table 2-1. In order to achieve such stringent performance, a holistic approach, not limited to the physical layer but also including the network system and architecture levels, is required.

In the first year of 5G-MiEdge project, we have investigated the efficient beamforming protocol to reduce overhead due to beam direction alignment, which needs to be executed periodically for each UEs. The outcome has been reported in details in the deliverable [D2.1].

Following that, we have moved to investigate integration of the content delivery network (CDN) and radio access technologies during 2nd and 3rd year. In particular, we put effort on developing the WiGig/Wi-Fi cooperated connection management that minimizes overhead of control signaling and realizes ultra-lean signaling at the mmWave frequency, to obtain full benefit of ultra-high-speed mmWave access.

In the following, overall architecture and details of the proposed scheme are described.

![Scenario examples of Omotenashi services](image)

**Figure 3.4-1 Scenario examples of Omotenashi services**

3.4.3 Overall system architecture

This section reviews the overall system architecture and key features of the proposed system [D2.4].

(a) Edge cloud contents delivery network

Figure 3.4-2(a) shows the high-level architecture of the overall network. The WiGig equipped digital signage (WiGig signage) employs 60 GHz mmWave wireless connection based on WiGig/IEEE 802.11ad standard, which provides multi-Gbps content delivery for UEs. To avoid backhaul congestion from the cloud to WiGig signages, the edge cloud content delivery network (edge cloud CDN) is introduced. The edge cloud consists of local storages and WiGig signages which are located at the edge of the network. The content and application data are pre-fetched to the local
storages based on the user context information. Most of the pre-fetching process can be done during low traffic periods such as overnight.

(b) Multi-user gigabit access

Assuming that multiple users download contents simultaneously, the content delivery system could suffer from throughput degradation due to congestion at the WiGig signage. To avoid this, the WiGig signage is equipped with multiple WiGig modules as illustrated in Figure 3.4-2. Each WiGig module adopts beamforming technology, which steers the antenna beam by using the phased array antenna. This mitigates interference among WiGig links, enabling multi-Gbps throughput in the multi-user environment.

(c) WiGig/Wi-Fi HetNet

Due to large path loss, the communication distance of WiGig is typically limited up to about 10 m. To extend the area coverage, the WiGig/Wi-Fi heterogeneous network (HetNet) is employed. Figure 3.4-2 shows the concept of WiGig/Wi-Fi HetNet where authentication, connection management as well as browsing the content list are executed via Wi-Fi to achieve wide coverage. The WiGig connection is available within the WiGig area for users to download the contents to their UEs with multi-Gbps throughput.

Figure 3.4-2 Overall architecture and key technologies
3.4.4 Proposed Application-centric WiGig/Wi-Fi cooperative connection management

In WiGig/Wi-Fi HetNet, the WiGig connection procedure directly affects user experience. For example, if the user’s download request triggers WiGig connection establishment, it introduces additional latency due to the connection establishment procedure. To minimize the latency, an application-centric connection management scheme is newly proposed [MTN17].

Figure shows a state transition diagram of the download application on the UE, which consists of (a) content catalogue, (b) content details, (c) downloading status, (d) download completed and (e) content playback.

When the user launches the application, the UE connects to the WiGig signage via Wi-Fi, and the (a) content catalogue which consists of preview thumbnails is displayed. When the user selects one of the available contents, the application transits to display (b) content details. At the same time, the UE starts connecting to the WiGig module in the WiGig signage. If the user presses the download button, the application displays the (c) downloading status, and content downloading begins. When downloading has finished, the application transits to show (d) download completed, and the WiGig link is automatically disconnected. The user may then proceed to view the content in (e) content playback.

Figure 3.4-4 illustrates the operation steps. In the proposed method, the WiGig connection is initiated when the user selects the content. Here we specify the required time for WiGig connection as $\Delta T_1$, and the time lag between content selection and pressing download button as $\Delta T_2$. Then, the WiGig connection is established in $\Delta T_1$. When the user presses the content download button after $\Delta T_2$, the application starts download without delay.

![State transition diagram of application](image-url)
Figure 3.4-4 Operation steps of application-centric connection management
3.4.5 Prototype design

To validate the effectiveness of the proposed method, a prototype system has been developed. Figure 3.4-5 shows the WiGig signage prototype and a block diagram of the WiGig signage. Six WiGig modules are housed in the base unit under the display monitor. Each WiGig module employs beamforming technology, achieving about 120° coverage in the azimuth direction.

