MIMO Processing for Satellites in the 5G Era

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Abstract—The integration of satellites in 5G networks is considered to complement terrestrial infrastructures and offer the availability and the data rates fulfilling the demands of future communication systems. This paradigm shift especially brings new challenges for the design of very high throughput satellites. In this work, the interest of the MIMO technology to meet 5G requirements is discussed. The advantages of the approach both for the feeder links and the user links of next-generation systems are presented.

Index Terms—5G mobile communications, Satellite communication, MIMO communication, Digital signal processors

I. INTRODUCTION

In the last years, the integration of non-terrestrial networks into the 5G standard has gained significant interest. Satellites and high altitude platforms indeed enable to extend the range of applications supported by 5G. Several studies on architecture aspects as well as on the physical layer design have especially been released by the 3GPP organization. Moreover, the ESA ARTES SATi5 [1] and the Horizon 2020 SaT5G [2] European research projects currently aim at identifying and demonstrating relevant use cases for satellites in 5G networks. Some of the most promising application scenarios for enhanced mobile broadband (eMBB) services are backhauling and broadband internet access in planes, vessels and remote locations without fiber access. In this context, innovative solutions are required to keep up the pace of wireless communications in the 5G era. Payloads with digital processing capabilities appear to be one of the key enablers to meet these requirements and ensure a seamless satellite-terrestrial network integration [3]. The advent of radiation-hardened digital processors has brought a significant improvement of satellite payload flexibility. Frequency and connectivity planning as well as beamforming belong nowadays to the most common features of on-board processors. Whereas the first commercial payloads embarking digital processing capabilities were only supporting narrowband communications [4], recent breakthroughs have now made digital on-board processing for broadband communication systems feasible [5], [6]. The next generation of high throughput satellites (HTSs), such as SES 17 or Eutelsat Quantum, will for example implement significant on-board processing capabilities.

Very high throughput satellite (VHTS) systems use hundreds or even more than a thousand (e.g. Viasat 3) of beams in their downlink. In each of these beams, the available downlink Ka-band spectrum is reused to cope with the traffic demands such that an aggregate user link bandwidth of hundreds of gigahertz can be supported. This especially makes the design of the feeder link challenging as tens of spatially separated gateways that fully reuse the uplink frequency resources are necessary to deliver the required sum throughput. A solution envisioned for next-generation systems is to use the Q/V-band in the uplink. This approach has the advantage to increase the available uplink bandwidth per feeder link and to free up the full Ka-band spectrum for the user links [7]. Moreover, aggressive frequency reuse schemes combined with gateway and/or space-based processing for inter-beam interference mitigation have been extensively investigated due to the expected throughput gains compared to the classical multi-color concept (e.g. four color scheme) [8]. All these technological advances can benefit from on-board processing to guarantee an optimal use of the available resources and, hence, minimize the cost-per-bit. However, the ever-growing demand for higher data rates in the 5G context necessitates further innovations. Therefore, we present a novel approach whose full potential can be exploited with modern payloads. It is known as the multiple-input-multiple-output (MIMO) line-of-sight (LOS) approach. It should not be mistaken with other MIMO schemes which have already been intensively researched [9]. Here, the proposed MIMO strategy takes advantage of the phase information of LOS links between ground stations and a satellite equipped with multiple reflector antennas. The scheme can be envisioned in both the feeder links and the multi-user downlink. While the approach is exploited in the feeder link to optimize the ground segment design and obtain significant diversity gains against rain fading, the multi-user downlink basically addresses a resource allocation problem to maximize the system throughput.

In Section II, the basic principle of MIMO LOS is presented, and a system model including a pre- and a post-processing of the data streams is provided. The application scenarios for MIMO LOS in the context of VHTS systems are then discussed in Section III. Section IV concludes this paper.

