Challenges for Enabling Virtual Reality Broadcast Using 5G Small Cell Network

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***Abstract*—In the recent past, with the ubiquitous adoption of smartphones and tablets, there has been an exponential increase in data rate demands which has become increasingly challenging for network operators to support. This trend is expected to continue in future, with the advent of high-performance gaming and increasing appetite for immersive applications and social media experiences. Such factors have contributed to the development of the fifth generation (5G) of mobile networks, which would be supporting significantly higher data rates with improved reliability and latency. 5G has also enabled the deployment of wireless virtual reality applications, with wide-ranging use cases. In this work, we consider the key challenges for broadcasting such content to a large number of audience thereby enabling new disruptions in mass media consumption. The technology potential and practical constraints for such deployments were also evaluated using realistic network settings. Based on the performance evaluations, it was shown that with slightly higher system bandwidth requirements, VR broadcast can be supported under ideal conditions, using 5G millimeter wave small cell networks. Potential areas for future work in order to make VR broadcast a reality is also discussed.**

I. Introduction

Currently there are activities ongoing from the academic and industrial research communities to empower 5G mobile networks to support a wide range of services, supporting a variety of use cases and scenarios [1]. The main motivation behind the development of the next generation of mobile network is the exponential growth in data rate demands from the end users, mainly driven by innovative and demanding applications [2]. Third generation partnership project (3GPP) is developing specifications for the end-to-end 5G or new radio (NR) system [3], mainly focusing on achieving extreme mobile broadband data rates during the first phase of deployments. Due to the support of a wide range of features – higher data rates, ultra-reliability and low-latency, 5G networks would be deployed to support new verticals beyond the capabilities of traditional cellular networks. The support for verticals have been a key paradigm within the 5G design principles [4], thereby making such networks significantly disruptive as compared to legacy networks. Some of the key new verticals industries and use cases where 5G networks are envisioned to be deployed are – health care, automotive, energy, connected home, media and entertainment (M&E), etc. [5]. A new operator paradigm which could enable localized service delivery of such verticals and use cases are called micro-operators (μO) [6] with privately deployed 5G cellular networks, since they have the flexibility to tailor the network to serve specific services or use cases. The ability to deliver such services to an increased number of users with minimal amount of spectrum improves the economic viability of such deployments, taking into account the related infrastructure costs.

Virtual reality (VR) technology enables users to have seemingly real audio and visual experiences, with the help of wearable devices. It has a wide variety of applications ranging from gaming, education and health care, to public safety and defense. Mobility is one of the main reasons for end users to adopt smartphones, hence wireless connectivity would be an essential component for VR technology adoption. Wireless VR is one of the most challenging 5G use case from M&E perspective, due to the need for simultaneous support of very high capacity, ultra-reliability (in terms of packet loss rates) and low-latency. In terms of capacity, VR would require about 7 Gbps user throughput with a latency of 10 ms [7]. With advanced compression techniques the network throughput requirement can be approximately 5.2 Gbps [8]. The work done in [8] investigates various means of enabling interconnected VR and challenges in realizing ideal VR (where real and virtual worlds cannot be distinguished). While ideal VR could be an aspirational future goal, in this work we limit our focus to the challenges in enabling wireless VR connectivity to a large number of users. Currently, there are various vendors providing VR devices with wireless connectivity expected to be provided using 60 GHz unlicensed millimeter wave (mmW) band, potentially using IEEE 802.11ad standard [7], [9].

The support for multicast/broadcast content delivery using cellular networks was initially developed for M&E services, but in recent past has been expanded for other verticals such as public safety [10]. This is a key topic which has so far received limited attention in the context of 5G, since enabling the delivery of linear or live (as compared to on-demand) content to a large number of users while supporting key 5G KPIs is a relevant and important topic. Such deployments could lead to new business cases in the context of μO networks, where the users are confined a finite physical coverage area. In this work, we consider the practical challenges of enabling indoor VR broadcast using 5G, but the evaluations are applicable for any radio access technology. Some of the key challenges include the need to provision such services using an optimal amount of 5G gigabit NodeBs (gNBs), the amount of spectrum that the μOs would require for such deployments based on the practical data rates that could be achieved, and the gains that could be achieved with the use of single frequency network

