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THROUGHPUT EVALUATION OF THE MILLIMETER-WAVE 5G COMMUNICATION SYSTEMS

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Abstract. The new, millimeter-wave (mmWave) Wi-Fi standard IEEE 802.11ay considers various indoor and outdoor scenarios, including multiple users access and backhauling with a range up to several hundred meters. Moreover, the 5G wireless communication systems are expected to adopt a heterogeneous network (HetNet) architecture, where small mmWave cells overlap a conventional macro cells network. The new applications require large antenna arrays and multi-stream transmission (MU-MIMO) with new beamforming algorithms, aimed not only at the single link quality maximization, but also at the optimization of the throughput in the whole deployment. In this paper, we evaluate the throughput of the mmWave communication systems for the main scenarios of their deployment. A comparative analysis of the different large antenna array techniques is carried out in application to MU-MIMO transmission at the small cells base station (BS) or Wi-Fi access points. The joint beamforming and scheduling algorithms utilizing the introduced antenna array architectures at the BS were developed. Finally, performance evaluation and comprehensive comparative analysis of the considered antenna array techniques are done using system level simulations for three deployment scenarios ("open space", "alleyway" and "hotel lobby") defined in the adopted millimeter-wave Wi-Fi standard IEEE 802.11ay. The proposed large antenna array architectures and the developed joint beamforming and scheduling algorithms for MU-MIMO transmission may find practical applications in millimeter wave Wi-Fi and 5G NR wireless communication systems.

Keywords: 5G, IEEE 802.11ay, mmWave, communication systems, hybrid beamforming, antenna arrays

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ОЦЕНКА ПРОПУСКНОЙ СПОСОБНОСТИ СИСТЕМ СВЯЗИ МИЛЛИМЕТРОВОГО ДИАПАЗОНА ДЛИН ВОЛН ПЯТОГО ПОКОЛЕНИЯ

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Аннотация. Новый стандарт Wi-Fi миллиметрового диапазона IEEE 802.11ay предполагается применять для высокоскоростной передачи данных как внутри, так и вне помещений, включая связь пользователей с точками доступа (малыми базовыми станциями) и радиорелейную связь между базовыми станциями с дальностью действия до нескольких сотен метров. Кроме того, ожидается, что системы сотовой связи 5G будут использовать гетерогенную архитектуру, в которой малые соты (радиусом порядка 50 м) обслуживают пользователей в миллиметровом диапазоне длин волн и перекрываются с обычными большими макросотами, работающими в диапазоне ниже 6 ГГц. Новые приложения систем связи миллиметрового диапазона длин волн требуют использования антенных решеток с большим числом элементов и многопотоковой передачи данных с алгоритмами формирования диаграмм направленности, нацеленными не только на максимизацию качества отдельной линии связи, но и на оптимизацию пропускной способности в целом во всей области развертывания. В статье дана оценка пропускных способностей систем связи миллиметрового диапазона для основных сценариев их развертывания, предусмотренных стандартом IEEE 802.11ay («открытое пространство», «узкая улица», «лобби отеля»). Проведен сравнительный анализ эффективности использования на базовых станциях (точках доступа) различных техник выполнения больших антенных решеток для реализации одновременной многопотоковой передачи данных многим пользователям. Разработаны совместные алгоритмы формирования диаграмм направленности и планирования передачи данных многим пользователям. Для оценки эффективности различных архитектур антенн использовано моделирование на системном уровне. Предположено, что базовая станция малой соты использует технологию радиосвязи с параметрами физического уровня, аналогичными стандарту IEEE 802.11ay. Предлагаемые архитектуры антенных решеток и разработанные алгоритмы могут найти практическое применение в системах связи миллиметрового диапазона Wi-Fi и 5G NR.

Ключевые слова: 5G, IEEE 802.11ay, миллиметровый диапазон, системы связи, гибридное формирование луча, антенные решетки

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Introduction

The rapid progress of millimeter wave technologies over the past fifteen years has enabled the development and mass production of low-cost Radio Frequency Integrated Circuits (RFIC) together with digital signal processing (baseband) chips [1]. Currently, these technologies are already used for internet access in Wi-Fi systems (IEEE 802.11ad, IEEE 802.11ay standards in the 57–71 GHz band) and they are planned to be widely used in the 5th generation of mobile communication systems (5G). The first phase of 5G New Radio (NR) will address bands below 40 GHz and the following phases will exploit bands up to 100 GHz [2].

The first millimeter-wave Wi-Fi standard IEEE 802.11ad, operating in the 57–64 GHz band, specifies the point-to-point links in the indoor scenarios [3]. In such conditions, the single small-size (about 8–16 elements) phased antenna arrays (PAA) with relatively low gain (about 12–15 dBi) [4] may be used for reliable data transmission up to several tens of meters. In this case, the beamforming algorithms may be limited to the simple sector sweep process, with exhaustive search of the optimal weight vector from the pre-defined codebook.

The new, millimeter-wave Wi-Fi standard IEEE 802.11ay adopted in 2021 year [5] considers various indoor and outdoor scenarios [6, 7], including backhauling and access with ranges up to several hundred meters. Moreover, the 5G wireless communication systems are expected to adopt a heterogeneous network (HetNet) architecture, wherein mmWave small cells are overlaid onto a conventional macro cells network [8].

