Can Massive MIMO Support Uplink Intensive Applications?

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Abstract—Current outdoor mobile network infrastructure cannot support uplink intensive mobile applications such as connected vehicles that collect and upload large amount of real time data. Our investigation reveals that with maximum-ratio (MR) decoding, it is theoretically impossible to support such applications with cell-free Massive MIMO, and it requires a very large number of service antennas in single cell configuration, making it practically infeasible; but with zero-forcing (ZF) decoding, such applications can be easily supported by cell-free Massive MIMO with very moderate number of access points (AP’s), and it requires a lot more service antennas in single cell configuration. Via the newly derived SINR expressions for cell-free Massive MIMO with ZF decoding we show that uplink power control is unnecessary, and that with 10 MHz effective bandwidth for uplink data transmission, in urban and suburban morphologies, on the 2 GHz band, 90/km² and 32/km² single antenna AP’s are enough to support 18 autonomous vehicles respectively. In rural morphology, using 450 MHz band, only 2/km² single antenna AP’s is enough.

Index Terms—Massive MIMO, cell-free, cellular, distributed antennas, power control, zero-forcing, maximum-ratio, matched-filter, connected vehicle.

I. INTRODUCTION

Unlike traditional wireless applications which are downlink intensive, many new IoT (Internet of Things) applications require very high uplink data rates, ultra-low latency and high reliability. While some applications, such as telesurgery, can be supported by wireline transmission technologies such as optical fiber, there are applications that must be supported wirelessly. For example, connected vehicles, such as fully autonomous moving automobiles and drones, may be required to continuously transmit large amounts of real-time data collected by the many sensors about their surroundings to the control center with high reliability and little delay. For those applications, the required uplink data rate can be magnitudes higher than what current 4G wireless technologies can support. For example, each connected car can generate more than 25 gigabytes of data every hour [1]. To upload those data in real time requires a sustained uplink data rate of about 56 Mbps per vehicle. Supporting such high throughput in a highly mobile environment requires very high spectral efficiency because the large bandwidth in mmWave (millimeter wave) is not suitable for mobile applications.

Can a Massive MIMO (multiple-input and multiple-output) wireless network meet such a demand? We shall investigate the feasibility of using MR (maximum-ratio) and ZF (zero-forcing) decoding to support such high uplink throughput applications in both cellular and cell-free configurations. Our investigation yields some surprises – both pleasant and unpleasant ones.

II. MASSIVE MIMO SYSTEM MODEL

Massive MIMO [2] utilizes a large number of service antennas and recurrently updated CSI (channel state information) to enable precise beamforming to a smaller number of user terminals. The service antennas can be co-located at base stations or distributed throughout the coverage area.

Cellular Massive MIMO divides the intended coverage area into cells. Each cell is served by a base station with many co-located service antennas. The base stations do not cooperate except for power control. In a multi-cell system, users in each cell is served by the cell’s base station antennas. Thus each user is served by all the service antennas in the system only in single cell case.

Cell-Free Massive MIMO distributes many service antennas as access points to provide data service throughout the entire intended coverage area. Each user is served by all the service antennas in the system.

A. Uplink Data Channel

For a single cell or a cell-free Massive MIMO, the uplink data channel is modeled as

\[ y = \sqrt{\rho_s} G s + w \]

where \( y \in \mathbb{C}^M \) is the signal vector received by the \( M \) service antennas; \( \rho_s > 0 \) is the normalized uplink SNR (signal-to-noise ratio); \( G \in \mathbb{C}^{M \times K} \) is the channel matrix between the \( M \) service antennas and the \( K \) mobile terminals, where \( M > K \); \( s = [\sqrt{\mu_1} q_1, \ldots, \sqrt{\mu_K} q_K]^T \in \mathbb{C}^K \) is the power controlled user message vector from the \( K \) mobile terminals.

\[
\eta = [\eta_1, \ldots, \eta_K]^T \in [0, 1]^K
\]

is the uplink power control vector. We assume that the user data symbols \( q = [q_1, \ldots, q_K]^T \in \mathbb{C}^K \) satisfies \( E(qq^*) = I_K \), where \( E \) denotes expectation, and \( w \in \mathbb{C}^M \) is the noise vector, with each entry of the vector distributed as \( \text{CN}(0,1) \) and mutually independent. Here \( \text{CN}(\mu, \sigma^2) \) denotes the circularly

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symmetric Gaussian random variable with mean equals $\mu$ and variance equals $\sigma^2$.