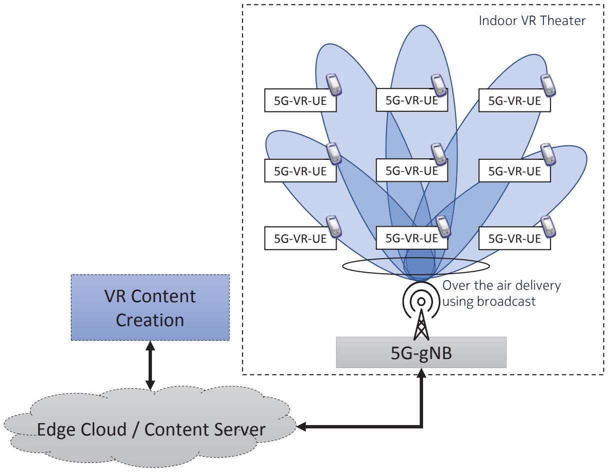


Fig. 1. Overall System Model.

(SFN) concept. The SFN concept was introduced as part of long term evolution (LTE) evolved multimedia broadcast multicast services (eMBMS) standards, with multiple cells send the same data using synchronized time-frequency physical resource blocks [10]. The transmissions are then combined at the user equipment (UE), improving SINR and enabling higher spectral efficiency for the multicast/broadcast data streams. The performance gain from having such mechanisms is evaluated in [11]. Through performance evaluations, we show how such deployments are practically feasible especially using the mmW bands where higher bandwidth requirements could be satisfied.

The rest of the paper is structured as follows: Section II gives an overview of the system model used. Section III discusses the key challenges for indoor VR broadcast. Section IV presents the simulation assumptions and system level parameters used for simulations, together with detailed performance results of the proposed scheme. Section V gives summary of the paper.

II. System Model

The system considered in this work is as shown in Fig. 1. Here we consider an indoor VR theater system, with the content located at the edge of the radio access network, in order to enable low-latency content delivery. The VR content is broadcast over the air interface to a multitude of users through several gNBs. If the gNBs are using SFN mode of transmissions, it is assumed that they are perfectly synchronized with the same data packets transmitted over the air and the VR-UE receives the combined transmission. For calculating the signal-to-interference ratio of the combined transmission, we use the model proposed in [11]. We also consider the usage of packet duplication mechanism where the gNBs transmit duplicate packets over the air interface to the VR-UEs which are combined after decoding. This mechanism achieves lesser throughput due to the added interference caused by the duplicated packets from different gNBs, but is much more simpler to implement since all the gNBs operate independently without the synchronization or coordination requirements.

It is assumed that the considered μO network is optimized for VR broadcast with appropriate placement of gNBs and the availability of requisite bandwidth. Broadcast would be the cost-efficient means of content delivery, since the μOs could deliver content at very high data rates, with the minimal amount of base stations and bandwidth, which is not possible using unicast. The key limitation with the usage of broadcast would be that the modulation and coding scheme (MCS) selected by the gNB would depend on the worst user in the system. Here worst user is assumed to be the user at the cell-edge, with the lowest received power value. The gNB selects the appropriate MCS value for transmission based on the feedback from the users or based on static parameter selection. Mobility is not assumed, since the users are expected to make movements within the finite area allocated to them in the theater. In order to further minimize the deployment and operation cost, we assume that the VR broadcast network uses unlicensed mmW band for operation, due to which there could be uncontrollable sources of interference which needs to be mitigated using sufficient radio isolation mechanisms, in particular if operation in the band requires LBT and SFN operation is desirable. Even though an indoor theater environment is considered in this work, the challenges and potential enablers are applicable to any indoor environment where large volumes of data needs to be broadcasted over the air.