Other possible deployment scenarios and use cases for mmWave systems are described in [9]. In most considered cases, the antenna gains should be significantly higher than for a usual indoor scenario, and antenna beams should be significantly narrower, which requires new approaches to the beam forming and beam selection [10–12] and new antenna technologies [13, 14]. In addition to the simple point-to-point links, IEEE 802.11ay standard will include point-to-multipoint links. The new applications require new beamforming algorithms, aimed not only to the single link quality maximization, but rather to the optimization of the throughput across the entire deployment. Maximum throughput of the new IEEE 802.11ay standard is considered to be about 100 Gbps [15]. Such challenging performance demands can be met with the help of MU-MIMO mode supporting multiple independent data streams as well as higher channel bandwidth up to 8.64 GHz [15, 16]. The multi-stream transmission is a right way of exploiting the multi-element antenna arrays for system performance improvement.

Due to the great importance of the task of the mmWave 5G communication systems development, a number of papers have been devoted to the investigation of possible approaches to large scale antenna arrays design and their performance characteristics evaluation. A large list of references in this area can be found in the overview papers [11, 12]. Along with deep theoretical investigations [17–19], several practical algorithms have been proposed for multiuser beamforming in mmWave massive MIMO (Multiple-Input-Multiple-Output) systems [20–25]. However, in the most of these papers beamforming algorithms were designed separately without taking into account the important scheduling procedure. Also the channel models used in these works for system performance evaluation did not adequately describe real multipath environment (scenarios) where the system should be deployed.

In this paper we focus on analysis of different large antenna array technologies, which may be used at mmWave small cell base stations (BSs) or Wi-Fi access points (APs). This will allow us to evaluate the mmWave communication system performance characteristics in different deployment scenarios and provide recommendations for practical system architectures.

It is assumed that BSs are equipped with antenna arrays with a large number of antenna elements. Three BS antenna array configurations were chosen as basic for consideration: the Multi-Stream Phased Antenna Array (MS PAA) architecture, which can be fully implemented in the RF part with codebook based analog beamforming only, the Fully Adaptive Array (FAA) configuration, fully implemented in the BB and considered as the most flexible solution with maximal available number of spatial degrees of freedom, and the Modular Antenna Array (MAA) configuration, which realizes a hybrid beamforming processing with coarse RF beamforming and fine BB beamforming [26–29]. To evaluate the performance of each antenna array technology, we will use the system level simulations approach, assuming that small cell BSs exploit the PHY layer technique with PHY layer parameters similar to IEEE 802.11ad and IEEE 802.11ay standards for orthogonal frequency division multiplexing (OFDM) modulations. The mmWave system performance investigation for these three BS antenna array configurations is done for the open area, street canyon and hotel lobby scenarios defined in the IEEE 802.11ay standard [5–7]. Therefore, this investigation will allow us to demonstrate advantages and drawbacks of the considered antenna array technologies in typical mmWave small cells deployment environments and elaborate the recommendations for their practical usage.

Base station architectures for multi-stream transmission

There are different ways for implementing multi-stream transmission/reception based on antenna array architecture.

The simplest solution lies in the division of the whole antenna array with N elements into a number K of smaller subarrays (one subarray per stream), and using these subarrays for independent transmission of K data streams (see Fig. 1*a*). The number of phase shifters in this scheme is equal to the number of the whole antenna array elements N. In reality this approach is equivalent to uniting K independent jointly controlled transmitters at one BS system. This does not introduce any additional complexity into the BB and RF parts in comparison with single stream transmission if no special inter-stream interference cancellation schemes are applied in baseband. However, such solution has one significant drawback: the apertures of the subarrays are K times smaller than the whole antenna array aperture. Therefore, the subarray antenna gains and directivities are reduced accordingly. Because of that drawback, we will not further study the multi-stream transmission with aperture division in this paper.

To avoid the aperture degradation, three multi-stream transmission antenna array schemes will be considered.

The first scheme is Multi-Stream Phased Antenna Array (MS PAA) BS architecture (see Fig. 1*b*). In this scheme, the whole phased antenna array aperture is used for transmission of each data stream, at the cost of increasing the number of phase shifters and RF end circuits' complexity. The number of phase shifters in this scheme is equal to the number of the antenna array elements N multiplied by the number of streams K. It can be seen that this BS antenna array architecture may be fully implemented in the RF part with analog beamforming only.

The second scheme is the Fully Adaptive Array (FAA) architecture with the number of RF chains equal to the number of antenna array elements N. Obviously this is the most flexible solution, because it may provide digital beamforming in the BB with maximal available number of spatial degrees of freedom N. The block diagram of the FAA for single carrier transmission is shown in Fig. 1*c*. It is realized by KxN complex multiplications (weighting) of the modulated and coded data stream signals. In this sense the FAA solution is optimal for MU-MIMO processing of K independent streams, and allows application of all existing MIMO processing techniques, like TX Maximum Ratio Transmission (MRT), RX Maximum Ratio Combining (MRC), TX and RX zero-forcing (ZF), and RX Minimal Mean Square Error (MMSE) reception [30]. However, for practical applications, especially for highly-directional steerable antenna arrays with a very large number of elements, having the same number of RF chains may be prohibitively complex and cost expensive.

