Challenges and Performance Evaluation of Multicast Transmission in 60 GHz mmWave

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Abstract. Recently, millimeter-wave (mmWave) technology has attracted significant attention due to its ambitious promise to deal with the rapid growth in wireless data traffic. Moreover, mmWave is expected to constitute a foundation for the fifth-generation (5G) communication systems' services, claimed to efficiently and effectively support both unicast and multicast transmission modes. However, the use of highly directional antennas at both user and access point sides is required to compensate for the severe path loss, high attenuation, and atmospheric absorption at extremely high-frequency bands, e.g., mmWave. Hence, multicast transmission needs special attention in directional systems due to the nature of group-oriented services, wherein a single beam simultaneously feeds receivers located at different positions. Since the widest possible beams at 60 GHz band are limited in terms of range and data rate and cannot serve all users, and, inversely, the use of only fine beams steered toward each user in unicast fashion requires long data transmission duration, the design of efficient directional multicast schemes is of utmost importance. Further, a slight beam misalignment due to mobility can generate a significant signal drop even between devices communicating in unicast fashions. The mission of this paper is to discuss the main challenges that must be faced to take advantage of mmWave communication for multicast data delivery. To this end, we investigate the performance of such systems in terms of data rate and data transmission duration via simulations considering both static and dynamic scenarios.

Keywords: 5G · mmWave · 802.11ad/ay · Unicast · Multicast.

1 Introduction

Millimeter wave (mmWave) communications are considered promising candidates for future wireless networks to meet the ever-increasing demands for high-data-rate multimedia access and spectrum requirement of fifth-generation (5G) mobile communication systems [1]. Furthermore, according to both academic and industrial communities, mmWave technology is expected to play a fundamental role even in beyond-5G (B5G) networks to ensure efficient massive data transmissions [2]. For example, the 3GPP New Radio (NR) technology will exploit the mmWave spectrum to achieve increased bandwidths and higher data rates [3]. IEEE 802.11ad/ay specifications use a similar approach and claim to achieve up to 100 Gbps rate communication [4]. Therefore, the envisioned performance of mmWave systems is ideal for satisfying the typical demands of the bandwidth-hungry 5G and B5G services and emerging applications, which mainly require disseminating a large amount of data traffic with low latency, e.g., autonomous driving, mobile video streaming, virtual/augmented/mixed reality (VR/AR/XR) applications, public/road safety, road infotainment, among others. Moreover, the throughput gain enhancement is an essential target in mmWave communication development.

Meanwhile, a beneficial technique for the system bandwidth efficiency improvement is multicast communication, wherein the same packet is delivered from a transmitter to an arbitrary number of receivers simultaneously by utilizing the same frequency and modulation and coding scheme (MCS). However, to compensate for the high path loss at extremely high frequency (EHF) bands and guarantee the gigabit capabilities, highly directional antennas are required for mmWave transmissions where the signal is sensitive to rapid channel variations, atmospheric absorption, and severe attenuation. This requirement makes multicasting more complex to implement compared to microwave networks where omnidirectional antennas are typically used. The beam steering, the size of multicast subgroups, and the beamwidth to cover all users have to be properly selected. Further, the presence of mobile users poses an additional challenge to mmWave wireless systems with directional group-oriented transmissions. To this end, the paper dedicates to discuss and analyze the challenging issues and advantages of mmWave multicast communication with a particular focus on WiGig/IEEE 802.11 specifications.

The paper is organized as follows. The description of IEEE 802.11ad/ay standards is given in Section 2. The design challenges of multicast and unicast modes with directional mmWave transmissions are discussed in Section 3. Section 4 describes the system model under analysis. Simulation results are discussed in Section 5. The conclusions of our study are given in the last section.

