A Comprehensive Analysis on Multicast and Unicast Performance and Selection

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Abstract*—With the need to serve multiple users intended for the same content, especially in mission-critical applications, multicast has long been studied with evolving standards. Compared with its counterpart unicast, multicast has an apparent advantage of sending one copy instead of multiple copies. However, in Long Term Evolution (LTE) Multicast-Broadcast Single-Frequency Network (MBSFN), multicast does not support Multiple Input Multiple Output (MIMO) technology, which is one major technology that improves unicast performance significantly. Multicast also differs from unicast in other aspects that have major performance impacts, such as constructive signals and significant interference reduction, no retransmissions, less available subframes, extended cyclic prefix, and denser reference signals, to name a few. While almost all existing work focuses on a single factor and few addresses MIMO, in this paper we study multicast and unicast in detail with all these factors included, together with their integrated impact on performance. Profound analysis reveals that, contrary to what is commonly assumed in existing studies, multicast and unicast would not share the same modulation and coding scheme, but rather differ significantly in how efficiently they use resources. In addition, the balance among various factors mentioned above leads to a switch point where multicast or unicast outperforms, and the switch point changes upon system configurations and the performance metric of interest. Given that multicast configuration is semi-static in LTE, the results provide insightful guidelines in unicast or multicast deployment in serving user traffic. The work can also be easily extended to other Single-Frequency Network (SFN) based multicast technologies.

***Index Terms*—Multicast, MIMO, throughput, file transfer time.**

I. INTRODUCTION

In wireless cellular networks, when there are multiple User Equipments (UEs) intending for the same content, the base station has two ways to deliver the content, unicast and multicast. In unicast, the base station sends multiple copies to the UEs, one copy per UE. Whereas in multicast, the base station sends one copy to all UEs of interest. Among multicast technologies and without loss of generality, in this paper we consider Long Term Evolution (LTE) Multicast Broadcast Single Frequency Network (MBSFN) due to that it is Single Frequency Network (SFN) based and has the potential to improve cell edge performance, which is critical to First Responders (FRs) to ensure coverage [1].

At first glance it appears that as long as there is more than one user, multicast would always outperform unicast in saving spectrum, since in case of N users, multiple copies in unicast would mean N times as much resource required as that in multicast. A closer look at this statement reveals that it is based on one assumption, that unicast and multicast use the resource as efficiently as their counterparts. This assumption is actually one implicit assumption made in most previous papers studying unicast and multicast, where it was typically assumed that one UE would share the same Modulation and Coding Scheme (MCS) for unicast and multicast [2]. However, this assumption does not hold in practice. On one hand, Multiple Input Multiple Output (MIMO) technologies are applied for LTE unicast, including both transmit diversity and spatial multiplexing, while for multicast, there is no transmit diversity and only one data stream is allowed. That is, MIMO technologies could allow unicast to use resources much more efficiently than multicast. On the other hand, multicast generates constructive signals and gains from interference reduction and diversity combining [3], which could favor multicast significantly in efficient resource utilization. The resulting resource efficiency for both multicast and unicast depends on multiple factors, such as UE distributions and channel conditions.

There are other factors that would lead to different performances, too [4]. One example is that in most cases multicast could use only six out of ten subframes (this constraint is relaxed conditionally to eight in later releases), while unicast could use all ten subframes. Other examples include extended Cyclic Prefix (CP) in multicast versus normal CP in unicast, and denser multicast reference signals (RSs) in resource grid. In addition, while unicast could use Hybrid Automatic Repeat Request (HARQ), there are no retransmissions in multicast, which means a lower target Block Error Rate (BLER) for reliability.

In this paper, we explore and compare unicast and multicast with all these factors embedded throughout the analysis. Since MIMO plays a significant role here, we start with antenna configurations in Signal to Interference plus Noise Ratio (SINR) and resource efficiency, the results of which distinguish unicast and multicast. We then consider the number of copies sent and proceed to throughput and file transfer time. We show that there exists a switch point in the number of users, where unicast or multicast outperforms. Also, the switch points differ upon different performance metrics selected and antenna configurations. The results provide guidelines in unicast or multicast deployment in serving user traffic, especially given that MBSFN configuration is semi-static as specified in 3GPP. To our best knowledge, this work is the first that considers these factors comprehensively. While the analysis and results are based on LTE MBSFN, they can be easily extended to other SFN based multicast technologies.