III. Challenges for Indoor VR Broadcast

In this work, we evaluate some of the key practical challenges for VR broadcast, especially from the perspective of μO network or localized deployments. Such deployments enable the network operator to tailor their network depending on the specific needs of the use case being targeted. One of the key challenge for VR broadcast would be the deployment costs involved, which might be a limiting factor for most local operators. Two factors influencing the CAPEX is the number of gNBs required and costs involved in acquiring the requisite bandwidth. The usage of VR broadcast as compared to unicast would ensure that the gigabits of data that needs to be transmitted over the air interface for a large number of users can be done in the most radio resource efficient manner. In terms of spectrum acquisition, the usage of unlicensed band would be an important enabler. 5G/NR standards is expected to natively support standalone operation using unlicensed band, similar to the Multefire [12] standards for LTE. The need for wider bandwidth would require such systems to operate on higher/mmW frequency bands, which introduces limitations in terms of higher probability of radio link blockage or failure. The usage of SFNs, with an optimal number of gNBs appropriately located, would be a straightforward means of ensuring higher reliability due to the simultaneous availability of VR data streams. Due to this, even when a link is blocked, there would be a sufficient number of links still available for the user to continue receiving the data without interruptions.

TABLE I
SYSTEM LEVEL SIMULATION PARAMETERS

Basic Radio Configuration Parameters	
Small Cell Deployment	Random, $N_{SC} = 4$
Shadowing Standard Deviation	Small Cell: 3 dB
Spectrum Allocation, Carrier Frequency	LTE: 3.5 GHz 5G: 60 GHz
Small Cell Max Tx Power [dBm]	30
Antenna Gain [dB]	Small Cell | 5
UE Tx Power [dBm]	21
Other Simulation Parameters	
Spectral Efficiency, S_{eff}	4.0
No. of RBs, N_{RB}	LTE: 500, 5G: 5000
PRB size, RB_{s}	180 kHz
Bandwidth Efficiency, B_{eff}	0.65
SINR Efficiency, $SINR_{\text{eff}}$	0.95
User Placement	Random, $N_{UE} = 600$
Traffic	Full Buffer

SFNs also help in improving the spectral efficiency of the network through mitigation of potential sources of interference. A potential alternative to avoid strict synchronization and coordination requirements for SFN would be the usage of packet duplication along with the multi-connectivity paradigm in 5G [13]. The added cost of packet duplication would be the slightly lower spectral efficiency due to the added interference.

The distribution of users would be another practical challenge for VR broadcast, since a uniform distribution of users could imply challenging worst user SINRs, which the system might not be able to serve with a finite amount of resources. In the considered theater scenario, since the users would be confined to finite areas and with the availability of line-of-sight (LOS) conditions to the roof, such a challenge can be mitigated. With the usage of unlicensed band with listen-before-talk regulatory constraints, advanced interference mitigation mechanisms which enables the system to support the stringent delay constraints would be required. Currently available data rate and latency requirements for VR are related to unicast traffic. VR broadcast would require the entire 360^o raw data to be transmitted over the air interface, which would mean higher data rate and bandwidth requirements even with the usage of data compression. While air interface scheduling latency can be guaranteed using appropriate quality of service class identifiers, ensuring reliability in terms of packet loss rates is significantly challenging. This would require simultaneous support for unicast and broadcast service flows with possible retransmissions for those packets which were not received by the VR-UE, which puts further constraints over the data rate and bandwidth requirements.

IV. SIMULATION RESULTS

A. Simulation Assumptions

In order to evaluate the technology potential for VR content delivery using broadcast, we consider the uniform deployment of $N_{UE} = 600$ VR-UEs in an LTE and 5G system setting. The LTE setting is characterized by the usage of 3.5 GHz frequency band with 100 MHz bandwidth, with number of physical resource blocks (PRBs) $N_{\text{RB}} = 500$, and pathloss model based on LOS channel model-1 for indoor hotzone, given by [14]:

$$L_{\text{LTE}} = 89.5 + 16.9 \log_{10}(R) \qquad (1)$$

where R [km] is the distance between the VR-UE and LTE small cell.