II. SPATIAL MULTIPLEXING MIMO

MIMO LOS for satellite communications has first been proposed in [10]. Up to now, theoretical investigations have emphasized the fundamental design trade-offs of such systems, and channel measurements have confirmed the expected MIMO gains. The reader is referred to [11] and the references
H MIMO channel

Carrier to noise ratio (CNR) per path 20 dB

Transmitter x Center of the Earth antenna array Luxembourg City (49.61° N, 6.13° E)

Orientation of the arrays East-West direction

Carrier frequency 20 dB

TABLE I

EXAMPLE OF A 2 × 2 MIMO SYSTEM DESIGN

<table>
<thead>
<tr>
<th>Satellite orbital position</th>
<th>9° E</th>
</tr>
</thead>
<tbody>
<tr>
<td>Satellite antenna separation</td>
<td>3 m</td>
</tr>
<tr>
<td>Center of the Earth antenna array</td>
<td>Luxembourg City (49.61° N, 6.13° E)</td>
</tr>
<tr>
<td>Orientation of the arrays</td>
<td>East-West direction</td>
</tr>
<tr>
<td>Carrier frequency</td>
<td>20 GHz</td>
</tr>
<tr>
<td>Carrier to noise ratio (CNR) per path</td>
<td>20 dB</td>
</tr>
<tr>
<td>Min. Earth antenna separation for maximum capacity</td>
<td>96 km</td>
</tr>
<tr>
<td>Tolerance region for a capacity loss ≤ 5 %</td>
<td>±42.8 km ±28.5 km ±21.4 km ±17 km</td>
</tr>
</tbody>
</table>

A. Principle of MIMO LOS

Let’s consider a MIMO geostationary satellite link with \( M \geq 2 \) transmit and \( N \geq 2 \) receive reflector antennas as illustrated in Fig 1 for an exemplary system with two antennas at both link ends. The resulting channel can be modeled as:

\[
\mathbf{H} = \begin{bmatrix}
    h_{11} & \cdots & h_{1M} \\
    \vdots & \ddots & \vdots \\
    h_{N1} & \cdots & h_{NM}
\end{bmatrix} \in \mathbb{C}^{N \times M},
\]

with \( h_{nm} \) the channel coefficient for the propagation path from the \( m \)-th transmit antenna to the \( n \)-th receive antenna. This coefficient is given by:

\[
h_{nm} = a g_{nm} \alpha_{nm} e^{j\theta_{nm}} e^{-j\frac{2\pi f_c r_{nm}}{c_0}},
\]

where \( a \) is the free-space propagation loss which can be assumed to be equal for all paths. The gains of the transmit and receive antennas are included in \( g_{nm} \) whereas \( \alpha_{nm} \) models the attenuation induced by the troposphere (clouds, rain,...). The phase \( \theta_{nm} \) stands for the phase impairment due to refraction in the atmosphere. The last term in (2) represents the phase rotation of the pure LOS link between the \( m \)-th transmit and the \( n \)-th receive antenna which are separated by the distance \( r_{nm} \). This latter phase rotation depends on the carrier frequency \( f_c \). Finally, the speed of light in free space is denoted by \( c_0 \). Based on the model from (2), a condition on the transmit and receive antenna positioning can be formulated [11] to obtain a maximum-capacity MIMO channel. However, in a practical system, this condition does not have to be exactly fulfilled to guarantee a sufficiently high capacity. Some deviation from the optimal arrangement can indeed be accepted without entailing a significant degradation. To illustrate this, an example for the design of a \( 2 \times 2 \) MIMO system with a single satellite equipped with two antennas is provided in Table I for different carrier frequencies \( f_c \). A separation of at least several tens of kilometers between the ground stations is required in this case to obtain a maximum-capacity MIMO channel. However, in current satellite communication systems, the deployment of ground stations with tens of kilometers separation is for example common to obtain diversity gains and improve the robustness against rain attenuation in higher frequency bands (Ka- and Q/V-bands) [12]. With MIMO, these ground stations would be simultaneously activated to perform spatial multiplexing. In the following subsection, MIMO processing strategies are now addressed.

B. Transmission Chain with Pre- and/or Post-processing

If \( \mathbf{x} \in \mathbb{C}^{K \times 1} \) is a vector of \( K \) symbols to be transmitted through the channel \( \mathbf{H} \) in a given time slot, the corresponding vector of receive symbols \( \mathbf{y} \in \mathbb{C}^{K \times 1} \) can be expressed as:

\[
\mathbf{y} = \mathbf{W}^\dagger \mathbf{H} \mathbf{B} \mathbf{x} + \mathbf{W}^\dagger \mathbf{n}.
\]