2 IEEE 802.11ad/ay specifications

The WiFi/WiGig standards (i.e., IEEE 802.11ad/ay) support wireless networking at 60 GHz. The IEEE 802.11ad standard, ratified in 2012, offers real multigigabit data rates. Its successor, IEEE 802.11ay, excels the capabilities of 802.11.ad by exploiting the same band and provides ultra-high-speed and super-low-latency services by introducing advanced physical layer (PHY) features. The second WiGig standard quadruples the bandwidth, adds MIMO up to 8 spatial streams, channel bonding, channel aggregation, and ensures non-uniform modulation constellation [5]. Besides, 802.11ay advanced power-saving feature makes it ideal for wearable devices. For instance, these kinds of requirements may be suitable for AR/VR applications [6].

2.1 IEEE 802.11ad

In this section, a more in-depth investigation and analysis of the beacon interval structure in IEEE 802.11ad (see Fig. 1) is conducted. The medium access control (MAC) design for 802.11ad may utilize both carrier sensing multiple access with collision avoidance (CSMA/CA) and scheduled service periods (SPs) channel access schemes depending on the type of application. In the case of SPs, 802.11ad uses time division multiple access (TDMA), where a personal basic service set (PBSS) central point (PCP) or access point (AP) utilizes the polling mechanism by asking devices and receiving their feedback. Alternatively, CSMA/CA is used for contention-based periods (CBP), where devices are allowed to use the same radio channel without pre-coordination with the help of *listen-before-talk* operating procedure. In this work, we consider SPs only.

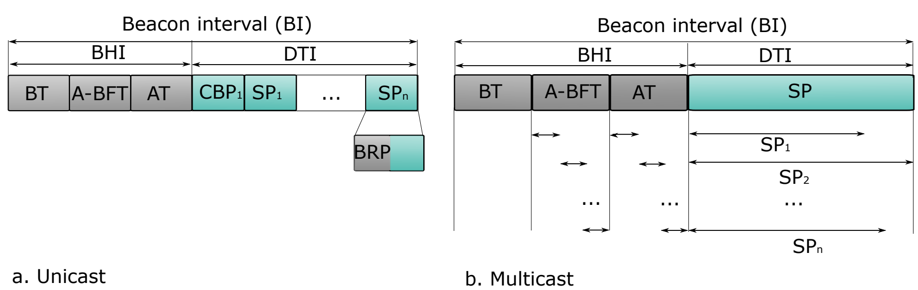

Fig. 1. IEEE 802.11.ad beacon structure.

The time is divided into beacon intervals (BIs) of total length T; each BI incorporates: (i) a beacon header interval (BHI), where devices perform initial beamforming, which generally involves sectored antennas (aka sector-level sweep, SLS), and adjust their wider transmit beams, and (ii) a data transmission interval (DTI), including SPs of different connected clients, while containing a beam refinement protocol (BRP) to improve the resulting instantaneous data rate.

More specifically, on the MAC layer each BI starts with a beacon time (BT) interval during which the *initiator* transmits sector sweep (I-TXSS) beacons across all M_{SLS} sectors with half-power beamwidth (HPBW) of $\theta_{\text{SLS,Tx}} = 2\pi/M_{\text{SLS}}$. The receive sector sweep (RSS) process and feedback during the association beamforming training (A-BFT) announced by the initiator are performed after I-TXSS by the *receiver*. Practically, in A-BFT interval, if more than one client selects the same transmission opportunity (up to eight slots for 802.11ad), the signals collide, and devices cannot establish a connection in the current BI.

The receive antenna operates in an omnidirectional mode during SLS and, after measuring the receive signal strength (RSS) across all N_{SLS} sectors, with $\theta_{\mathrm{SLS,Rx}} = 2\pi/N_{\mathrm{SLS}}$, it provides the SLS feedback to the transmitter identifying the sector with maximum RSS value. Based on the RSS indicator as well as by using an angle of arrival (AoA) or time difference of arrival (TDoA), the AP can determine the user location information. The training packets are transmitted with the low-power low-rate MCS 0, which provides the reliable communication required to establish the initial beamformed link.