As illustrated in the block diagram, the WiGig signage consists of WiGig modules, a Wi-Fi access point (AP), a local storage and an AP controller (APC). The APC manages the WiGig connections. While the UE is connected to Wi-Fi, the APC periodically collects expected link quality via Wi-Fi for connection management [Figure 3.4-5(1)]. When the UE requests WiGig connection, the APC connects the UE to one of the WiGig modules which provides the best link quality [Figure 3.4-5(2)]. When the user requests the content download from the application, the UE starts downloading from the local storage via WiGig [Figure 3.4-5(3)].

Figure 3.4-6 shows the screen capture of the application on the UE. As explained earlier, the WiGig connection is established while (b) content details is displayed.

![Figure 3.4-5 Picture of WiGig signage and its block diagram](image-url)
3.4.6 Measurement results

The performance of the prototype system was evaluated. In this measurement, all the content data are assumed to be prefetched to the local storage and latency of CDN is ignored. Table 3.4-2 summarizes the measurement conditions.

Figure 3.4-7 shows the measured effective throughput. In this measurement, three users downloaded a 2 GB content per user with 2 second delay interval. Throughput via Wi-Fi (20 MHz BW, 2x2 MIMO) was also measured for comparison.

As shown in Figure 3.4-7(a), the maximum throughput via Wi-Fi was about 100 Mbps. The throughput deteriorates as the number of users increases, which is due to carrier
sense multiple access with collision avoidance (CSMA/CA) operation under the multi-user environment. To download a 2 GB content, it takes about 480 s per user. On the other hand, the maximum throughput of WiGig reached about 1.8 Gbps, achieving the 2 GB content download in 10 s for all users.

**TABLE 3.4-2 Measurement conditions**

<table>
<thead>
<tr>
<th>Wireless standard</th>
<th>Wi-Fi: IEEE 802.11ac</th>
<th>WiGig: IEEE 802.11ad</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of users</td>
<td>3</td>
<td></td>
</tr>
<tr>
<td>Size of downloaded content</td>
<td>2 GB</td>
<td></td>
</tr>
<tr>
<td>Distance between WiGig signage and UEs</td>
<td>1 m</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 3.4-7 Measured throughput](image)

In the WiGig signage download scenario, it is reasonable to assume that the maximum number of multi-access users, who download a content at the same time, will be below three because each downloading event completes within 10 s. However, in order to
observe the system behaviour under stringent conditions, stress test is performed. Figure 3.4-8 shows test environment where the number of users are increased up to six with about 30 cm spacing as an extreme example. Figure 3.4-9 shows examples of the measured throughput. Due to co-channel interference, some of the users exhibit low throughput. In the prototype system, frequency channel is automatically adjusted if the link quality is unstable. This helps find better frequency channel and improves significant degradation. As shown in Figure 3.4-9, each user achieves more than 1.4 Gbps after 5 s in most cases.

![Stress test environment](image)

**Figure 3.4-8 Stress test environment**

![Throughput graphs](image)

**Figure 3.4-9 Measured throughput under stress test environment**
Next, in order to evaluate the effectiveness of the proposed application-centric connection management, a field experiment has been executed. About 100 participants joined it and the system behaviour was recorded in the system log.

Figure 3.4-10 shows the cumulative distribution function (CDF) of time lag from content selection to download request, (which corresponds to $\Delta T_2$ in Figure 3.4-4). The users remained in (b) content details for more than 0.5 s before requesting content download.

Figure 3.4-11 shows the latency between the user’s download request and download start. In the conventional method, the user’s download request triggers WiGig connection establishment which introduces $\Delta T_1$ latency. As shown in Figure 3.4-10, the conventional method requires at least 0.2 to 0.3 s before actually starting the download. The proposed method, on the other hand, establishes the WiGig connection before the download request with about 90% probability. The remaining 10% includes the case that WiGig link was unstable due to signal blockage by human body, misalignment of direction between WiGig signage and the UE etc. The robustness will be improved by introducing distributed antennas, multi-link connection, etc., which are subjects of future study.
3.4.7 Extension toward 10 Gbps link aggregated system

As reported in the deliverable [D1.1], one of the target use cases of 5G-MiEdge is the moving hotspot. As illustrated in Figure 3.4-12, it is required to have communication measure for synchronizing and sharing contents between the local server on airplane/train/bus and service servers in the cloud while stopping at airport/train station/bus stop. As an example, in the in-flight entertainment (IFE) system, the total volume of the content, which includes video, multimedia content, games etc., reaches 500+ GB on average. Therefore, extreme ultra-high speed wireless capability is needed to realize wireless content update.

The WiGig signage prototype introduced in the previous section supports multi-user mmWave access, which can be extended to a link aggregated system where multiple mmWave links are simultaneously used to enhance point-to-point throughput.