The vector \( \mathbf{n} \in \mathbb{C}^{M \times 1} \) contains realizations of an additive white Gaussian noise process and is such that \( E[\mathbf{n}\mathbf{n}^H] = 2\sigma_n^2 \mathbf{I}_N \). The matrices \( \mathbf{W} \in \mathbb{C}^{N \times K} \) and \( \mathbf{B} \in \mathbb{C}^{M \times K} \) are post-processing and pre-processing matrices, respectively. The considered transmission chain is represented in Fig. 2. The maximum transmit power \( P \) per antenna should not be exceeded such that the diagonal elements of \( \mathbf{BB}^H \) must fulfill the condition:

\[
[\mathbf{BB}^H]_{mm} \leq P, \quad 1 \leq m \leq M.
\]

According to the application scenario, either the post-processing or the pre-processing can be performed on-board the satellite. In Section III, transmission chains with only pre-processing or with a joint pre- and post-processing will be assumed. If no post-processing is performed, the matrix \( \mathbf{W} \) is simply an identity matrix. Obviously, MIMO processing can only be realized if cooperation between the antennas is ensured. For example, such a cooperation cannot be guaranteed at the receiver side in the multibeam downlink of a VHTS. Here, the receive reflector antennas indeed belong to different
users, and the MIMO processing is only feasible at the transmitter i.e., the satellite. In the sequel, it is assumed that $K = N \leq M$, and the well-known zero-forcing (ZF) criterion is used to optimize the matrices $B$ and $W$. The benefits of pre- and/or post-processing for advanced MIMO-ready VHTS systems with flexible on-board processors are now going to be addressed.

III. APPLICATIONS IN THE CONTEXT OF VERY HIGH THROUGHPUT SATELLITES

In this section, the potential of on-board processors to fully exploit the advantages of the MIMO approach is discussed. In particular, the ability of this technology to pave the way to a fulfillment of 5G requirements in terms of availability and data rate is emphasized. To this end, two application scenarios are considered: MIMO feeder links (Application 1 in Fig. 3a) and multiuser multiple-input-multiple-output (MU-MIMO) downlinks (Application 2 in Fig. 3b).

A. Application 1: Feeder Links

1) Motivations and principle: As already mentioned in the introduction, the design of feeder links for VHTS systems is a challenging task. Because of the large aggregate bandwidth that must be supported (hundreds of gigahertz), tens of spatially separated links are required even if the Q/V-band is used. The search for gateway deployment sites is thus difficult as several constraints must be considered. These constraints include especially the need to avoid deployment regions where rain fades regularly occur and to reduce the costs of the backbone network infrastructure (length of peering links, distance to the internet service provider point of presence) [13]. On the other hand, the angular separation between the links must be sufficient to limit the inter-link interference. Thus, in state-of-the-art architectures, each active ground station is separated by several hundreds of kilometers. To address these challenges, MIMO feeder links are proposed. With this innovative solution, gateway antennas are paired to form clusters of two time- and phase-synchronized antennas which are only a few tens of kilometers apart. Instead of having $L$ active ground stations separated by hundreds of kilometers each, $L/2$ antenna arrays are now obtained. This simplifies the backbone network and the search for deployment regions with favorable weather conditions. In each array, a central processing unit is necessary to control the synchronization of the antennas and perform a pre-processing of the transmit data. On the satellite, an array of two multifeed reflector antennas placed a few meters away illuminates the gateway deployment sites as shown in Fig. 3a. In this way, MIMO spatial multiplexing is feasible.

2) Hardware requirements: To provide a given sum throughput, MIMO feeder links necessitate the same number of ground antennas and of receive RF chains (feeds, filter, LNAs, etc...) than current systems. The hardware resources are simply reorganized to form transmit and receive arrays. On Earth, the cooperation between the two antennas of an array can be realized using the radio-over-fiber technology [14]. Here, we concentrate more specifically on the receive part of the link displayed in Fig. 4. The frequency downconversion in the two receive paths is driven by the same local oscillator (LO). An optical LO distribution and frequency mixing can be used for this purpose [15]. After the frequency conversion, the receive signal, which occupies the available uplink frequency band (e.g. 4 GHz of bandwidth in 42.5 GHz to 43.5 GHz and 47.2 GHz to 50.2 GHz), is split into frequency channels whose bandwidth complies with the sampling rate of the analog-to-digital converters (ADCs). The digitized signals are then delivered to the on-board processor where MIMO post-processing can be done. For each frequency channel, the signal after the MIMO post-processing is expressed as in (3). The
vector of receive uplink symbols can be further processed before the data is forwarded to the downlink. However, in this example, the specific strategy adopted for the downlink transmission is not of interest.