For the 5G setting, we consider the use of 60 GHz frequency band and 1 GHz bandwidth as a baseline for evaluations. The LOS pathloss model used is based on the one considered in [15], [16]:

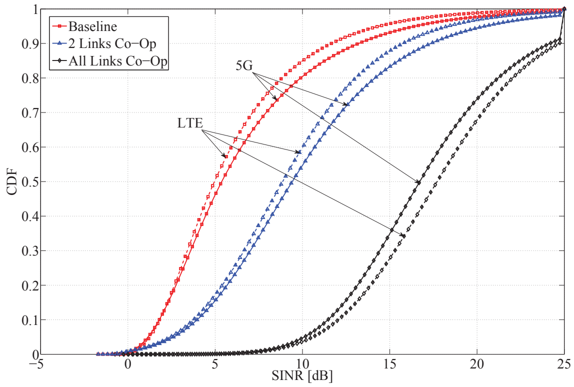
$$L_{\text{5G}} = 92.4 + 20 \log_{10}(f) + 20 \log_{10}(d) \qquad (2)$$

where f is the carrier frequency in GHz and d [km] is the distance between the VR-UE and LTE small cell.

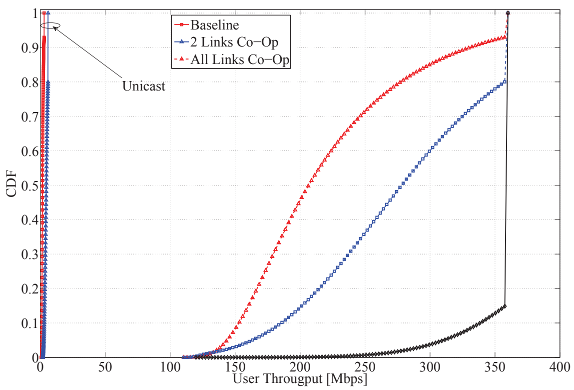
The detailed parameters used for performance evaluations are as shown in Table I. Here we consider LOS scenario, assuming that the gNBs are appropriately placed (on the ceiling) within the indoor area to provide LOS coverage for all the users. In the scenario, N_{SC} small cells are deployed randomly and provide connectivity to the users. Unless otherwise mentioned, single user traffic was considered for evaluations with the system optimized for delivering worst user traffic using broadcast. Unicast throughput results for LTE is also shown for reference in comparison to broadcast, with full-buffer and round-robin scheduling assumptions.

The baseline case used for comparison is the fully uncoordinated deployment scenario with packet duplication, where all the gNBs transmit duplicated packets independently using the best possible MCS for the worst user. The users then combine the packets received from multiple gNBs using the multi-connectivity paradigm, in order to generate the VR content. Here the added cost is lower spectral efficiency and added computational complexity for the VR-UE. We also consider the case where two of the gNBs are part of an SFN area, whereas the other gNBs transmit packets independently with packet duplication as well. The optimal scheme is considered to be the SFN scenario where all the links transmit VR data in a synchronized manner. The throughput calculations are done based on the modified Shannon formula proposed in [17], with multicast/broadcast specific parameters considered in [10]. 5G-gNBs with omni-directional antennas are used for evaluations in order to investigate cost-efficient solutions, with lower spectral efficiency.

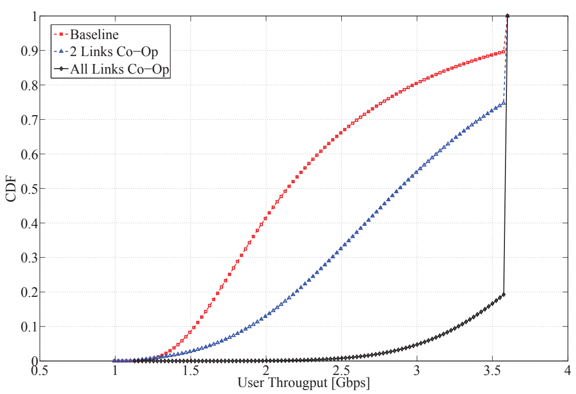
We also evaluate the performance of the 5G system using a theater setting of 80 m x 60 m, with 600 VR-UEs located in 20 rows with 30 users each. The users are separated from each other by 2 m, and has a 10 m separation from the theater walls. The users are assumed to have the flexibility to move within the confines of their location, in order to gain complete experience of the 360^o VR content. While 1 GHz system bandwidth has been considered as a reference baseline, we also evaluate the spectrum scaling requirements for delivering VR content using broadcast. Here we consider 5.2 Gbps data requirement, based on the evaluations done in [8]. We consider the presence of a randomly deployed interferer gNB within the scenario, in order to emulate the potentially unpredictable



(a) SINR distribution for LTE and 5G



(b) LTE user throughput distribution



(c) 5G user throughput distribution

Fig. 2. Performance evaluation with LTE and 5G system setting with uniform user distribution.

interference conditions with the usage of unlicensed bands. For both uniform distribution and theater scenario, sufficiently large drops were simulated with random placement of gNBs, in order to obtain sufficiently randomized results.