In the announcement time interval (ATI), management information is exchanged between the PCP/AP and the receivers. Once the best sector pair is identified, the beam refinement phase (BRP) iteratively trains the transmit and receive antenna beams found during the SLS to select a beam pattern pair with finer beamwidths determined by the beam refinement factor b, $b > 1$. Therefore, for the transmit antenna training, both devices sweep through exactly b narrower beams (within the initial transmit sector), while during the receive training, all $M = bM_{\mathrm{SLS}}$ or $N = bN_{\mathrm{SLS}}$ directions should be covered.

We remark that the SLS and BRP phases of beamforming usually precede data transmission. They are always executed at the beginning of the beamforming process. However, the DTI can be used for all the beamforming phases to enable the repetition of the beamforming process as and when required.

The optional beam tracking phase is used during data transmission (DT) to adjust for channel changes. Beam tracking is accomplished by appending training (TRN) fields to data packets [7].

The basic principle of 802.11.ad BI is briefly reviewed in this section, interested readers for more details can refer to [8], and the detailed description of the protocol may be found in [9].

2.2 IEEE 802.11ay

IEEE 802.11ay is an amendment of great interest for applications ranging from high-speed short-range links to wireless backhaul that enable 100 Gbps communications in the unlicensed 60 GHz mmWave band. IEEE 802.11ay incorporates a variety of technical advancements at the PHY over IEEE 802.11ad standard, such as channel bonding and aggregation, single-user (SU) and downlink (DL) multi-user (MU) Multiple-Input Multiple-Output (MIMO) transmissions, and nonuniform modulation constellation, as well as improved channel access and enhanced beamforming training.

In 802.11ay, the enhanced directional multi-gigabit (EDMG) PCP/AP can allocate multiple clients on different channels to communicate with the PCP/AP simultaneously. Moreover, two EDMG clients can communicate with each other on a bonded channel or an aggregated channel to achieve higher throughput and improve channel utilization.

A new packet structure is defined in IEEE 802.11ay to support MIMO wireless links and channel bonding. The EDMG packet contains new fields necessary to support the additional capabilities defined for EDMG stations and a redefined TRN field that is more flexible and efficient than the one specified in 802.11ad.

In this section, we summarized the main improvements of the IEEE 802.11ay standard. The detailed overview of the IEEE 802.11ay can be found in [4, 5].

3 Design Challenges of mmWave Multicast and Unicast Modes

3.1 Unicast in Directional Networks

A considerable amount of research recently investigated mmWave communications by focusing on unicast data transmission optimization [10, 11], where the AP performs serial TDMA transmissions. In mmWave wireless personal area networks (WPAN), each user is served independently of the others with minimum beamwidth (on the order of 10-20 degrees or less) to provide high data rates. The reliability of such transmissions is very high since the beamwidth is equal to the resolution and provides the maximum available signal-to-noise ratio (SNR). However, the AP requires a long time to serve all users, as it generates a separate beam for each user to transmit the data sequentially.

3.2 Multicast in Traditional Networks

Multicast is a bandwidth-conserving technology, the basic concept of thereof consists in the traffic reduction by simultaneous delivering a single stream of information to a group of users, i.e., data packets are transmitted only once. Consequently, it considerably improves the bandwidth efficiency compared to unicast mode since all users are served simultaneously by using a single wide transmission beam (omnidirectional), which generally provides very short transmission duration. In the past literature, several efficient solutions improving traditional multicast schemes in omnidirectional networks were proposed [12–14]. However, pure multicast schemes are almost infeasible in mmWave directional systems due to the propagation specifics at EHF bands. The adaptation of the directional nature of mmWave communication for existing methods, as well as the development of novel mmWave-specific schemes [15, 16], is of particular interest for the research community.

3.3 Multicast in Directional Networks

The use of highly directional transmission beams in mmWave systems represents an outstanding feature with respect to traditional networks and allows coping with high attenuation at EHF bands. Most phased array antennas that have been designed in past years have used analog beamforming where the phase adjustment is performed at RF, and there is one set of data converters for the entire antenna (one RF chain). Note that analog mmWave systems utilize sequential multicast. The beam orientation and the beam resolution (beamwidth), which need to be adjusted in addition to the beam radius, make these systems different from conventional omnidirectional networks. By contrast, in the case of hybrid or digital beamforming techniques, which allow transmitting to more than one user at a time, the power budget constraint at the transmitter side has to be taken into consideration [17]. Therefore, when multiple RF chains are available, new opportunities and challenges (e.g., determining the shape of numerous beams to be swept simultaneously under the total transmission power constraint) appear.