3) Signal processing: For a joint pre- and post-processing approach, the considered optimization problem is:

$$\max_{B, W} \min_k \frac{1}{2\sigma^2_k} \left\| w_k \right\|^2_2$$

subject to:

$$BB^H \leq P \cdot I_2$$

$$W^H HB = I_2.$$ (5)

It corresponds to a maximization of the minimum effective carrier to noise ratio (CNR) under a ZF constraint. The power constraint in (5) is equivalent to saying that $BB^H - P \cdot I_2$ is a positive semi-definite matrix [16]. It enables to limit the diagonal elements of $BB^H$ as expected from the condition in (4). A solution to (5) is [17]:

$$B = \sqrt{P} \cdot V \Omega, \quad W^H = (HB)^{-1},$$ (6)

with $V \in \mathbb{C}^{2 \times 2}$ the matrix of eigenvectors of $H^H H$ and $\Omega \in \mathbb{C}^{2 \times 2}$ the unitary DFT matrix. With (6), the effective CNR values are identical for all data streams. We note that the channel state information (CSI), i.e. the matrix $H$, is required to determine $B$ and $W$. A possible approach is to acquire an estimation of the channel $H$ and compute both $B$ and $W$ in the central processing unit of the antenna array. The on-board processing matrix $W$ can then be transferred to the satellite through a high-speed configuration link [18].

In the following, the interest of a joint pre- and post-processing is going to be emphasized. To this end, a solution with only pre-processing is also considered. $B$ corresponds in this case to the normalized inverse of $H$ such that:

$$B = \frac{P}{\max_m \left[ H^{-1} (H^{-1})^H \right]_{mm}} \cdot H^{-1}.$$ (7)

4) Numerical results: The effective CNR achieved in a MIMO feeder link for a gateway array located in the region of Munich, Germany, and oriented in the East-West direction is here studied. The satellite is positioned at 9° E, and its antenna array is also aligned with the East-West axis. Moreover, the link budget from Table II is considered. If a state-of-the-art feeder link with one ground station and one receive antenna per link is used, the assumed link budget would lead to an uplink CNR of 23 dB in clear-sky conditions. Finally, the antenna geometry is such that signal paths originating from a gateway antenna experience identical weather impairments. Based on the model from (2), it implies that $\alpha_{1m} = \alpha_{2m} = \alpha_m, m = 1, 2$. In the following, the signal power attenuations due to the troposphere are expressed in dB as $A_m = -20 \log_{10} \left( \alpha_m \right)$.

In Fig. 5, the CNR achieved with only pre-processing and with a joint pre- and post processing is shown as a function of the distance between the two gateway antennas for the carrier frequencies $f_c = 43$ GHz and $f_c = 50$ GHz. Several tropospheric attenuations have been used at the first and the second transmit antenna in order to analyze their impact on the system performance. In all configurations, the highest CNR value is observed for an antenna separation of approximately 45 km at $f_c = 43$ GHz and 38 km at $f_c = 50$ GHz. This is in agreement with the analytical solution for the antenna spacing optimization from [11]. In clear-sky conditions, this
maximum value reaches 26 dB which is 3 dB higher than for a state-of-the-art link. This gain is obviously due to the use of two transmit antennas per link instead of one\(^1\). Even though the CNR is dependent on the carrier frequency and the inter-antenna distance, the system can still be optimized to guarantee a high CNR at both frequencies. An inter-antenna separation between 35 km and 46 km allows for example to operate the feeder link at these frequencies without entailing a loss higher than 0.5 dB with respect to the maximum value. When \(A_1 = A_2\), an approach with only pre-processing achieves the same CNR than the more advanced scheme with pre- and post-processing. However, the superiority of the joint pre- and post-processing approach becomes apparent as soon as one of the gateway antennas experiences a stronger atmospheric attenuation than the other. In the case \(A_1 = 2\) dB, \(A_2 = 5\) dB and \(A_1 = 2\) dB, \(A_2 = 10\) dB, the CNR loss with only pre-processing is equal to the strongest attenuation i.e., 5 dB and 10 dB, respectively. On the other hand, pre- and post processing enables to reduce these losses to 3.75 dB and 7.63 dB. The poorer performance of the approach without post-processing is a consequence of an inefficient use of the transmit power. When the gateway antennas experience different tropospheric attenuations, the latter strategy indeed reduces the power radiated from the antenna with the most favorable weather conditions. This is not the case with a joint pre- and post-processing where the available power can always be fully exploited. Obviously, flexible payloads will play a key role for an effective use of MIMO feeder links in frequency bands (Ka- and Q/V-band) where weather conditions (mostly rain) significantly influence the link availability. In the 5G requirements for a system with satellite access, service availabilities of at least 99.99 % shall be supported [19].