The following articles study various aspects of multicast technology in LTE. An overview of LTE Evolved Multimedia Broadcast Multicast Services (eMBMS) structure and mechanisms is given in [5]. The standards evolution of multicast broadcast technology in 3GPP is reviewed in [6]. In [7], the authors derive an MBSFN area formation algorithm with optimized overall throughput. In their modeling, the same per Resource Block (RB) throughput is applied for unicast and MBSFN, which is not practical in real cases due to MIMO in unicast and extended CP in MBSFN. We resolve this problem by including them in our modeling. With mobile edge computing and cache ability, the deployment of multicast can be even more flexible and efficient, which is modeled and examined in [8]. Our results could be extended with application of mobile edge computing facilities. Since MBSFN has an advantage in broadcasting but a disadvantage in MCS limitation from the worst SINR among UEs, its scheduling becomes an optimization problem on multicast grouping, which is discussed in [9]. Our analysis could be used to enhance the study by providing practical assumptions for modeling.

The rest of the paper is organized as follows. In Section II, we analyze the differences between unicast and multicast due to antenna configurations, in SINR and resource efficiency. In Section III we explore user performance and the resulting switch points in number of users. Lastly, we conclude our study in Section IV.

II. SINR, RANK, AND RESOURCE EFFICIENCY

In the section we explore how efficient unicast and multicast utilize resources. We start with SINR then move to resource efficiency.

A. Network Design

The network studied has a typical hexagonal grid of 37 tri-sectored sites or 111 cells in total. Inter-site distance is 500 m. Base station transmission power used is 40 w, with transmitter (base station) and receiver (UE) heights of 32 m and 1.5 m, respectively. Band 14 with bandwidth of 10 MHz is applied. Consequently, each subframe has 50 RBs. Urban channel model defined by 3GPP [10] is used for path loss, and Claussen model for shadowing [11]. The small scale fading employed is the International Telecommunication Union (ITU) 'VehA' model with speed of 30 km/h. The center 7 sites, or 21 cells, define the area of interest where UEs are dropped, with other sites generating interference. For multicast, unless mentioned otherwise, the center 7 sites/21 cells form the MBSFN area, which is called 21-cell multicast in this paper.

TABLE I: Antenna Configurations

Number of Tx Antennas	Number of Rx Antennas	Unicast Transmission Mode
1	1	Single Input Single Output (SISO)
2	2	Open Loop Spatial Multiplexing (OLSM)
4	2	OLSM
4	4	OLSM
8	2	TM9
8	4	TM9
8	8	TM9

Seven antenna configurations are studied for both unicast and multicast, as listed in Table I. For unicast, transmission modes specified in 3GPP [12] are listed, which reflect MIMO technologies. For multicast, 3GPP [13] specifies no transmit diversity and single layer transmissions.

The link curves in [4], which consider the extended CP and denser RS pattern for multicast, are used for physical abstraction. For target BLERs, the typical value of 0.1 is selected for unicast, and 0.01 for multicast to compensate for no retransmissions.

B. Unicast

For LTE unicast, as discussed previously, spatial multiplexing is supported and data from multiple layers is jointly coded. For each transport block (TB) sent with MCS m and number of layers L, by using Mutual Information Effective SINR Mapping (MIESM) averaging [14] over all Resource Elements (REs) and layers, we can derive the Additive White Gaussian Noise (AWGN) equivalent post-equalization SINR as below:

$$\gamma(m, L) = f_m^{-1}\left[\frac{1}{LN_{\text{RE}}}\sum_{l=1}^{L}\sum_{c=1}^{N_{\text{RE}}} f_m(\gamma_l^c)\right], \quad (1)$$

where $f_m(\cdot)$ represents the Bit-Interleaved Coded Modulation (BICM) capacity with MCS m; N_{RE} is the total number of REs used; and γ_l^c is the post-equalization SINR over RE c for layer l.