To reduce the complexity of the BS antenna system and to retain both BB processing advantages and very high antenna gains, the Hybrid Beamforming technique [31] was proposed on the base of the Modular Antenna Arrays (MAA scheme), which consists of M subarray modules and RF chains (see Fig. 1*d*). The hybrid beamforming processing incudes coarse beamforming performed in the RF part by the controlled phase shifters (built-in in the subarray modules, each module comprises L antenna elements) and fine beamforming performed in the BB by applying a set of the complex weights to each RF branch of the modulated and coded data stream signals. Such MAA scheme allows benefiting from the BB processing having a relatively small number M of the RF chains – one per each subarray module. At the same time, this scheme has less adaptation possibilities in comparison with the FAA (only M digital degrees of free-

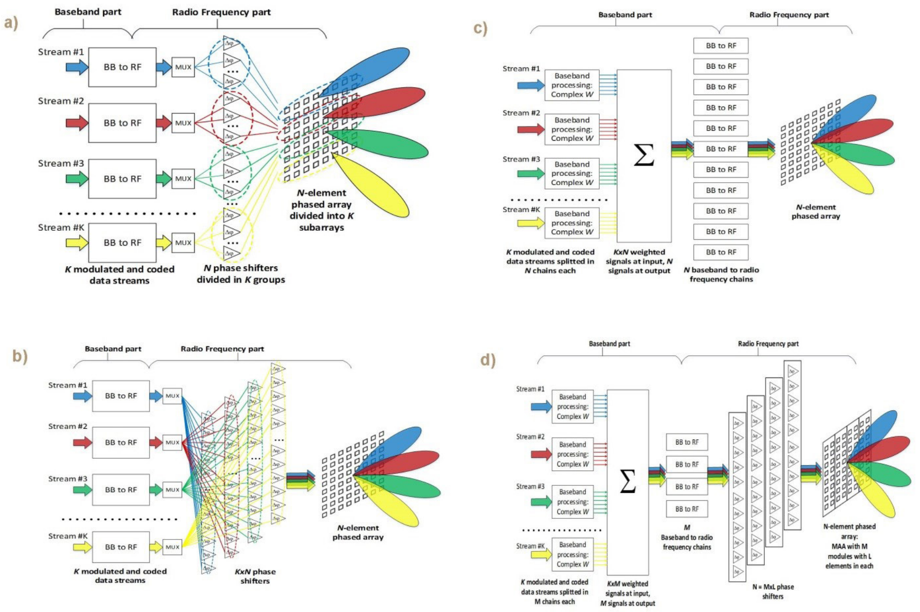

Fig. 1. *a* – Aperture division multi-stream transmission;
b – Multi-stream phased antenna array (MS PAA) scheme; *c* – Fully adaptive array (FAA) scheme;
d – Hybrid beamforming technique for MAA scheme

dom versus N degrees in the FAA, $M = N/L$). Therefore, the MAA may also be referred to as the partially adaptive array.

MU-MIMO – joint beamforming and scheduling algorithms at the BS

In practical implementation of multi-user transmission in MU-MIMO mode, the beamforming task is inseparable from the scheduling procedure. Indeed, for some environments groups of simultaneously scheduled users determine the beam directions and required inter-stream interference cancellation processing. And vice versa, the beamforming determines potential user data rates and, finally, the throughput metrics that the scheduler should take into account for transmission assignments. Thus, a joint beamforming and scheduling algorithm for simultaneous transmission to several users should be applied at the BS [26–28].

In this paper, we use a joint BF and scheduling algorithm [28] that dynamically solves the problem of maximizing the total throughput at the BS with an antenna array for DL MU-MIMO transmission. This algorithm will assign the available space-time-frequency communication system resources to several users based on some pre-defined criterion (metrics) calculated for each user. The widely used criterion is based on the proportional fair (PF) metric. For each DL packet transmission act, the PF scheduling algorithm assigns available space-time-frequency resources for transmission of K independent modulated and coded data streams to K different users (see Fig. 1). At the same time, preference in service is given to a group of K users demonstrating for the current state of the channel the maximum value of the PF metric, which is the sum of K available individual user throughputs, each normalized by the amount of data already received by the particular user. The optimal number of users and individual users involved in the given group may be determined "step-by-step" as describe below.

The most suitable for practical implementation of the PF scheduling is the so called greedy scheduling algorithm. It is an iterative algorithm which makes the "best choice" at each step for including a new user in the group of users for simultaneous transmission. At each iteration step of the MU-MIMO greedy scheduling one user is picked up considering the maximization of the total group PF metric. The user selection

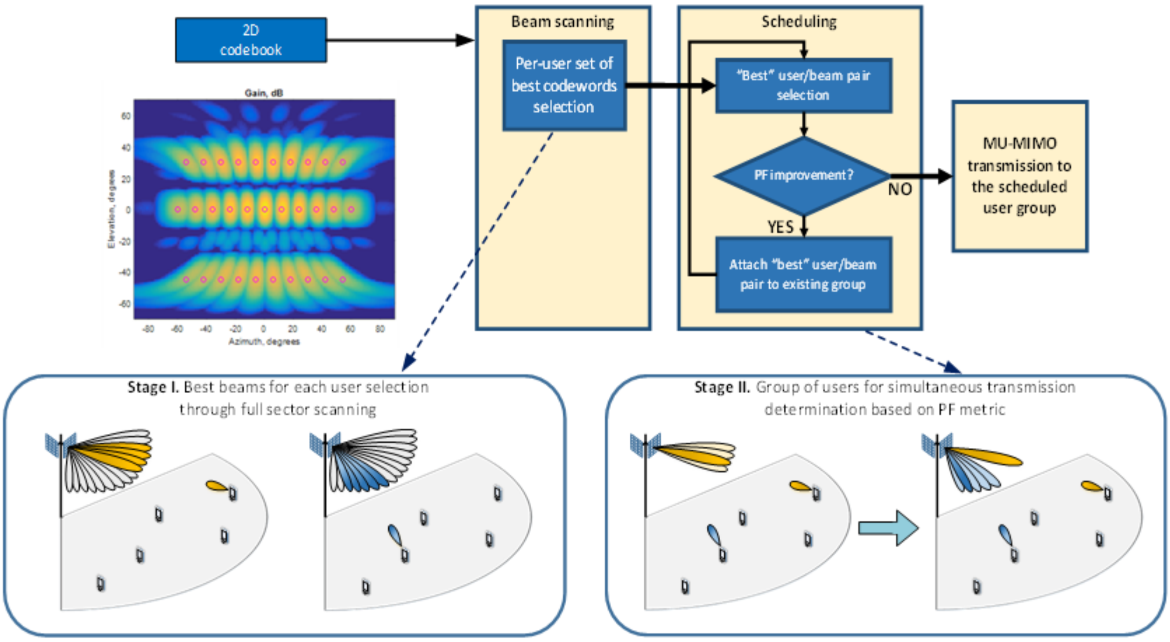

Fig. 2. Codebook-based joint beamforming and scheduling algorithm for MS PAA scheme