B. Application 2: User links

1) Motivations and principle: In order to optimize the exploitation of the limited downlink spectrum in VHTS systems, aggressive frequency reuse schemes, where neighboring beams have access to the complete bandwidth, are considered. Meanwhile, the interbeam interference becomes non-negligible, especially for users positioned at the beam edges. User scheduling and signal pre-processing are thus necessary to cope with this impairment. To this end, the channel between all the transmit feeds and a given user is modeled as a vector. Users with quasi-orthogonal channel vectors are scheduled in the same time slot, and a full-rank MIMO channel is obtained. Using the channel state information, a pre-processing matrix is then designed. Mitigation techniques that have been proposed so far in the literature consider, however, that the user beams are generated by a unique multifeed reflector antenna [20]. In this case, the LOS components of the channel vector entries can be assumed to have the same phase. As illustrated in Fig. 3b, typical satellite payloads (e.g. Ka-Sat, SES-17, …) are nevertheless equipped with multiple reflectors. Very large multifeed assemblies able to generate all the user beams (> 100) from a single reflector are indeed not feasible in practice. Since the transmit reflectors are generally separated by several meters, the identical phase assumption is not accurate anymore. Signals originating from separate reflectors experience different phase rotations after their LOS propagation. In [21], these phase differences have been exploited to design a new user scheduling algorithm. Its objective is to construct MIMO channels with a quasi-optimal antenna arrangement based on an appropriate selection of the users. This represents a fundamental difference with state-of-the-art scheduling algorithms where user orthogonality is only based on the inequal power levels received from the different feeds. Thanks to the multiple reflector architecture, all the power received by a user can be exploited constructively using spatial multiplexing. Such a solution can be seen as a beam-free architecture since the multibeam pattern is resolved and reduced to nothing more than a shaping of the power flux density on Earth. In the following, the payload design and the MIMO pre-processing needed to take full advantage of the MIMO LOS approach in the user links are discussed.

2) Payload architecture: In Fig. 6, the downlink part of the payload architecture required to perform on-board MIMO

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\(^1\) However, we recall that, at a system level, the total number of ground antennas required to reach a given sum throughput with a set of MIMO feeder links is the same than for state-of-the-art links.
pre-processing is shown. Similarly to the payload design in Fig. 4, the optical distribution of a common LO to the frequency converters is used to ensure the phase coherence of the different paths. Whereas the signals could be pre-processed on ground in the gateway, the resort to on-board processing has several advantages:

- The degradation of the pre-processed signals due to imperfections (e.g. noise) in the uplink channel is avoided.
- The problem of outdated channel state information is less critical. Here, users send an estimation of their channel vector to the satellite which then determines the pre-processing matrix. The delay between the channel estimation and its exploitation is significantly reduced compared to a scheme where the channel knowledge has first to be provided to the gateway.
- Some 5G edge computing use cases consider the possibility to deliver commonly accessed content (e.g. TV series, news reports,...) directly from the satellite which acts as an edge server. In this case, the MIMO pre-processing can only be performed where the data streams are generated, i.e. in the satellite.

3) Signal processing: If the transmission chain model from (3) is considered, \( x \) corresponds to a vector of \( K \) user symbols scheduled in the same time-frequency slot. Because users do not cooperate, \( W \) is obviously an identity matrix, and the ZF criterion can only be met using the pre-processing matrix \( B \).