Let (m_0, L_0) denote the optimal value of m and L where the UE maximum throughput is achieved. That is,

$$(m_0, L_0) = \arg\max_{(m,l)} throughput. \quad (2)$$

Then

$$\gamma_0 = \gamma(m_0, L_0) \quad (3)$$

is essentially the layer-level AWGN equivalent SINR that maps to the maximum throughput achievable by this TB.

For the seven antenna configurations under study, Figure 1 plots the cumulative density function (CDF) of the resulting γ_0. Note that the equivalent SINR is capped at around 25.76 dB. This is due to the limitation of the BICM mapping. The mapping is designed for SINR in range of [-20, 30] dB, and the highest equivalent SINR mapped back from BICM is 25.76 dB. When the input SINRs before mapping to BICM are above 30 dB, linear averaging is used instead, which we will see later in multicast equivalent SINR.

Figure 1 shows that the CDFs for cases 2x2 and 4x2 are similar which has around 5 dB gain over SISO. Additionally, the cases of 4x4 and 8x2 have comparable SINRs. In these cases a limited set of codebook-based precoders are used. We also observe significant gains by using eight Tx antenna over less Tx antennas. Furthermore, with the same Tx antennas, SINR advances with increasing number of Rx antennas. This is consistent with gains from multiple antennas.

For MIMO, in addition to SINR, another important factor to performance is number of layers, or rank, which maps to number of data streams. For SISO, the rank is always 1. To study rank for other antenna configurations, we drop UEs to saturate the area of interest, and list in Table II the resulting percentage of UEs whose optimized ranks are above 1. It can be seen that although for configurations 2x2 and 4x2, the percentage is low, for other configurations (4x4, 8x2, 8x4, and 8x8), unicast does make good use of multiple data streams.

TABLE II: Percentage with Rank above 1

Antenna Config.	2x2	4x2	4x4	8x2	8x4	8x8
Rank >1	0.85 %	0.15 %	57.0 %	27.0 %	71.4 %	93.4 %

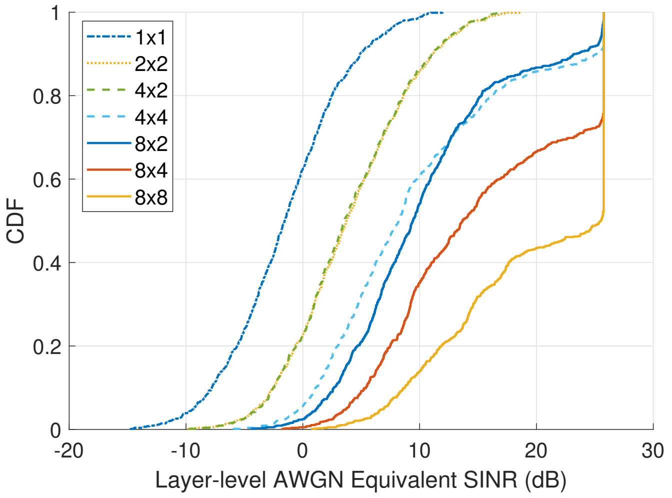

Fig. 1: Unicast Layer-level AWGN Equivalent SINR

SINR together with rank could reflect how efficient unicast uses resources. Instead of two metrics, a more straightforward way is to directly use one metric, resource efficiency, which is the sum of the number of bits each Orthogonal Frequency Division Multiple Access (OFDMA) symbol carries over all layers. Table 7.1.7.1-1 in 3GPP [12] lists the mapping from each MCS index to resource efficiency. Using this table, unicast resource efficiency can then be calculated from the Channel Quality Indicator (CQI) switching points in [4] and the optimal m_0 and L_0 from Eq. (2). For different antenna configurations, Figure 2 plots the resulting CDFs of the resource efficiency at the optimal point (m_0, L_0). As expected, the CDFs share similar trends as the SINR CDFs in Figure 1. In addition, 4x2 and 2x2 almost double the resource efficiency of SISO; and 8x8 almost double the ones of 8x2. This again indicates that unicast improves its performance significantly by taking advantage of MIMO technologies.