on each iteration should take into account available throughputs of all already chosen users, recalculating their SINRs and therefore their modulation and coding schemes (MCSs) and throughputs, considering possible new inter-stream interference and transmit power splitting, and afterwards recalculating their PF metrics. The iterative process stops when addition of any further new user reduces the total group PF metric [28].

However, it should be noted that making the "best choice" at each step of the PF greedy scheduling algorithm does not necessarily produce a global optimal solution to the overall maximization problem. However, in many instances it is rather close to the optimal one, which may be found by an exhaustive searching algorithm that has exponential complexity.

Codebook-based analog MU-MIMO beamforming for multi-stream phased antenna array. In this assumption, the BS is equipped with a multi-stream phased antenna array (MS PAA) with a number of possible beams (or partial antenna patterns) defined in the codebook. For example, a 2D DFT codebook can be used for RF beamforming both in elevation and azimuthal plane. The codebook-based MU-MIMO beamforming flowchart with the illustration of per-user codebook construction and PF greedy scheduling procedure is shown in Fig. 2.

At the first stage of the beam scanning procedure, each user will store and feedback to BS several indexes of the best beams with maximum received signal power, for creating a set of "perspective" codewords for each user. Then, at the second stage of the PF greedy scheduling procedure, both the best user and its beam most suitable for MU pairing are chosen at each step. Once the new user with the certain beam (codeword) was selected for including in the group of users for simultaneous transmission at any step of greedy scheduling, it will not change that beam at the subsequent steps.

Baseband digital MU-MIMO beamforming techniques. In a rich scattering environment, the full advantages of the massive MIMO system can be exploited using such beamforming strategies as maximum ratio transmission (MRT) or zero-forcing (ZF).

In case of the user equipment (UE) with one antenna element, the MRT algorithm uses the measured channel matrices to calculate the first eigenvector for establishing beamforming (a partial antenna pattern) for each user separately. Then the PF greedy scheduler tries to find a suitable MU group of users without *a*) FAA *b*) MAA

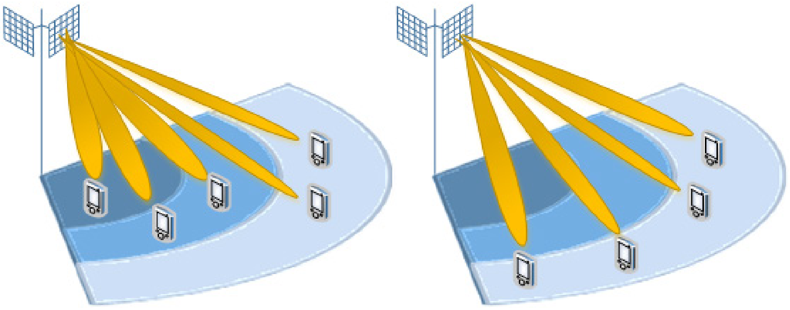

Fig. 3. MU-MIMO for FAA case (*a*) and MAA case (*b*)

any additional TX beamforming adjustment. Therefore, using the MRT algorithm for TX antenna array beamforming does not allow combining the users located a shot distance away from each other in one MU group for simultaneous data transmission. For example, in case of the one-path line-of-sight (LOS) channel, these users should be at an angular distance from each other at least 3-4 times greater than the half power beam width (HPBW) of the BS antenna array pattern to successfully avoid inter-stream interference.

The purpose of ZF technique is to suppress the mutual MU inter-stream interference arising due to simultaneous multiuser data transmissions, by modifying the initial MRT beamforming vectors using the inverse covariance interference matrix with regularization by the minimal mean square error (MMSE) algorithm [28]. Physically, this beamforming modification will lead to establishing near to zero values of one UE partial antenna pattern in the directions of main beams of all other UEs included in the same MU-MIMO group for simultaneous data transmission. It is obvious that using a more complex ZF beamforming algorithm allows simultaneously transmitting data to users located more densely in space. For example, in case of the LOS channel, these users may be located at an angular distance of about one HPBW.

There are huge beamforming capabilities for the full adaptive antenna array (FAA) because the number of degrees of freedom is equal to the number of antenna elements. Therefore, the FAA may effectively form equivalent beams in any direction and provide better selection of scheduled users from the whole cell (see Fig. 3*a*).

For the MAA with vertical module placement, the array may have limited ability for vertical beamforming to several users and almost full adaptation ability in the horizontal plane. So, in this case, the average direction in the elevation plane is used for all users in the group and per-user directions in the horizontal plane are used for MRT and ZF operations. Thus, in the multi-user mode in the mmWave small cell with such type of MAA, the users for simultaneously scheduled group should be selected from the same "ring" around the BS, with the same elevation angle and distance (see Fig. 3*b*).

One of the significant advantages of digital MU-MIMO beamforming is that the baseband processing of the OFDM (OFDMA) signals allows using frequency selective beamforming for the a more accurate communication system adaptation to the frequency selective millimeter-wave channel. In the following section, a comparison between wideband and per-subcarrier beamforming will also be provided.

mm-WAVE communication system performance analysis

The investigation of mm-Wave 5G communication systems performance was made by direct modeling of physical (PHY) and medium access control (MAC) layers in accordance with the IEEE 802.11ay specification. These also included the multipath channel modeling and usage of the channel state information for near to optimal BS antenna array beamforming and data multi-stream scheduling for MU transmission.