In alignment with the Friis transmission equation, the received power is directly proportional to the transmitter channel gain, which, in its turn, strongly depends on the beam orientation and resolution.

Then, multicast traffic delivery in mmWave systems presents the following problems, which have to be considered [17]:

1. Wide beams are more likely to reach all multicast receivers since they can cover a larger angle range and, thus, serve more users simultaneously. However, due to the lower antenna gain that wide beams provide, the supported transmission rate is limited.
2. Narrow beams provide higher antenna gain and thus can support higher transmission rates. However, they are limited in coverage in terms of the aperture angle and may not simultaneously serve a number of users. As a consequence, multiple unicast transmissions are required to reach all multicast users.
3. The presence of moving users is more challenging for multicast transmission. In fact, in the case of unicast, the AP is beamformed toward the only receiver, and small movements of the receiver still allow to guarantee a good reception. Differently, in the case of multicast, beams are steered in between users. Hence, some receivers may be close to the edge of a beam's coverage area and, due to the even small mobility, can be out of the beam coverage.

The integrated problem of directional beamforming and multicast communications is under investigation in this paper.

4 System Model

In this paper, we consider a general public scenario where owners of *wearable devices* are interested in receiving the same content, i.e., the AP transmits data to multiple users thought multicast mmWave links. We assume analog beamforming only to analyze the performance of sequential multicast in TDMA fashion. This means that the AP can transmit through a single beam at a time to serve the users.

4.1 Antenna and Channel Models

In what follows, we assume that devices transmit directionally with the same antenna beam pattern, which is symmetrical w.r.t. the boresight [18]. By this symmetrical assumption, we mean that antennas have a unique beam shape in both elevation and azimuth planes, i.e., their antenna pattern is akin to a conical shape.

In terms of the channel model, when HPBW θ is used, the received signal power at receiver i is calculated by the Friis equation:

$$P_{\text{rx},i} = \frac{P_{\text{tx}} D_0 \rho(\alpha_i) \lambda^2}{(4\pi)^2 r_i^{\kappa}}, \tag{1}$$

where P_{tx} is the transmit power, α_i is the current angular deviation of the transmit/receive direction from the antenna boresight for receiver i, $\rho(\alpha_i) \in [0; 1]$ is a piece-wise linear function that scales the antenna directivity D_0 [18][6], λ is the wavelenght, r_i is the separation distance between the transmitter (Tx) and receiver (Rx) i, and κ is the path loss exponent.

We assume the line of sight (LoS) path only. Hence, the maximum achievable rate D_i of the Tx-Rx$_i$ link could be estimated according to Shannon's channel capacity as:

$$D_i = W \log_2 \left(1 + \frac{P_{\text{rx},i}}{P_{\text{noise}}}\right), \tag{2}$$

where P_{rx} incorporates both transmit and receive antenna gains after the BRP phase, W is the bandwidth, P_{noise} is noise power in the channel, which corresponds to

$$P_{\text{noise}} = W N_0 \text{NF}, \tag{3}$$

where N_0 is the power spectral density of noise per 1 Hz, and NF is the noise figure.

For a multicast group containing n receivers, the overall performance of multicast transmission depends on the user with the worst channel. Thus, the achievable rate of a multicast transmission is given by

$$D = W \log_2 \left(1 + \min_i \left(\frac{P_{\text{rx},i}}{P_{\text{noise}}}, 0 | P_{\text{rx},i} < P_{\text{thr}}\right)\right), \tag{4}$$

where P_{thr} guarantees the minimum required received power for data transmission.

The data transmission duration for multicast transmission is given by

$$T_{DT} = \frac{B}{D}, \tag{5}$$

where B is the packet size.