C. Multicast

Multicast MBSFN no longer employs transmit diversity and spatial multiplexing. However, multicast does have multiple cells transmitting constructive signals simultaneously to UEs, which results in significant interference reduction and diversity combining gain [3] [4]. Multicast also uses extended CP. By taking these into account, the post-equalization SINR for RE c can be modeled as:

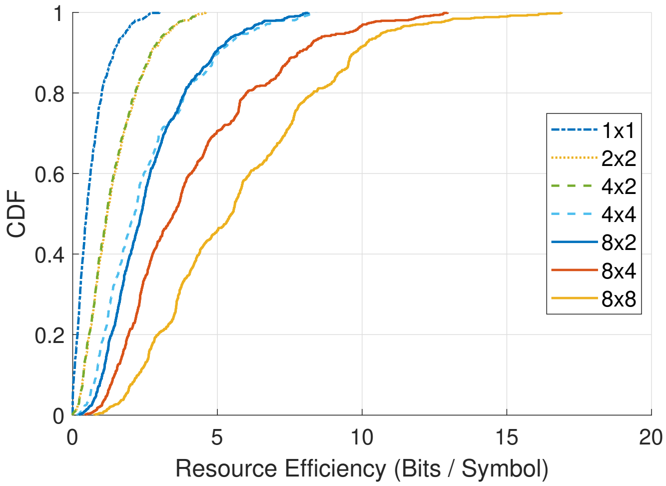

Fig. 2: Unicast Resource Efficiency

$$\gamma^c = \left(\sum_{i=1}^{N_{\mathrm{M}}} (1-\omega_i) P_i^c \|\boldsymbol{f}^c \boldsymbol{H}^{(i,c)} \mathbf{1}_{N_{\mathrm{Tx}}}\|^2 + \sum_{l=N_M+1}^{N} P_l^c \|\boldsymbol{f}^c \boldsymbol{H}^{(l,c)} \boldsymbol{W}^{(l,c)}\|^2 + \|\boldsymbol{f}^c\|^2 \sigma_N^2 \right)^{-1} \tag{4}$$

where N_M cells of total N cells are for MBSFN; ω_i represents the effective portion of signal from cell i within the extended CP; P is the signal power after path loss and shadowing but no small-scale fading; $\boldsymbol{H}$ stands for the frequency domain channel gains; $\boldsymbol{f}$ is for zero-forcing receiver; $\boldsymbol{W}$ represents the corresponding channel precoding matrix; and σ_N^2 serves as the thermal noise.

Similar to unicast, we apply MIESM averaging to obtain AWGN equivalent SINR:

$$\gamma(m) = f_m^{-1} \left[\frac{1}{N_{\mathrm{RE}}} \sum_{c=1}^{N_{\mathrm{RE}}} f_m(\gamma^c) \right]. \tag{5}$$

Different from unicast in Eq. (1), there is no longer averaging over number of layers. Also, there are values of γ^c higher than 30 dB before mapping to BICM. For these SINRs, as mentioned in Section II-B, linear averaging is applied instead of MIESM averaging.

Similar to unicast, let m_0 denote the MCS that achieves the maximum throughput. Then

$$\gamma_0 = \gamma(m_0) \tag{6}$$

is essentially the AWGN equivalent SINR that maps to the multicast achievable throughput. Note that by comparing Eq. (1) and (2) with Eq. (5) and (6), it is apparent that unicast and multicast differ in their optimal MCSs, and in number of data streams as well.

For the seven antenna configurations under study, Figure 3 plots the CDFs of the resulting γ_0. It shows that either increasing number of Tx antennas or number of Rx antennas or both will result in higher SINR. Also because of the MBSFN gain from interference reduction and diversity combining [3], the SINR could achieve very high values, significantly above 20.5 dB required for the highest CQI [4].