The efficiency of the considered MU-MIMO antenna array technologies and beamforming algorithms was studied on the system level for three scenarios with the growing complexity of environment and channel models exactly defined in the IEEE 802.11ay evaluation methodology documents [32]:

Open area – minimal number of passes (rays). Only one-two quasi-deterministic (Q-D) rays give significant impact (direct LOS and ground reflected rays).

Street canyon – the number of significant rays increases up to four (additional reflections from building walls). Azimuthal diversity of these rays gives significant impact to the channel.

Hotel lobby – the environment causes a big number of significant rays (all rays up to second order wall and ceiling reflections).

The consideration of these scenarios enables a full assessment the capabilities of different MU-MIMO modes. For these scenarios, the Q-D channel models developed in [7] were used. More detailed simulation assumptions are provided in Table 1. The same type of 8x16 elements antenna arrays (8 vertical and 16 horizontal elements size) are used at the BS/AP for all antenna techniques. The MAA consisted of 16 subarrays, each containing 8×1 elements. The basic IEEE 802.11ay PHY layer OFDM mode parameters for channel bandwidth 2.16 GHz were used for simulations. The OFDM is based on a 512-point FFT with 336 active data subcarriers, and 16 fixed pilot tones. The subcarriers at DC and on either side of DC are nulled to avoid any issues with carrier feed-through and the cyclic prefix is fixed at 25 % of the OFDM symbol period.

Table 1

Scenarios for Q-D channel models

Parameters		Assumption
Channel model/Pathloss		Q-D channel model
Carrier / BW		60 GHz / 2 GHz
BS antenna array	Array types	MS PAA / FAA / MAA
	Height	6 m (5.5 m for Hotel lobby scenario)
	Configuration / TX power	8x16 elements / 19 dBm
	Element gain	5 dBi
User antenna	Height	1.5 m
	Gain	Omni, 0 dBi
MU-MIMO Transmission scheme		SVD-based MRT/ZF, 2D-128 DFT codebook-based MRT, 8 spatial streams maximum for any antenna technique
Beamforming granularities		Wideband / Per subcarrier
Channel estimation		Perfect (the overhead is considered)
Scheduling type		Greedy PF MU scheduling

The deployment assumptions for considered scenarios are illustrated in Fig. 4–6. The open area scenario is very close to the "pure" free space LOS environment. The outdoor street canyon scenario represents a more complex millimeter-wave propagation environment. The users are mostly grouped on the relatively narrow sidewalks. So, from the physical point of view, the realization of MU-MIMO transmissions in the street canyon scenario are much more difficult due to the denser UEs deployment and mutual interference between spatial streams produced by reflected rays.

The system level simulation main results for all considered scenarios are summarized in Table 2.

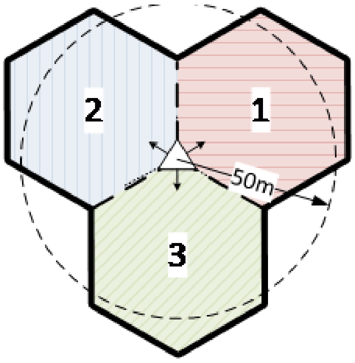

Fig. 4. Open area scenario deployment assumptions

Isolated small cell with three BSs (antenna height 6 m) each serving its own 120° sector and operating in its own channel (frequency reuse-3).

Users are placed randomly (with uniform distribution) within the cell considering 50 users per cell sector.

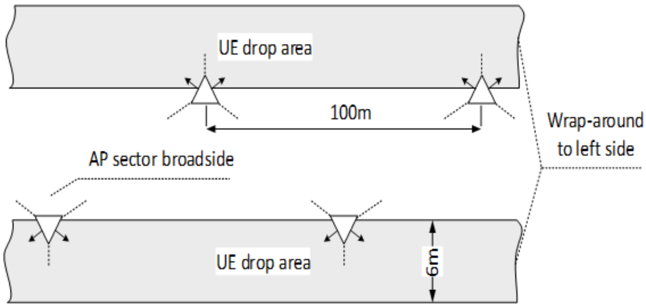

Fig. 5. Street canyon scenario deployment assumptions

Two BSs are mounted at each lamppost serving two sectors (frequency reuse-2) along the sidewalk.

Users are placed randomly (uniform distribution) within the sidewalks considering 45 users per each BS sector.

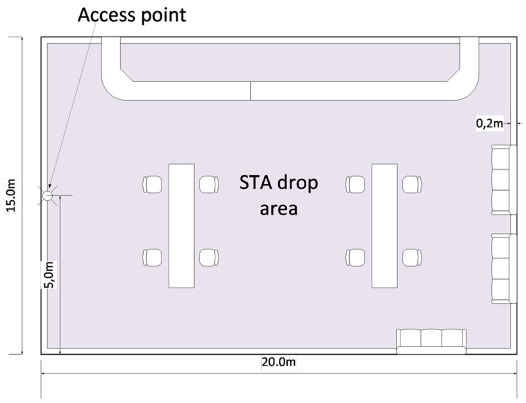

Fig. 6. Hotel lobby scenario deployment assumptions

One BS, mounted at the center of the shortest side, has a single sector, directed to the center of the lobby.

40 users are placed randomly (with uniform distribution) within the lobby area.