The channel between the $m$th service antenna and the $k$th user is modeled as

$$g_{m,k} = \sqrt{\beta_{m,k}} h_{m,k},$$

where $\beta_{m,k}$ models the large-scale fading that accounts for geometric attenuation and shadow fading; $h_{m,k}$ models the small-scale fading that accounts for random scattering. In a rich scattering propagation environment, the magnitude of the signal typically varies randomly according the Rayleigh distribution, thus $h_{m,k}, \forall m, k$ are modeled as independent and identically distributed $\text{CN}(0,1)$ random variables.

In single cell, the $M$ service antennas are co-located at a base station. The large-scale fading between the $k$th user and each of the $M$ service antennas is substantially the same, i.e.,

$$\beta_{m,k} = \beta_k, \quad \forall m.$$

### III. Uplink Performance

In this section, we shall examine the possibilities of using MR and ZF decoding to support uplink intensive wireless applications in both single-cell and cell-free settings, where each user is served by all the service antennas in the system.

Theoretical investigation accompanies a practical example to demonstrate the performance differences among these four configurations.

The example is to support 18 connected vehicles. Each vehicle must upload 25 GB of data per hour [1] continuously. To upload this amount of data to the control center we need an uplink throughput of about 56 Mbps for each vehicle. A Massive MIMO with TDD (time division duplex) operation expend a portion of coherence interval for uplink pilot, and the rest of coherence interval is divided between downlink and uplink for data transmissions [5]. We assume a total spectral bandwidth of 20 MHz. If we use half of the coherence interval for uplink data transmission, then effectively 10 MHz is used for uplink data transmission, leaving 10 MHz for both uplink pilot and downlink data transmission. Thus 6 bps/Hz spectral efficiency will provide 60 Mbps uplink throughput. We assume that each vehicle terminal has 2 Watts of available radiated power. All the antenna gains are 0 dBi; the receiver noise figure is 9 dB. These parameters are used to calculate $\rho_n$ as in Appendix F of [5]. Note that the total bandwidth of 20 MHz is used to calculate the noise power. Simulations are carried out to determine the required number of service antennas $M$ to achieve per vehicle uplink spectral efficiency of 6 bps/Hz.

Using $\hat{G}$ and $\tilde{G}$ to denote the MMSE (minimum mean square error) estimation and estimation error respectively, we have [3]

$$[\hat{G}]_{m,k} \sim \text{CN} \left( 0, \frac{\rho_a \tau \beta^2_{m,k}}{1 + \rho_a \tau \beta^2_{m,k}} \right)$$

(2)

and the estimation error

$$[\tilde{G}]_{m,k} \sim \text{CN} \left( 0, \frac{\beta_{m,k}}{1 + \rho_a \tau \beta^2_{m,k}} \right)$$

(3)

where $[A]_{m,k}$ denotes the entry at the $m$th row and $k$th column of the matrix $A$, and $\tau$ denotes the length of mutually orthogonal uplink pilot sequences that are used for channel estimation.

### A. Simulation Parameters

1) Propagation Models: Traditional Hata/COST213 propagation models are not suitable for cell-free systems because the distances between transmitters and receivers can be much shorter than the applicable range of these models. We use the “NLoS” propagation models specified in [4], for which the path loss in dB is given by

$$
\text{PL}(d) = 161.04 - 7.1 \log_{10}(W) + 7.5 \log_{10}(h) \\
- [24.37 - 3.7(h/h_{AP})^2] \log_{10}(h_{AP}) \\
+ [43.42 - 3.1 \log_{10}(h_{AP})][\log_{10}(d) - 3] \\
+ 20 \log_{10}(f_c) - (3.2[\log_{10}(11.75 h_{AT})]^2 - 4.97)
$$

where $W$ is the street width (in meters); $h$ is the average building height (in meters); $h_{AP}$ is the access point antenna height (in meters); $h_{AT}$ is the user access terminal antenna height (in meters); and $f_c$ is the carrier frequency in GHz; $d$ is the distance between transmitter antenna and receiver antenna, also in meters.

The simulation parameters for the propagation models are compatible with [4] and are summarized in Table I, where $\sigma_{sf}$ is the standard deviation of the lognormal shadow fading.