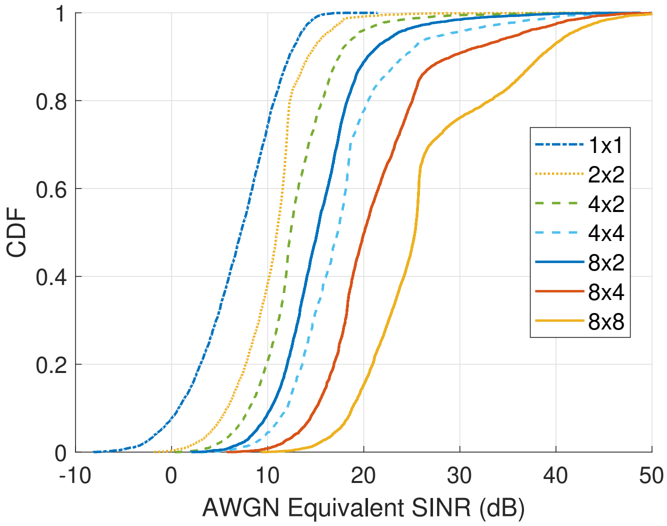

Fig. 3: Multicast AWGN Equivalent SINR

Unfortunately these high SINRs do not necessarily lead to throughput superiority because of the highest CQI cap [12] and lack of MIMO support. Figure 4 shows the resource efficiency, which demonstrates a more realistic achievable performance under various antenna configurations. Note that the extended CP, denser RSs and no retransmissions in multicast have been embedded into the calculation [4]. As expected, the relative positions of the CDFs follow the SINR CDFs in Figure 3. In contrast to unicast where very high resource efficiency can be achieved due to multiple layers (Figure 2), the multicast resource efficiencies are upper bounded by its single layer limitation, which is approximately 5.5 bits per symbol [12].

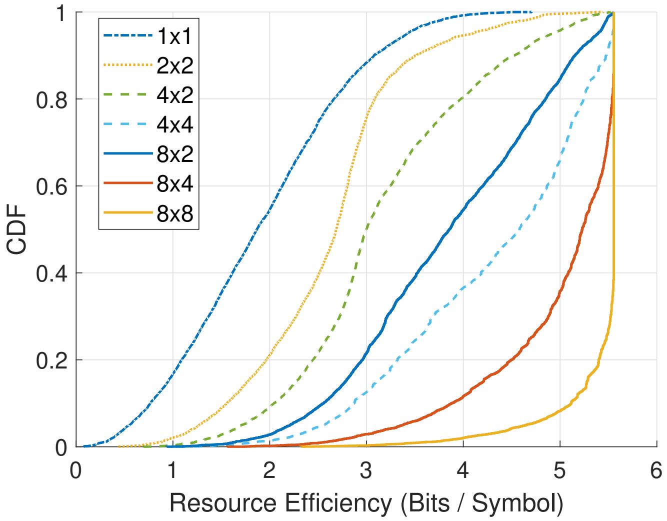

Fig. 4: Multicast Resource Efficiency

In LTE release 10, up to 8-layer downlink transmissions have been specified. Considering realistic device capabilities, the rest of the paper will concentrate on 8x4 antenna configuration with conclusive results for other configurations.

III. Switch Points

In this section we proceed to the impacts of the number of copies sent. Two performance metrics are selected, throughput and file transfer time. Consistent with 3GPP [15], multicast uses six subframes while unicast uses ten.

Due to its complexity and the amount of parameters involved, we use system level simulations for this analysis. The network considered is the same as Section II-A with 8x4 antenna configurations unless mentioned otherwise. For unicast, the typical proportional fairness scheduler is applied; whereas for multicast, all cells within the MBSFN area generate constructive signals by mapping all resources in a subframe to one TB and sending the TB to UEs simultaneously [15]. Additionally, to ensure that all UEs can correctly decode packets, multicast employs the lowest MCS among all UEs.

A. Potential Throughput

We start with potential throughput where there is one UE per cell, so that the impact from other UEs is removed. Consequently, both unicast and multicast send one copy. In addition, for unicast, this means that the entire resource, instead of a portion of it, is assigned to the UE of interest. For multicast, this means that the best MCS for this UE is applied, i.e., the restriction of the lowest MCS among all UEs is lifted. Essentially potential throughput is the highest throughput one UE can achieve at a particular location.