Table 2

Simulation results for considered scenarios

BS antenna array model	Beamforming scheme	Beamforming frequency granularity	Open area scenario				Street canyon scenario				Hotel lobby scenario			
			BS throughput, Gbp	Avg user throughput, Mbps	Cell-edge throughput, Mbps	Avg size of MU group	BS throughput, Gbps	Avg user throughput, Mbps	Cell-edge throughput, Mbps	Avg size of MU group	BS throughput, Gbps	Avg user throughput, Mbps	Cell-edge throughput, Mbps	Avg size of MU group
MS PAA	CBB	Wideband	7.2	144	70	3.76	7.8	173	75	2.26	11.5	575	367	3.48
FAA	MRT	Wideband	10.2	205	107	4.78	10.0	222	81	2.52	17.0	848	484	4.46
		Per subcarrier	10.2	205	115	4.64	11.2	249	112	2.66	16.5	826	494	4.54
	ZF	Wideband	11.4	229	110	5.23	12.4	275	81	3.16	29.4	1471	645	7.34
		Per subcarrier	**13.9**	**278**	**131**	**6.03**	**22.3**	**495**	**180**	**6.11**	**41.2**	**2060**	**1201**	**9.66**
MAA	MRT	Wideband	8.8	175	95	4.16	6.0	134	68	1.46	10.0	503	377	2.54
		Per subcarrier	8.7	173	98	4.13	6.5	145	102	1.44	9.8	492	378	2.54
	ZF	Wideband	9.3	186	100	4.44	6.3	139	68	1.56	11.2	559	400	2.88
		Per subcarrier	9.9	198	107	4.71	7.7	171	109	2.08	11.9	597	424	2.98

The table includes main characteristics (metrics) specified in the official mmWave communication system evaluation methodology [32], such as: BS total throughput, average UE throughputs, average size of MU group (average number of UEs grouped for simultaneous transmission) and cell-edge UE throughput (only 5 % of the served UEs may have the throughput below this threshold).

The numbers in the Table 2 are illustrated by histograms shown in Fig. 7, 8, for more convenient representation of the simulation results. For simplicity, only wideband scheduling/beamforming results are presented in the illustrative histograms.

It can be seen from presented simulation results that the ideal FAA antenna predictably demonstrates better performance metrics in comparison with the MAA and MS PAA for all beamforming schemes for all scenarios.

The comparison of the practical schemes such as MS PAA and MAA looks more interesting. In the LOS-dominant scenario of the Open area, the MAA demonstrates 20—30 % better system performance (depending on the applied beamforming technique) for all metrics: BS and UE throughputs, as well as cell-edge throughput and MU aggregation metrics. However, for more complex multipath scenarios, such as

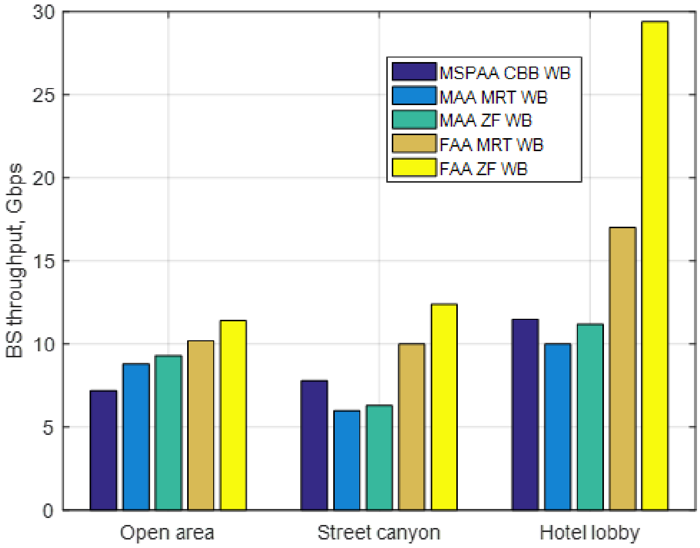

Fig. 7. BS aggregate throughput comparison for different scenarios and techniques

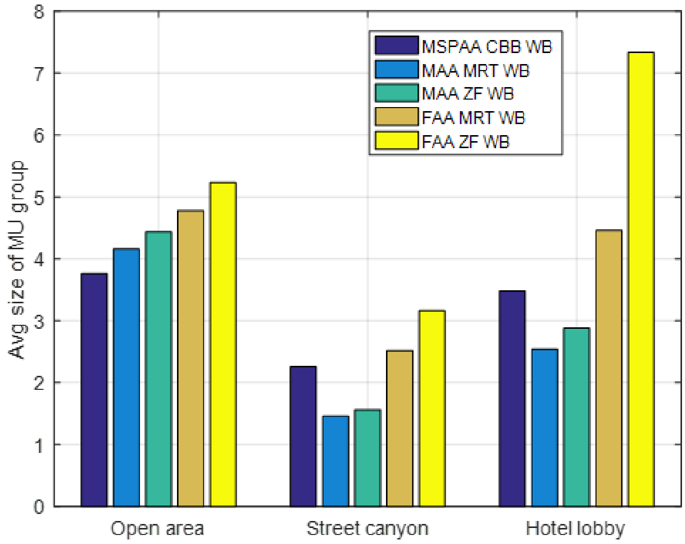

Fig. 8. Average number of UE in MU group comparison for different scenarios and techniques

Street Canyon and Hotel Lobby, the main system performance metrics of analog-based MS PAA scheme and MAA with ZF algorithm looks very similar. The reduction of the MAA system performance in these scenarios can be explained by the fact that MAA can schedule in the same MU group only the UEs that are seen from the BS/AP on nearly the same elevation angle (see Fig. 6), while MS PAA has a freedom to select different beams in azimuth and elevation for the same MU group. In the rich multipath and compact scenarios, the elevation angles may be very different, which gives the MS PAA scheme an upper hand for simultaneous data transmission to a larger number of UEs (see Table 2). So, "the freedom" of the MAA beamforming in the frequency domain is counterpoised by "the freedom" of the MS PAA beamforming in space domain.