B. Simulation Results and Analysis

The performance evaluations using LTE and 5G system setting with uniform user distribution is as shown in Fig. 2. The LTE results are shown for benchmarking purposes, especially in terms of SINR distribution and also for showing the limitations of using unicast when common content has to be delivered to a wide range of users. From the SINR

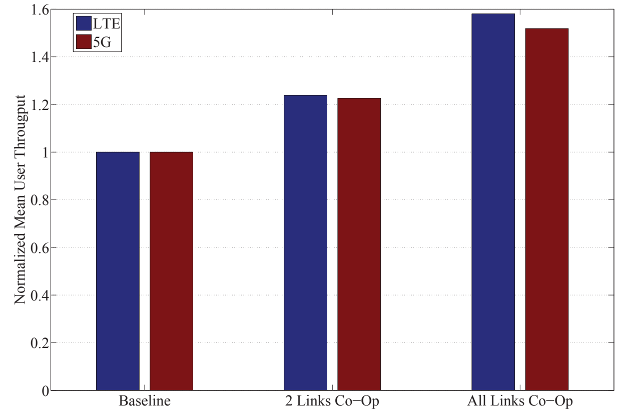
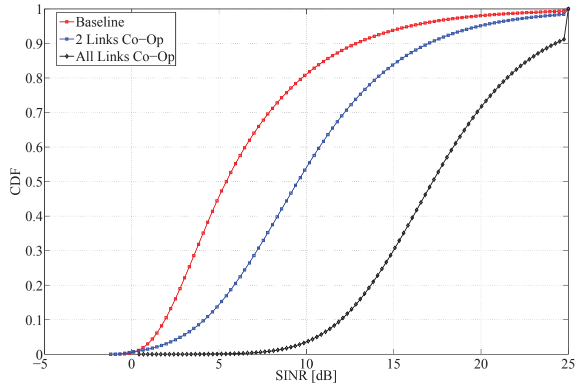


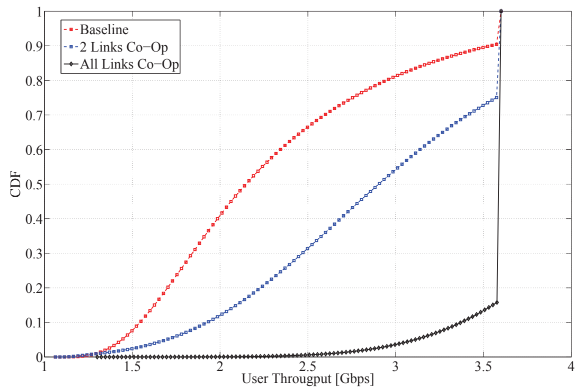
Fig. 3. Mean user throughput normalized to the baseline scenario.

distribution for LTE and 5G shown in Fig. 2(a), we can observe that the baseline case of distributed deployment with packet duplication provides the worst performance in terms of SINR. This is due to the fact that all the gNBs are sources of interference for each other, due to the uncoordinated transmissions. The two link cooperative scenario provides slightly better performance, whereas the SFN or all links cooperative scenario provides the best performance. Since the deployment occurs in a relative small indoor coverage area, all the transmissions from the gNBs are considered to be useful transmissions with no destructive interference apart from the randomly deployed interferer gNB. We can also observe that the SINR curves show slight improvement for the reference cases using the 5G system setting, whereas a slight degradation in performance is observed for the SFN case. The reason for this is the higher pathloss values for the 60 GHz band lowering the interference for the reference cases, whereas it lowers the signal power levels in the SFN scenario.