Figure 5 plots the potential throughput of one UE when it is located at each position within the entire center 7 sites, for both unicast and multicast. It shows that unicast potential throughput has a large spread, approximately (0 to 100) Mb/s. Contrarily, multicast potential throughput falls into a relatively small range (0 to 16) Mb/s. In other words, depending on its location, in unicast one user could experience excellent throughput in some areas, while suffer in some other areas; whereas in multicast the user experience is relatively consistent across the whole area, yet much lower than the high end of unicast throughput. The excellent unicast throughput is mainly due to unicast spatial multiplexing, which does not apply to multicast. Nevertheless, multicast improves throughput especially at cell edges, which comes from constructive signals and interference reduction [3]. This is consistent with our previous analysis in Section II on resource efficiency.

If we average potential throughput over the area, unicast gets around 30.5 Mb/s versus multicast 13.87 Mb/s. That is, on average unicast MIMO gains outweigh multicast gains. While unicast outperforms when there is a single UE, in the next subsection we investigate whether this holds with multiple UEs, where unicast sends multiple copies versus one copy in multicast.

B. Actual Throughput and Switch points

Potential throughput heatmaps provide a good view on the highest throughput one UE could achieve across the area. A

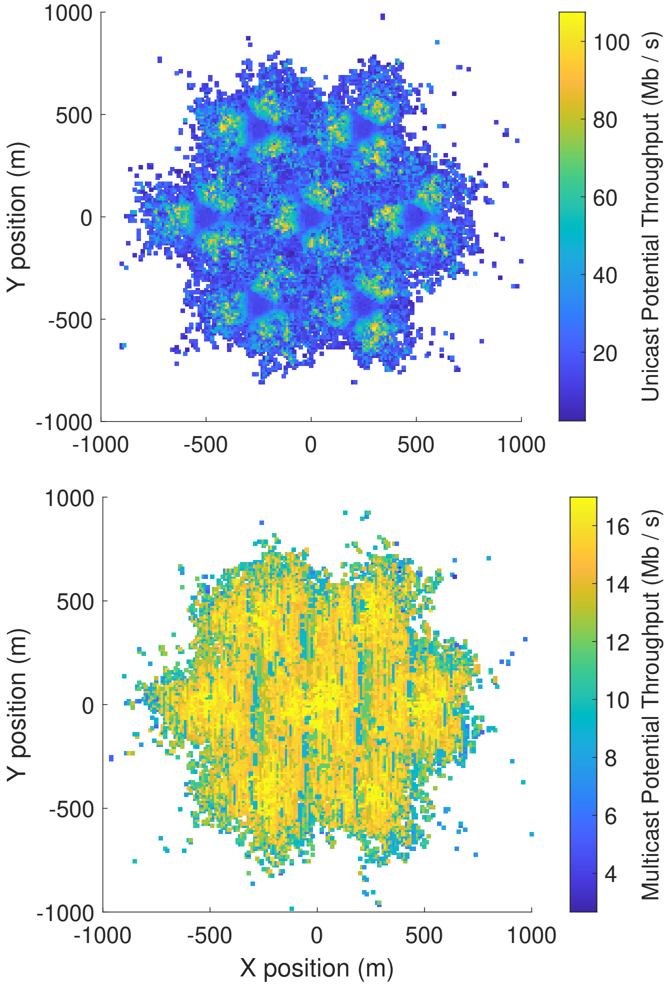

Fig. 5: Potential Throughput Heatmap

more realistic situation is when there are multiple UEs being served. We call throughput in this case actual throughput.

On one hand, in unicast, multiple UEs mean that more copies will be sent and the resource is no longer assigned to a single UE but rather split among multiple UEs. We hence expect that the more UEs being served, statistically the less resource each UE would get, and consequently the less actual unicast throughput. On the other hand, in multicast, it appears that multiple UEs do not affect throughput since one copy will be sent regardless of the number of UEs. However, recall that to ensure correct decoding, the lowest MCS among all UEs is used. Therefore, we also expect that the more UEs being served, statistically the lower MCS that would be used, and consequently the less actual multicast throughput.