The optimization problem for a maximization of the minimum effective CNR is given by [21]:

\[
\begin{align*}
\max_{B, \{\mu_k\}_{k=1}^K} & \quad \min_k \frac{\mu_k}{2\sigma^2} \\
\text{s.t.} & \quad [BB^H]_{mm} \leq P, \quad 1 \leq m \leq M \\
& \quad HB = \text{diag} \{\sqrt{\mu_1}, \ldots, \sqrt{\mu_K}\}.
\end{align*}
\]

If \( N = M \), the solution is the normalized inverse of \( H \). On the other hand, no closed-form solution exists if \( N < M \).

However, convex optimization tools [22] can be used.

4) Numerical results: An exemplary system with four reflectors each creating a different beam is considered. The reflectors are arranged as a uniform circular array (UCA) with a diameter of 3 m, and the satellite payload is positioned on the geostationary orbit at 9° E. For the sake of comparison, two different frequency re-use schemes are studied:

- Four color scheme (FR4): The downlink frequency band is split between the four different beams to avoid inter-beam interference.
- Full frequency reuse (FFR): The complete downlink frequency spectrum is re-used in each beam.

The link budget for both scenarios is provided in Table III. The CNR at the beam center corresponds here to the ratio between the maximum power received on Earth from a given reflector to the noise power. The same antenna radiation pattern than in [11] is used, and the beam coverage is shown in Fig. 7. Four users within the multibeam coverage are selected by the scheduling algorithm to ensure that a close-to-optimal MIMO LOS channel can be built in the case of a FFR scheme. In this specific example, a \( 4 \times 4 \) MIMO channel matrix \( H \) is obtained. The achievable per-user data rates (Shannon limit) are shown in Table IV. To emphasize the importance of the

<table>
<thead>
<tr>
<th></th>
<th>Full frequency reuse</th>
<th>Four color scheme</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier frequency</td>
<td>20 GHz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Bandwidth per carrier</td>
<td>40 MHz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Maximum Tx power per antenna and carrier</td>
<td>1 W</td>
<td></td>
</tr>
<tr>
<td>Tx antenna diameter</td>
<td>1.7 m</td>
<td></td>
</tr>
<tr>
<td>Tx antenna efficiency</td>
<td>70 %</td>
<td></td>
</tr>
<tr>
<td>Weather conditions</td>
<td>Clear-sky</td>
<td></td>
</tr>
<tr>
<td>User terminal G/T</td>
<td>17 dB/K</td>
<td>16 dB/K</td>
</tr>
<tr>
<td>CNR at beam center</td>
<td>10 dB</td>
<td>16 dB</td>
</tr>
</tbody>
</table>
phase information for the pre-processing matrix design with FFR, the data rate is also shown when this information is ignored. The results clearly point out that, in the considered scenario, the proposed MU-MIMO downlink increases the achievable data rates by a factor of at least 2.5 compared to the state-of-the-art four color scheme. In light of the high downlink data rates required for 5G satellite user equipments [19], this approach enables to make VHTS systems 5G ready.

IV. CONCLUSION

The benefits of MIMO LOS in the context of VHTS systems with advanced digital processors have been discussed. Applications for the feeder links and the user links have been presented, and possible payload architectures based on existing technologies have been introduced. The proposed solution especially enables to address the uplink/downlink bandwidth congestion which is a major bottleneck in the design of integrated 5G satellite-terrestrial networks. Illustrative examples have shown how the MIMO LOS technology paves the way to a fulfillment of 5G availability and data rate requirements with satellite links.

Future research efforts will focus on an in-depth analysis of the impact of channel estimation errors on the proposed schemes. Meanwhile, preliminary investigations did not reveal significant performance loss due to such imperfections. Moreover, over-the-air tests have already been conducted to verify the feasibility of MIMO LOS for VHTS systems. Further demonstrations are planned for the near future to validate the specific use cases discussed in this work.

REFERENCES


TABLE IV

| User data rates (Shannon limit) for three different downlink transmission strategies |
|-----------------------------------|-----|-----|-----|-----|
| Four color scheme                 | 52.3 Mbit/s | 50.2 Mbit/s | 53.1 Mbit/s | 45.4 Mbit/s |
| FFR/phase information             | 132.8 Mbit/s |
| FFR/no phase information          | 26.6 Mbit/s |

Fig. 7. 3 dB beam contours and user positions