Figure 3.4-13 shows a prototype system. The prototype utilizes three WiGig channels (CH1:58.32GHz, CH2:60.48GHz, CH3:62.64GHz) combined with polarization MIMO (vertical/horizontal), resulting in up to six mmWave links that are activated simultaneously. As illustrated in Figure 3.4-14, the two-stage prefetching is newly introduced where the data stream controller prefetches the transferring data to the 2nd cache prior to the arrival of the airplane/train/bus in order to avoid wired network congestion from the local storage. Table 3.4-3 summarises the specification of the prototype.

Figure 3.4-15 shows the measured throughput. Each mmWave link achieves 1.8 Gbps maximum throughput, leading to 10 Gbps total throughput by link aggregation. As shown in Figure 3.4-16, an application software is also implemented for demonstration, which exhibits 18 files of a 2-GB video content (36 GB total data) to be downloaded within 30 sec. The outcome has been presented at international conferences such as [TMN17].
**Figure 3.4-13 Prototype system**

**Figure 3.4-14 Two-stage prefetching**

**TABLE 3.4-3 Specification of the prototype system**

<table>
<thead>
<tr>
<th>Spec.</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>EIRP</td>
<td>20 (typ) dBm</td>
</tr>
<tr>
<td>Number of mmWave link</td>
<td>6</td>
</tr>
<tr>
<td>Channel Frequency</td>
<td>58.32, 60.48, 62.64 GHz</td>
</tr>
<tr>
<td>Polarization</td>
<td>Vertical/Horizontal</td>
</tr>
<tr>
<td>Beam width</td>
<td>20 deg.</td>
</tr>
<tr>
<td>Beam steering range</td>
<td>120 deg.</td>
</tr>
</tbody>
</table>
Figure 3.4-15 Measured performance

(a) Throughput per mmWave link

(b) Total throughput
Figure 3.4-16 Demonstration of 10 Gbps link aggregated system

(a) Demonstration setup

(b) Application software
4. Summary

This deliverable reported details of the work done in Task2.1 (Design of mmWave ultra broadband access for 5G). In order to achieve multi-gigabit throughput under stringent environments such as high user density, signal blockage, etc., Task 2.1 developed four key enablers, (1) spatial multiplexing, (2) multi-link coordination, (3) channel bonding/higher order modulation and (4) ultra lean signaling/control plane.

In spatial multiplexing, the mmWave multi-user MIMO systems has been investigated. The performance was evaluated using hybrid beamforming with a LOS component-only channel model, assuming stadium use case. The proposed user scheduling algorithm (beam round Robin) considers the joint beam and user selection and it can reduce the inter user interference between the selected stations. The evaluation results show that the average system throughput is larger than 16 bps/Hz, when both the analogue beamforming and digital beamforming are adapted.

Multi-link coordination aims to develop an efficient method for handling users’ mutual interferences in case of spatial division multiple access in the uplink direction, when users are served in the same frequency band at the same time. The convenience of exploiting multi-link communications by coordinating multiple access points is shown by numerical results. The presented algorithms aim at finding the optimal users’ precoding matrices in order to minimize the transmit power under QoS constraints, taking into account interferences.

In the study of channel bonding/higher order modulation, a phase-noise-robust channel estimation for mmWave MU-MIMO OFDM systems is proposed and evaluated. A simulation results verified that the proposed channel estimation method outperforms the conventional CPE-only compensation scheme, when the total phase noise level is $-88 \text{ dBc/Hz @ 1MHz offset}$, while achieving maximum throughput of around 27 Gbps with 4 STAs.

As an extension of ultra lean signaling/control plane, the cooperative WiGig/Wi-Fi connection management scheme is proposed to minimize latency due to WiGig connection while reducing overhead of mmWave control signals. Measurement shows that the WiGig connection can be established before the download request from stations with about 90% probability, validating the effectiveness of the proposed scheme.

These outcomes are transferred to WP4 and some of the developed technologies will be integrated for PoC through collaborative work with WP4. The results will be reported in WP4 deliverables (D4.2 and D4.3) by the end of the final year.
5. References

[D1.1] 5G-MiEdge deliverable D1.1, “Use Cases and Scenario Definition,” Available online at: http://5g-miedge.eu


[D2.1] 5G-MiEdge Deliverable D2.1, “Requirement and scenario definition for mmWave access, antenna and area planning for mmWave edge cloud,” Available online at: http://5g-miedge.eu

[D2.3] 5G-MiEdge deliverable D2.3, “Design of mmWave antennas for 5G enabled stadium,” Available online at: http://5g-miedge.eu

[D2.4] 5G-MiEdge Deliverable D2.4, “Method of site specific deployment of mmWave edge cloud,” Available online at: http://5g-miedge.eu