Then, the total duration of data transmission can be calculated as

$$T = T_{\text{SLS}} + U(T_{\text{BRP}} + T_{\text{DT}}) + T_0, \tag{6}$$

where $T_{\text{SLS}} + U(T_{\text{BRP}})$ is the overhead on the beam training, U is the average number of clients per AP, and T_0 is the total signaling overhead, which is independent of the number of beams.

[6] $\rho(\alpha_i) = 1 - \frac{\alpha_i}{\theta}$, if $\alpha_i \leq \theta$, otherwise $\rho(\alpha_i) = 0$; $\rho(\alpha_i) = 1$ corresponds to the antenna boresight in the case of perfect alignment (e.g., unicast transmission after the beamforming procedure). In the case of multicast transmission, each user deviates on angle α from the boresight of the transmitter.

5 Performance Analysis

In this section, we evaluate the multicast transmission performance in directional mmWave networks via simulations. To this end, we focus on a scenario composed of a group of people in a museum interested in receiving the same multimedia content by means of high-end wearable devices equipped with IEEE 802.11ad/ay chipsets operating at 60GHz. We consider an analog beamforming technique (one RF chain), which means that the AP can transmit over a single beam at a time, to assess the performance of sequential multicast.

For the evaluation purpose, we consider resource-hungry applications in scenarios with and without mobility. We also analyze two patterns of users' distribution: (i) within a sector (see Section 5.1) to investigate sequential multicast performance characteristics, and (ii) in a line (see Sections 5.2, 5.3) to explore the angle coverage of the antenna. The transmit power is fixed at the level of $P_{\text{tx}} = 23$ dBm, whereas $P_{\text{thr}} = -68$ dBm (MCS 1) [9]. Main simulation parameters are summarized in Table 1.

5.1 Static scenario: unicast vs. multicast performance

To simulate sequential multicasting, we assume that the AP sweeps beams of equal resolution (i.e., fixed predefined beams) to cover the sector under analysis, as illustrated in Fig. 2.

We first analyze the system performance in terms of aggregated data rate (ADR) for sequential multicast and unicast schemes (see Fig. 3). For this purpose, we uniformly distribute users within a sector of 90° of radius $Rd = 40$m. The choice of the service area radius can be explained by the fact that sequential multicast with the widest width (i.e., $\theta = 58°$) requires the lowest number of sequential beams, whereas it can cover the smallest Rd in comparison with narrower beams. More precisely, for given system parameters, the beam of 58° can cover only a distance of 45 m. However, due to the beam misalignment in multicast, we set Rd to 40 m to guarantee reliable communications for every

Table 1. Main simulation parameters

Notation	**Parameter**	***Value***
f	Carrier frequency	60 GHz
λ	Wavelength	0.005 m
k	Propagation exponent	2
C	Propagation constant	$6.3165 \cdot 10^6$
P_{thr}	Sensitivity	-68 dBm [9]
P_{tx}	Transmit power	23 dBm
θ	Beamwidth	var
R_d	Radius of the area of interest	40 m
$\text{SNR}_{\max}$	SNR corresponding to choosing MCS19 (rate 13/16)	20 dB
NF	Noise figure	6 dB
B	Packet size	1 Gb

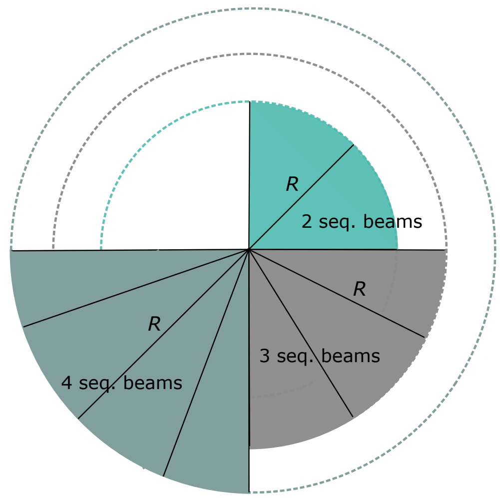

Fig. 2. Illustration of the multicast scheme with fixed beams.