The maximum spectral efficiency is provided by the most complex FAA with an SVD-based ZF beamforming scheme and per subcarrier frequency granularity. This scheme allows achieving very high throughputs due to very flexible resource allocations in the space-frequency domain and denser grouping of UEs for simultaneous transmission. There are about 6 users per MU group in average even in the most complex (from the MU grouping point of view) open area and street canyon scenarios, and up to 9 users in the hotel lobby scenario with maximum total BS throughput 41 Gbps.

From the general point of view it is clear that such behavior of the considered MU-MIMO schemes and beamforming algorithms may be explained by different multipath propagation channels for the open area, street canyon and hotel lobby scenarios. The richer multipath channel theoretically has greater MIMO capacity, but to realize of this opportunity for increasing the system throughput we need to implement a very complex FAA MU-MIMO scheme.

Finally, it should be noted that BS and UE throughputs represented in Table II and by histograms in Fig. 7, 8 are given for omni user antennas with 0 dBi gain and channel bandwidth of 2.16 GHz. The mounting of the small PAA with 4—8 elements at the user equipment and application of the effective asymmetric links beamforming technique [10] will make it possible to support data transmission in 4.32 GHz and 8.64 GHz channels with the same modulation and coding schemes, thereby to multiply throughputs by 2 and 4 times respectively.

Summary

In this paper we investigated large antenna array technologies for MU-MIMO transmission in mmWave small cells with different involvement of radiofrequency and baseband parts for signal processing. The investigation in different environments was done for the Multi-Stream Phased Antenna Array (MS PAA) architecture, which can be fully implemented in the RF part with codebook based analog beamforming only, the Fully Adaptive Array (FAA) configuration, fully implemented in the BB and considered as the most flexible solution with the maximum available number of spatial degrees of freedom, and the Modular Antenna Arrays (MAA) configuration, which realizes a hybrid beamforming processing with coarse RF beamforming and fine BB beamforming.

The FAA scheme predictably demonstrates better performance metrics in comparison with the MS PAA and the MAA for all beamforming schemes and frequency granularities in all considered scenarios. The maximum spectral efficiency is provided by the most complex FAA with ZF beamforming scheme and per subcarrier frequency granularity, but for the large antenna arrays with a large number of antenna elements such FAA scheme has high complexity and cost. The MS PAA with 8 streams (2D-128 DFT) and the MAA with 16 degrees of freedom demonstrate acceptable performance metrics in typical environments and therefore may be considered as good candidates for further practical implementations at the BSs or APs of the future mmWave small cells.

We should emphasize that the main results of the paper were obtained by direct system simulations based on strict compliance with the parameters of the IEEE 802.11ay standard and the usage of generally accepted signal processing, beamforming and scheduling algorithms. Therefore, these results are practically important for cellular operators, communication equipment manufacturers and vendors to make decisions on the implementation of available antenna technologies for deploying the new mmWave cellular and Wi-Fi communication systems of the 5th and further generations.

REFERENCES

1. **Liu D., Pfeiffer U., Grzyb J., Gaucher B.** *Advanced millimeter-Wave technologies: Antennas packaging and circuits*. USA NY: Wiley, 2009.

2. **Dahlman E., Parkvall S., Skold J.** *5G NR: The next generation wireless access technology*, 2nd ed., 2020.

3. **Nitsche T., Cordeiro C., Flores A.B., Knightly E.W., Perahia E., Widmer J.C.** IEEE 802.11ad: Directional 60 GHz communication for multi-gigabit-per-second Wi-Fi. *IEEE Commun. Mag.*, 2014, vol. 12, no. 4, pp. 132–141.

4. **Pan H.K., Horine B.D., Ruberto M., Ravid S.** Mm-Wave phased array antenna and system integration on Semi-Flex packaging. *IEEE AP-S Conference on Antenna and Propagation for Wireless Communications*, 2011, pp. 2059–2062.

5. IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems Local and Metropolitan Area Networks—Specific Requirements Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specifications Amendment 2: Enhanced Throughput for Operation in License-exempt Bands above 45 GHz, *https://standards.ieee.org/ieee/802.11ay/6142/*

6. IEEE 802.11-14/1185r0: NG60 usage scenarios. *http:// mentor.ieee.org/802.11/dcn/14/11-14-1185-00-ng60-ng60-usage-scenarios.pptx*

7. *Channel models for IEEE 802.11ay*. IEEE doc.: 802.11-15/1150r9, 2017.

8. **Okasaka S., et al.** Proof-of-concept of a millimeter-Wave integrated heterogeneous network for 5G cellular. *SENSOR*, Aug. 2016.

9. **Sakaguchi K., et al.** Where, when, and how mmWave is used in 5G and beyond. *IEICE Transactions on Electronics*, Oct. 2017, Vol. E100-C, no. 10, Pp. 790–808.

10. **Maltsev A., Pudeyev A., Bolotin I., Bolkhovskaya O.** Asymmetric links beamforming for mmWave overlay in LTE-based heterogeneous network. *2017 IEEE 86th Vehicular Technology Conference* (*VTC-Fall*), Toronto, Canada, 2018, pp. 1–5.

11. **Heath R.W., et al.** An overview of signal processing techniques for millimeter Wave MIMO systems. *IEEE J. Sel. Topics Signal Processing*, 2016, vol. 10, no. 3, pp. 436–453.