As both actual throughputs decrease with increasing number of UEs, and unicast outperforms when there is a single UE as shown in potential throughput, it becomes interesting to see their relative performance with increasing number of UEs. For this purpose, we use Monte Carlo simulations with randomly dropped UEs in the area. The number of UEs per cell ranges from 1 to 10 with 100 simulation runs for each. The actual throughputs averaged over 100 runs are plotted in Figure 6, in blue and green. With increasing number of UEs, Figure 6 shows a sharp drop in unicast actual throughput, much faster than multicast. Plus the higher initial unicast actual throughput with one UE, together they lead to a switch point. Before the switch point, unicast outperforms, while beyond the switch point, multicast outperforms. In this particular setting, the switch point is 4 UEs per cell.

Moreover, in unicast the resource each UE gets is almost inverse to the number of UEs, statistically. It is thus expected that the unicast actual throughput is close to a reciprocal function, and that the throughput would converge to zero. On the contrary, for multicast, the limitation comes from the lowest MCS. It is thus expected that multicast actual throughput would eventually converge to the throughput that maps to the lowest MCS, excluding those UEs falling out of coverage.

Since the MBSFN area size affects performance [16], actual throughput with MBSFN area size of one cell is also plotted in Figure 6 in yellow. Similar to the 21-cell multicast and as expected, the one-cell multicast actual throughput also drops, and there also exists a switch point. Interestingly, although one-cell multicast gets less multicast gains from multiple cell transmissions, it has slightly higher actual throughput than 21-cell multicast, and this higher throughput also leads to a leftward shift of the switch point. This is because the lowest MCS employed is among all UEs within the entire MBSFN area. With the same number of UEs per cell, the more cells in the MBSFN area, the higher probability of a lower lowest MCS, hence a lower actual throughput in 21-cell multicast.

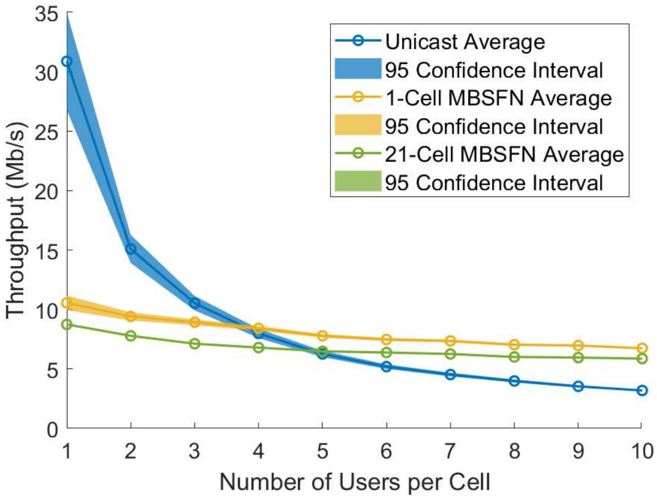

Fig. 6: Throughput Switch Point

Note that the switch point discussed above is based on average actual throughput. While it holds statistically, there exist individual cases that do not follow the switch point. We call these cases irregular cases. For example, when the number of UEs per cell is 2, which is before the switch point, unicast outperforms statistically. However, out of our simulation runs, around 18 % of the runs have multicast outperforming. These cases count towards the irregular cases. Table III lists the percentage of irregular cases for different numbers of UEs per cell. As expected, the percentage rises as the number of UEs per cell gets closer to the switch point, and it can be as high as almost 50 %. Further digging into the data shows that its penalty could be as high as about 2 Mb/s in throughput or about 30 % in throughput percentage. This means that while we could use switch points as a guideline in selecting unicast or multicast to serve traffic, further investigation into irregular cases could help ensure the performance of individual cases.

TABLE III: Percentage of Irregular Cases

UE per Cell	1	2	3	4	5	6	7	8	9	10
%	7.3	18.2	31.1	49.1	36.6	26.1	19.2	14.9	10.6	7.9

The above analysis focuses on 8x4 antenna configuration. As discussed in Section II, different antenna configurations lead to different resource efficiencies for both unicast and multicast, hence different relative actual throughput and switch points. Table IV lists the switch points for the seven antenna configurations studied. Interestingly, on one hand, in unicast higher number of antennas leads to higher MIMO gains, and hence higher unicast throughput and potentially larger switch point. On the other hand, in multicast higher number of antennas also leads to higher resource efficiency as in Figure 4, and hence higher multicast throughput and potentially lower switch point. The numbers in Table IV show that these two effects balance differently under different antenna configurations. Consequently, switch points differ under different antenna configurations, but there is no obvious pattern in switch points versus antenna configurations.