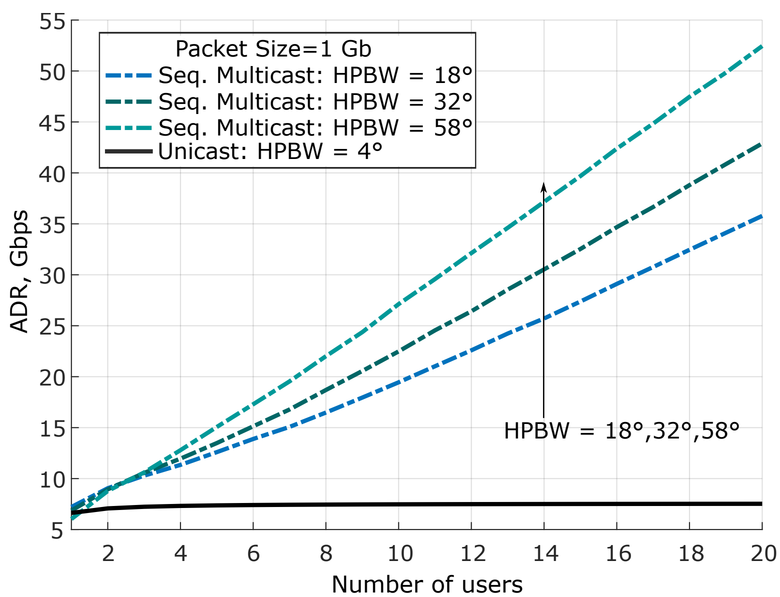

Fig. 3. Aggregated data rate vs. number of users.

considered transmission scheme. We recall that the wider HPBW of the predefined beams, the less number of beams needs to be swept by the AP to cover the considered sector (in terms of the angle coverage). One may deduce that the wides beams, e.g., HPBW=58°, can improve the system throughput.

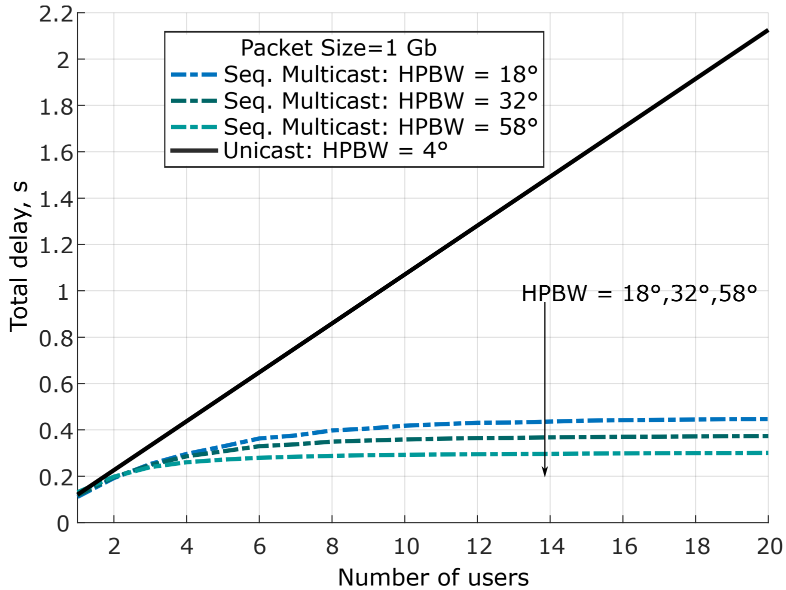

Fig. 4. Total transmission duration vs. number of users.