In Table I, the base station antenna array height for the cellular system is denoted by $h_{BS}$. Taking into account that it is more convenient and cost effective to place all the service antennas in the same tower, we assume a higher antenna tower for cellular case. The valid range for $d$ is between 10 m and 5000 m. In our scenarios, we always have $d > 10$ because all the service antennas are placed more than 10 meters higher than the user antenna.

2) Coverage Region: The service region is a circular disk with radius $R$. For the cellular system, a Massive MIMO base station with $M$ service antennas is located at the center of the circle, and $K$ autonomous vehicles are randomly distributed inside the circle. For the cell-free system, $M$ single-antenna access points and $K$ autonomous vehicles are randomly distributed inside a circle. Fig. 1 depicts an example of the cell-
free system. In both systems, vehicles near the center of the service area are statistically different from those near the edge.

**B. Single Cell with MR Decoding**

The uplink effective SINR for single-cell Massive MIMO with MR decoding is given by [5]

\[
\text{SINR}_{\text{cl,MR}}^k = \frac{M\rho_k\gamma_k\eta_k}{1 + \rho_u\sum_{k'=1}^{K} \beta_k'\eta_k'}, \quad k = 1, \cdots, K
\]

where

\[
\gamma_k = \frac{\rho_u\tau\beta_k^2}{1 + \rho_u\tau\beta_k}
\]

is the mean-square of the channel estimate, and \(\eta_k\) is the uplink power control with individual constraint expressed in (1).

The max-min power control that maximize the minimum uplink SINR can be easily obtained [5]. The resulting maximal common SINR that can be achieved by all users is explicitly as

\[
\text{SINR}_{\text{mm}}^{\text{cl,MR}} = \frac{M\rho_u}{\min_{k'}\{\gamma_k'\}} + \rho_u\sum_{k'=1}^{K} \frac{\beta_{k'}}{\gamma_{k'}}
\]

The max-min power control is given by

\[
\eta_k = \frac{\min_{k'}\{\gamma_{k'}\}}{\gamma_k}, \quad k = 1, \cdots, K.
\]  

The top table in Table II tabulates the SE (spectral efficiency) performance of single cell Massive MIMO with MR decoding. It is known [6] that due to the severe near-far problem in cellular networks, full power strategy (i.e., each user terminal transmits full power) with MR decoding does not work. However, max-min power control can be used to achieve the 6 bps/Hz target with high probability. Note that suburban and rural scenarios require very large numbers of service antennas due to the large path losses. Furthermore, the suburban and rural SE numbers (in red with an asterisk) are 95% likely instead of 99% likely as in the urban case.

**Remark 3.1:** To achieve 6 bps/Hz spectral efficiency, we need an SINR of \(2^6 - 1 = 63 \approx 18\) dB. It has been shown [5] that for any power control, the arithmetic mean of the effective SINR given in (4) over \(K\) users is upper bounded by \(M/K\). Thus for single cell MR decoding we must have \(M \geq 63K = 63 \times 18 = 1134\). The top table in Table II shows that we need many more than 1134 antennas to support suburban and rural scenarios.

**C. Single Cell with ZF Decoding**

The uplink effective SINR for single-cell Massive MIMO with ZF decoding is given by [5]

\[
\text{SINR}_{\text{cl,ZF}}^k = \frac{(M-K)\rho_u\gamma_k\eta_k}{1 + \rho_u\sum_{k'=1}^{K} \left(\beta_k' - \gamma_k'\right)\eta_k'}, \quad k = 1, \cdots, K
\]

where \(\gamma_k\) is given by (5).

The maximal common SINR that can be achieved by all users is

\[
\text{SINR}_{\text{mm}}^{\text{cl,ZF}} = \frac{(M-K)\rho_u}{\min_{k'}\{\gamma_{k'}\}} + \rho_u\sum_{k'=1}^{K} \frac{\beta_{k'} - \gamma_{k'}}{\gamma_{k'}}
\]

The corresponding max-min power control is given by (6) also.

The bottom table in Table II tabulates the spectral efficiency performance of single cell Massive MIMO with ZF decoding. The severe near-far problems in cellular network are effectively mitigated by ZF decoding. We see that full power strategy actually outperforms max-min power control in terms of 99% likely throughput (for urban) and 95% likely throughput (for suburban and rural, indicated by red numbers with asterisk). Remark 3.4 below explains how this is statistically possible. Note that suburban and rural scenarios still require large numbers of service antennas due to the large path losses.