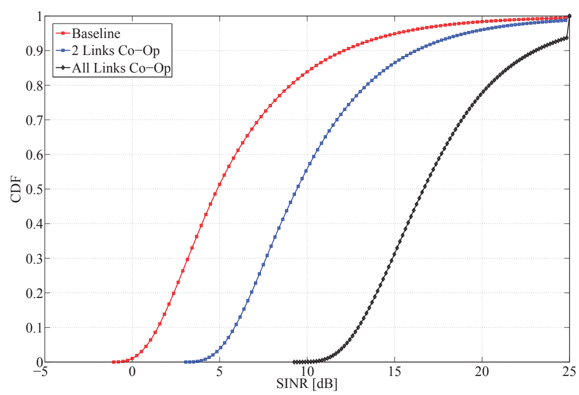
The LTE single user throughput distribution in comparison to unicast case is shown in Fig. 2(b), and we can observe that there is significant reduction in the throughput values when a common content is delivered to each individual user using unicast. The figure is shown to illustrate the immense gains broadcasting of common content can enable, with the same number of gNBs and spectral resources. While the throughput distribution is for single user throughput, here the key indicator to consider is the cell-edge user throughput, since the broadcast system would be optimized based on the cell-edge user parameters. From the figure, we can observe that with a uniform distribution there is only marginal gain for the cell-edge users in the SFN scenario as compared to the uncoordinated and partially coordinated reference scenarios. Similar trends can be observed in the 5G scenario as well, shown in Fig. 2(c). The reason for this is that with uniform distribution, there is always a user with bad channel conditions, which is only marginally improved with an SFN setting. Due to this, provisioning VR broadcast optimized for the worst user would be significantly challenging. The mean user throughput normalized to the baseline scenario is shown in Fig. 3, from



(a) SINR distribution with slow-fading



(b) User throughput distribution with slow-fading



(c) SINR distribution without slow-fading

Fig. 4. Performance evaluation with 5G system setting and theater scenario.

which we can observe that such deployments are ideal to be optimized for the mean user.

The performance evaluations using 5G settings within an indoor theater scenario where VR-UEs are dropped in fixed positions are as shown in Fig. 4. The evaluations were done with and without slow-fading in order to present results in an ideal system setting which could indicate the future technology potential of VR broadcast. From the SINR distribution with slow-fading results shown in Fig. 4(a), we can observe that even with fixed user placement there is no significant difference compared to the uniform distribution. The main reason for this is that the gNB placement is still random, rather at

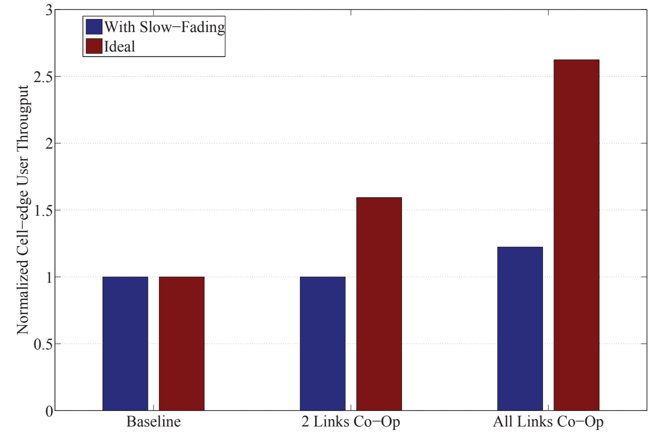


Fig. 5. Cell-edge user throughput for theater scenario normalized to baseline case.

the most optimal locations within the theater. The throughput distribution trends shown in Fig. 4(b) is also similar to the uniform place case, with marginal improvement in the cell-edge user throughput, thereby improving the practical viability of VR broadcast using such deployments. For the ideal scenario shown in Fig. 4(c), we can observe significant cell edge SINR performance improvements making such deployments attractive for VR broadcast. The ideal scenario could be achieved with optimal user and gNB placement, with sufficient radio environment isolation provided within the theater setting. This could be practically viable, especially considering the lower costs involved in providing radio isolation relative to optimal voice performance provisioning which is already done inside the theaters.