The effects of sequential transmissions on the total delay in mmWave systems are further highlighted in Fig. 4. As one may observe, sequential multicast with $\theta = 58°$ guarantees the shortest data transmission duration; hence, the lower total transmission delay. However, it provides lower SNR value as well as higher outage probability due to the lower antenna directionality. Using the widest possible beam at EHF bands severely limits the data rate and transmission range. In contrast, narrow beams require a longer data transmission duration. Therefore, we may conclude that the resource management algorithms are of crucial importance since they allow to dynamically make decisions based on the number and resolution of beams in directional multicast by taking into consideration (i) the multicast group size, (ii) the shape and size of the service area, (iii) users' locations and density, as well as (iv) QoS requirements. In addition, in the case of hybrid beamforming, power models have to be applied to split the power among composite multi beam patterns.

5.2 Static scenario: coverage area estimation

In this section, we show results in terms of achievable data rate and total transmission delay for multicast, unicast, and sequential multicast schemes when a group of *ten users* is located within a line of length d. Here, in the case of sequential multicast, we assume that the group of users is always served by a fixed number of beams $N = 3$, independently from the beam resolution. We investigate the maximum possible distance d at which the connection can be established, for the three considered schemes.

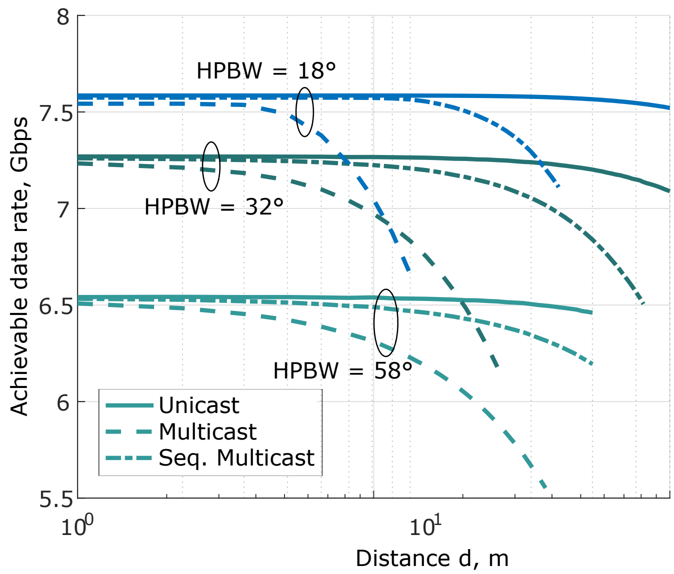

Fig. 5. Data rate vs. distance d for unicast, multicast, and sequential multicast.

By analyzing the results presented in Fig. 5, we learn that the distance d does not affect unicast transmission as a separate aligned beam is swept to serve each user. Regarding the pure multicast scheme, we can see that there is a threshold that determines the maximum coverage angle of the beam. For example, HPBW= $58°$ provides the larger distance d, whereas the narrowest beam (i.e., HPBW= $18°$) covers the lowest distance d. We also highlight that sequential multicast achieves higher data rates for the same distance d compared to the multicast scheme. It can be explained by the fact that multicast (with a single beam only) experiences difficulties or even fails to provide sufficient data rates to users located far apart in terms of the angle coverage.

Achievable multicast, sequential multicast, and unicast bit rates as functions of distance d are depicted in Fig. 6 for different HPBWs. Due to the sequential nature of unicast in mmWave, pure multicast guarantees the shortest data transmission duration. Meanwhile, both sequential schemes ensure higher distance d with respect to multicast transmission, which means that more users can receive data. We also emphasize that the beamforming overhead for narrow beams is greater than for wide beams and affects the total transmission delay (see, for instance, the curves related to HPBW=$4, 8°$ for three transmission fashions).