**D. Cell-Free with MR Decoding**

The uplink effective SINR for cell-free Massive MIMO with MR decoding is given by [7]

\[
\text{SINR}_{\text{cf,MR}}^k = \frac{\rho_u \left( \sum_{m=1}^{M} \gamma_{m,k} \right)^2 \eta_k}{\sum_{m=1}^{M} \gamma_{m,k} + \rho_u \sum_{k'=1}^{K} \eta_{k'} \sum_{m=1}^{M} \gamma_{m,k}\beta_{m,k'}}, \quad k = 1, \cdots, K
\]
where

\[
\gamma_{m,k} = \frac{\rho_a \tau \beta_{m,k}^2}{1 + \rho_a \tau \beta_{m,k}}
\]

(8)
is the mean-square of the channel estimate.

Remark 3.2: It is known [8], [9] that the SINR given by (7) is in general too conservative, due to slower channel hardening in cell-free Massive MIMO. Yet, the 99% likely data rates given by (7) are reasonably accurate, as shown in [9].

Let \( \mathbb{R}^M_{+0} \) denote the set of \( M \) dimensional real vectors with non-negative entries, and

\[
\gamma_k = [\gamma_1,k, \cdot \cdot \cdot, \gamma_{M,k}]^T \in \mathbb{R}^M_{+0}
\]

\[
\beta_k = [\beta_1,k, \cdot \cdot \cdot, \beta_{M,k}]^T \in \mathbb{R}^M_{+0}
\]

\[
1_M = [1, \cdot \cdot \cdot, 1]^T \in \mathbb{R}^M_{+0}
\]

The max-min power control and the achieved common maximum SINR can be obtained by using bisection to search for the largest \( \zeta \) that satisfies linear equation (9), with solution \( \eta \) satisfying (1).

\[
\begin{bmatrix}
< \gamma_{1,1}\cdot 1_M >^2 & \cdots & 0 \\
\vdots & \ddots & \vdots \\
0 & \cdots & < \gamma_{K,1}\cdot 1_M >^2 \\
\end{bmatrix}
- 
\begin{bmatrix}
< \gamma_1, \beta_1 > \\
\vdots \\
< \gamma_K, \beta_K > \\
\end{bmatrix}
\eta
= 
(\frac{\zeta}{\rho_a})
\begin{bmatrix}
< \gamma_1,1_M > \\
\vdots \\
< \gamma_K,1_M > \\
\end{bmatrix}
= (\frac{\zeta}{\rho_a}) [\gamma_k]\]

(9)

From (7), regardless what power control strategy is used, we can upper bound the effective SINR for the \( k \)th terminal as follows:

\[
\text{SINR}^{\text{cf,MR}}_k < \frac{\left(\sum_{m=1}^{M} \gamma_{m,k}\right)^2 \eta_k}{\sum_{k'=1}^{K} \sum_{m=1}^{M} \gamma_{m,k} \beta_{m,k'}} 
\]

\[
\leq \frac{\left(\sum_{m=1}^{M} \gamma_{m,k}\right)^2}{\sum_{m=1}^{M} \gamma_{m,k} \beta_{m,k}} 
\]

\[
= \left(\frac{\sum_{m=1}^{M} \gamma_{m,k}}{\|\gamma_k\|_2^2} \cdot 1_M \right)^2 
\]

(10)

In particular, for max-min power control, the achieved common SINR for all \( K \) user terminals is upper bounded by

\[
\min_{k=1, \cdot \cdot \cdot, K} \left(\frac{\gamma_k}{\|\gamma_k\|_2} \cdot 1_M \right)^2
\]

(11)

Lemma 3.3: Let \( x = [x_1, \cdot \cdot \cdot, x_M]^T \in \mathbb{R}^M_{+0} \). Then

1) \( \max_{x \in \mathbb{R}^M_{+0}, \|x\|_2=1} \langle x, 1_M \rangle = \sqrt{M} \)

and \( \langle x, 1_M \rangle = \sqrt{M} \) if and only if \( x_1 = \cdot \cdot \cdot = x_M \).