C. File Transfer Time and Switch Points

In addition to throughput, another typical performance metric is file transfer time used for small file transfer. It is the duration from the start of the file transfer to the time the last UE receives the file. We simulate three file sizes with 200 repetitions for each. The resulting average file transfer time is shown in Figure 7.

It can be noted in Figure 7 that unicast file transfer time increases almost linearly with the number of users per cell, whereas multicast file transfer time increases but at a much slower rate. The underlying reasons are the same as those in previous throughput analysis, that more UEs in unicast means less resource for each UE and in multicast means lower MCS employed. Also, with small UE numbers, unicast has shorter file transfer time. Together with the faster increasing rate of unicast, a switch point is formed. In cases of the three file sizes simulated, the switch points are all around three UEs per cell. Recall that the throughput switch point is between 4 and 5. This difference in switch points is due to different amount of data transferred. In case of actual throughput, different UEs will have different amount of data transferred due to the proportional fairness scheduler; while in case of file transfer time, all UEs will have the same amount of data transferred. That is, with the same amount of data transferred, multicast has larger relative gains.

The switch points for all seven antenna configurations are listed in Table IV. Similar to the throughput case, switch points differ under different antenna configurations, but there is no obvious pattern. Note that compared with throughput, all switch points shift lower, which is consistent with the 8x4 configuration discussed above.

TABLE IV: Switch Point

Antenna Config.	1x1	2x2	4x2	4x4	8x2	8x4	8x8
Average Actual Throughput	10	10	4	3	5	4	5
File Transfer Time (0.05 Mb)	1	3	1	2	3	3	3

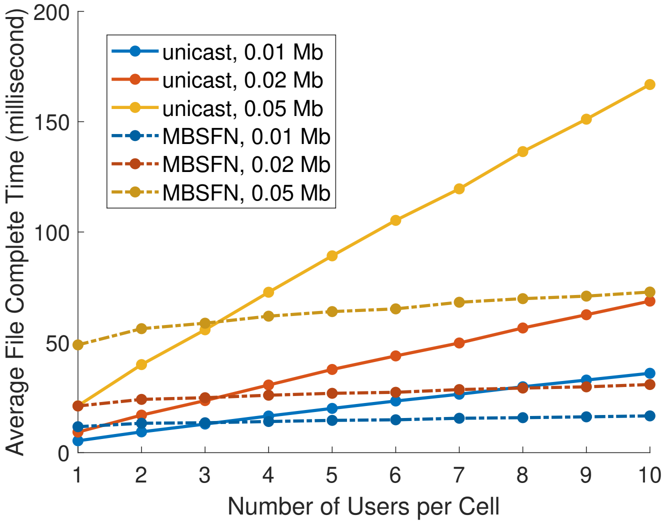

Fig. 7: File Transfer Time Switch Point

IV. CONCLUSION

In this paper we noted that MIMO technologies provide significant gains for unicast transmissions, whereas multicast gains from sending one copy to multiple users instead of multiple copies. We also noted other major factors on performance such as multicast constructive signals and less available subframes. With all the factors included in analysis, we first studied resource efficiency and showed that higher number of antennas improves resource efficiency not only for unicast, but also for multicast. We then explored user experience in terms of throughput and file transfer time. Detailed analysis revealed that there exists a switch point in number of users, where unicast or multicast outperforms.

Although the analysis and results are based on LTE MBSFN, they can be easily extended to other SFN based multicast technologies. Additionally, while the switch points can provide guidelines in selecting unicast or multicast in serving traffic, there exist irregular cases that do not follow switch points. Our next step is to extend the work to other multicast technologies, and to investigate irregular cases to ensure performance of individual cases.

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