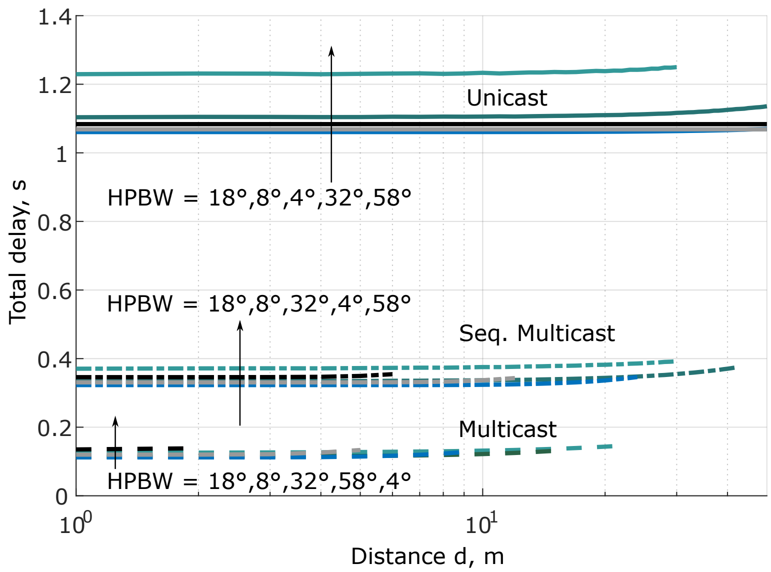

Fig. 6. Total transmission delay vs. distance d for unicast, multicast, and sequential multicast.

5.3 Dynamic scenario: mobility impact on multicast transmission

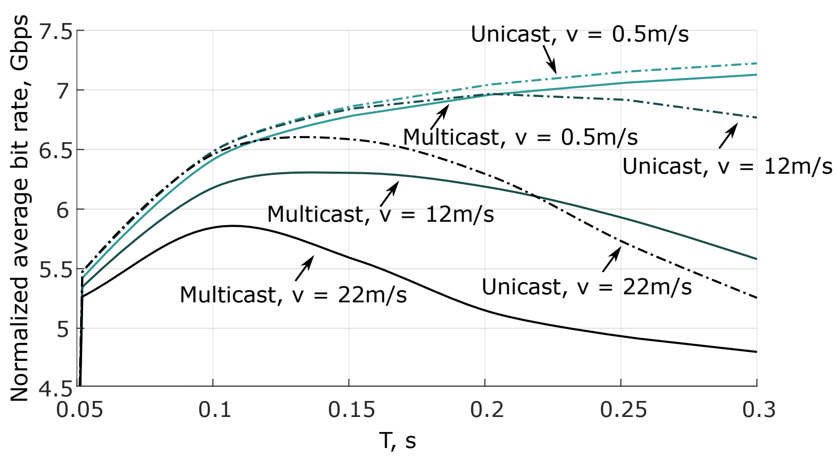

Fig. 7. Normalized average achievable data rate over time T for different speeds, $\theta = 8°$.

To facilitate a more detailed performance evaluation, we proceed by considering the scenario with mobile users.

The mobility influence on the three transmission modes is evaluated in Fig. 7. We assume a simple case with two devices located in a line of size $d = 16$ m for $\theta = 8°$. We analyze the behavior of unicast and multicast transmissions in the presence of mobile users by considering a rectilinear mobility pattern with user speeds of $v = 0.5$ m/s (as per walking or rolling stairs), $v = 11$ m/s (as per segway), and $v = 22$ m/s (as per bicycle). We also consider the overhead on beam training and recalculate the data rate over the total BI duration, i.e., $D_{\text{norm}} = D \cdot T_{\text{DT}}/T$. As one may notice from Fig. 7, the multicast transmission is more vulnerable to dynamic users' behaviors due to the fact that the beam is steered in between users, and some of them may be located at the edge of the beam. Hence, mobility management in directional multicast systems is even more challenging compared to unicast transmissions.

6 Conclusion

This paper presented an initial investigation of multicast transmissions using mmWave links with particular emphasis on the channel access of 802.11ad/ay standards operating at the unlicensed band. We experimentally evaluate multicast and unicast performance in directional mmWave networks. From the numerical evaluation of the model, it is clear that multicast in directional networks poses additional challenges compared to conventional systems. Since using the widest possible omnidirectional beam at EHF bands severely limits the data rate and range, the AP needs to transmit data sequentially by utilizing a resource management algorithm, which is our future research task. In addition, scenarios with the presence of mobile users receiving group-oriented services in directional mmWave networks is an essential issue to be faced by the research community.

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