The improved cell-edge throughput performance for the scenarios with and without slow-fading is shown in Fig. 5, normalized to the baseline case in order to show relative performance improvements. From the figure we can observe that for the scenario with slow-fading, the SFN case provides only marginal improvements as compared to the reference mechanism. For the ideal scenario, significant performance gains of up to 2.6 times can be observed for the SFN case, as compared to the baseline case. This means that the worst user throughput which is the maximum achievable rate using VR broadcast for the SFN scenario is 2.6 times higher than the uncoordinated baseline scenario. Similar trends can be observed in the spectrum scaling requirement values shown in Fig. 6. There is approximately 18 % reduction in the spectrum requirements for the SFN case as compared to the baseline case, with slow-fading. For the ideal scenario, the reduction is much more significant with spectrum requirements reduced by almost 62 %. Thus, using the considered 5G setting, under ideal conditions the VR broadcast traffic can be sent over the air interface with approximately 1.8 GHz of system bandwidth.

In this work, we discuss various challenges that could be encountered for delivering immersive VR content using broadcast in an indoor scenario, with localized network deployments. For some key challenges such as deployment costs

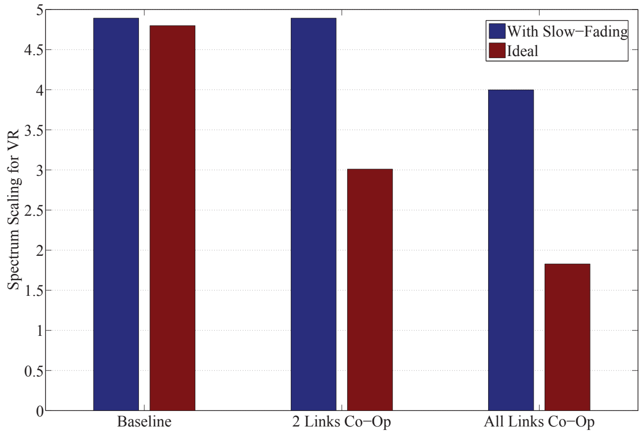


Fig. 6. Spectrum scaling requirement for VR broadcast.

and bandwidth, solutions in terms of usage of SFN type of deployments and unlicensed mmW bands were considered. Performance evaluations using realistic LTE and 5G settings were shown in terms of SINR distributions and possible VR broadcast throughput rates. From the evaluations, we can observe that the challenging requirements in terms of data rates can be achieved under ideal conditions with slightly higher provisioning of system bandwidth. It can also be observed that achieving the target requirements using uniform deployment of users is much more challenging, without densifying the network further which involves significant CAPEX investments. The considered scenario is applicable for mass delivery of common content which could be applied to use cases such as immersive learning environments in classrooms, virtual operas/concerts, apart from disrupting the future cinematic experience.

V. Conclusion

Applications which deliver immersive experience to the end users such as virtual/augment reality remain at the forefront of driving higher data rate demands in mobile networks. The delivery of such services using unicast have been the main focus from the academic and industrial research community. In this work, we investigate the key challenges facing delivery of such applications to a mass audience using broadcast. Performance gains were also investigated in order to evaluate the technology potential using LTE and 5G setting, under ideal and non-ideal conditions and various user placement considerations. From the evaluations, it was shown that under ideal conditions VR data rates can be achieved using broadcast with a slightly higher system bandwidth of 1.8 GHz using an SFN setting.

Future work in this area would include the added capacity requirement for VR broadcast in comparison to unicast and the increase in VR-UE computation complexity due to the higher amount of data being sent over the air. Practical constraints in terms of support for limited mobility and optimal gNB postioning would also be interesting areas of further study. The challenges of supporting system bandwidths higher than 1 GHz, related impacts on operational and energy efficiency of the devices, needs to be further investigated. The feedback mechanism for ensuring reliability and simultaneous support of unicast/broadcast streams would also require further enhancements. The application of beamforming for broadcast, the gains in terms of increase in spectral efficiency and tradeoff with increased base station cost could be evaluated further.

Acknowledgment

This work was supported in part by the European Commission under the 5G-PPP project 5G-Xcast (H2020-ICT-2016-2 call, grant number 761498). The views expressed in this contribution are those of the authors and do not necessarily represent the project.

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