12. **Molisch A.F., et al.** Hybrid beamforming for massive MIMO: A survey. *IEEE Communications Magazine*, 2017, vol. 55, no. 9, pp. 134–141. DOI: 10.1109/MCOM.2017.1600400

13. **Maltsev A., Sadri A., Pudeyev A., Bolotin I.** Highly directional steerable antennas: High-Gain antennas supporting user mobility or beam switching for reconfigurable backhauling. *IEEE Veh. Tech. Mag.*, 2016, vol. 11, no. 1, pp. 32–39.

14. **Maltsev A.A., Lomaev A., Pudeyev A.V., Bolotin I.A., Bolkhovskaya O.V., Seleznev V.M.** Millimeter-wave toroidal lens-array antennas experimental measurements. *2018 IEEE International Symposium on Antennas and Propagation & USNC/URSI National Radio Science Meeting*, 2018, pp. 607–608.

15. **Ghasempour Y., da Silva C.R.C.M., Cordeiro C., Knightly E.W.** IEEE 802.11ay: Next-generation 60 GHz communication for 100 Gb/s Wi-Fi. *IEEE Communications Magazine*, 2017, vol. 55, no. 12, pp. 186–192.

16. **da Silva C.R.C.M., Lomayev A., Chen C., Cordeiro C.** Analysis and simulation of the IEEE 802.11ay single-carrier PHY. *2018 IEEE International Conference on Communications* (*ICC*), 2018, pp. 1–6. DOI: 10.1109/ICC.2018.8422532

17. **El Ayach O., Rajagopal S., Abu-Surra S., Pi Z., Heath R.** Spatially sparse precoding in millimeter wave MIMO systems. *IEEE Trans. Wireless Commun.*, 2014, vol. 13, no. 3, pp. 1499–1513.

18. **Alkhateeb T.A., El Ayach O., Leus G., Heath R.W.** Channel estimation and hybrid precoding for millimeter Wave cellular systems. *IEEE Journal of Selected Topics in Signal Processing*, 2014, vol. 8, no. 5, pp. 831–846. DOI: 10.1109/JSTSP.2014.2334278

19. **Sohrabi F., Yu W.** Hybrid digital and analog beamforming design for large-scale antenna arrays. *IEEE Journal of Selected Topics in Signal Processing*, 2016, vol. 10, no. 3, pp. 501–513. DOI: 10.1109/JSTSP.2016.2520912

20. **Feng Y., Kim S.C.** Hybrid precoding based on matrix-adaptive method for multiuser large-scale antenna arrays. PLoS ONE 12(12):e0188723, 2017. *https://doi.org/10.1371/journal.pone.0188723*

21. **Shaban A.W., Damen O., Xin Y., Au E.** Statistically-aided codebook-based hybrid precoding for millimeter Wave channels. *IEEE Access*, 2020, vol. 8, pp. 101500–101513. DOI: 10.1109/ACCESS.2020.2997190

22. **He S., Wang J., Huang Y., Ottersten B., Hong W.** Codebook based hybrid precoding for millimeter Wave multiuser systems. *IEEE Transactions on Signal Processing*, 2017, vol. 65, no. 20, pp. 5289–5304. DOI: 10.1109/TSP.2017.2723353

23. **Chen J.** Efficient codebook-based beamforming algorithm for millimeter-Wave massive MIMO systems. *IEEE Transactions on Vehicular Technology*, 2017, vol. 66, no. 9, pp. 7809–7817. DOI: 10.1109/TVT.2017.2677957

24. **Liang L., Xu W., Dong X.** Low-complexity hybrid precoding in massive multiuser MIMO systems. *IEEE Wireless Commun. Lett.*, 2014, pp. 653–656.

25. **Ruan H., Xiao P., Xiao L., Kelly J.R.** Joint iterative optimization based low-complexity adaptive hybrid beamforming for massive MU-MIMO systems. *IEEE Transactions on Communications*, 2021, vol. 69, no. 3, pp. 1707–1722. DOI: 10.1109/TCOMM.2021.3053021

26. **Nam J., Adhikary A., Ahn J.-Y., Caire G**. Joint spatial division and multiplexing: Opportunistic beamforming, user grouping and simplified downlink scheduling. *IEEE J. Sel. Topics Signal Process*, 2014, vol. 8, no. 5, pp. 876–890.

27. **Saqib N.U., Cheon K.-Y, Park S., Jeon S.-W.** Joint optimization of 3D hybrid beamforming and user scheduling for 2D planar antenna systems. *2021 International Conference on Information Networking* (*ICOIN*), 2021, pp. 703–707. DOI: 10.1109/ICOIN50884.2021.9334028

28. **Sergeev V., Bolkhovskaya O., Maltsev A.** A practical approach to hybrid beamforming for 5G Wi-Fi systems. *2021 Wave Electronics and Its Application in Information and Telecommunication Systems* (*WECONF*), St. Petersburg, Russia, pp. 1–9. DOI: 10.1109/WECONF51603.2021.9470612

29. **Maltsev A., Sadri A., Pudeyev A., Bolotin I., Davydov A., Morozov G., Weiler R.** Partially adaptive arrays application for MU-MIMO mode in a mmWave small cells. *IEEE PIMRC 2015*, pp. 315–319.

30. **Paulraj A., Nabar R., Gore D.** *Introduction to space-time wireless communications*. U.K. Cambridge: Cambridge Univ. Press, 2008.

31. **Maltsev A., Pudeyev A., Sadri A., Cordeiro C.** *Millimeter-Wave transceiver with coarse and fine beamforming with interference suppression and method*. US Patent 20130308717, Pub.: Nov. 2013.

32. *TGay Evaluation Methodology*. IEEE doc.: 802.11-15/0866r2, 2015.

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