2) \( \min_{x \in \mathbb{R}^M_{+0}, \|x\|_2=1} \langle x, 1_M \rangle = 1 \)

and \( \langle x, 1_M \rangle = 1 \) if and only if there exists an entry \( x_i \) of \( x \) such that \( x_i = 1 \) and \( x_j = 0 \) for \( j \neq i \).

Proof: 1) is obtained by the Cauchy-Schwarz inequality.

To prove 2), noting that \( \sum_{m=1}^{M} x_m^2 = \|x\|_2^2 = 1 \), we have \( x_m \leq 1 \) \( \forall m \). Thus \( \langle x, 1_M \rangle = \sum_{m=1}^{M} x_m \geq \sum_{m=1}^{M} x_m^2 = 1 \).

If two or more entries of \( x \) are greater than zero, then \( \left(\sum_{m=1}^{M} x_m^2\right)^2 > \sum_{m=1}^{M} x_m^2 = 1 \). Thus only one entry of \( x \) can be nonzero if \( \langle x, 1_M \rangle = 1 \). The nonzero entry must be 1 since \( \|x\|_2 = 1 \).

By Lemma 3.3, the upper bound (10) is maximized (= \( M \)) if and only if

\[
\gamma_1,k = \cdot \cdot \cdot = \gamma_{M,k},
\]

which is precisely the single cell case where \( M \) access point antennas are co-located. In the cell-free case, this bound can often be very close to 1, which is the minimum for this upper bound by Lemma 3.3, in the case when there is a dominant access point with large \( \beta \), and the rest of the \( \beta \)'s are much smaller relatively. This means that the uplink SINR for the cell-free Massive MIMO with MR decoding is not scalable: the upper bound for the SINR can be very close to 1, regardless how large \( M \) is.

Figure 2 shows the CDF (cumulative distribution function) of the per-vehicle uplink rate in the urban scenario. Even though 1700 AP's are employed, there is a non-negligible probability that the SINR is close to 1, which corresponds to a spectral efficiency of \( \log_2(1 + 1) = 1 \) bps/Hz. It is impossible to achieve a 99%-likely per user rate of 6 bps/Hz even with a huge \( M \). A similar behavior is also observed in suburban and rural scenarios. It is interesting to note that the upper bounds (10) and (11) are remarkably tight in Figure 2, and as \( M \) increases, these upper bounds virtually overlap the corresponding CDF curves in suburban and rural scenarios. Note that no power control strategy can do better than the “MR upper bound”, but the full-power strategy comes close.

The top table in Table III tabulates the spectral efficiency performance of cell-free Massive MIMO with MR decoding. Same as in Table II, the red numbers with asterisk are the 95% likely rates. Since the effective SINR’s are upper bounded by (10) and (11), supporting uplink intensive applications like connected vehicles with MR decoding in cell-free configuration is, unfortunately, not possible.

Remark 3.4: Note that Figure 2 and Table III show that full power strategy gives better 99%-likely per vehicle rate than max-min power control. This can be explained as follows. We use 1000 independent realizations of large-scale fading profiles to produce Figure 2. Thus each CDF curve is generated.
users, and thereby better control the interference. Note that each access point can allocate different powers to different min rates for many other large-scale fading realizations. It is in one large-scale fading realization is higher than the max-
al vehicles. But often the lowest rate for full power strategy
of large-scale fading, at least one of the vehicles with full
1000
power strategy will have a lower rate than all the vehicles
18 = 18000
of ZF decoding matrix is

\[ \hat{G} = \rho_u \eta_k \]

The effective uplink SINR for the \( k \)th user is then given by
\[ \text{SINR}^{\text{ZF}}_k = \frac{\rho_u \eta_k}{\rho_u \sum_{k'=1}^K \eta_{k'} E \left( |b_{k',k}|^2 \right) + \left[ E(G^*G) - 1 \right]_{k,k} \} \]

with 1000 × 18 = 18000 data points. Within each realization of large-scale fading, at least one of the vehicles with full power strategy will have a lower rate than all the vehicles with max-min power control, which imposes the same rate to all vehicles. But often the lowest rate for full power strategy in one large-scale fading realization is higher than the max-min rates for many other large-scale fading realizations. It is theoretically possible that among 18000 rates from full power control strategy, only one is lower than all 1000 max-min rates.

**Remark 3.5:** We note that downlink performance for cell-free Massive MIMO with MR precoding [7], [10] is not confined by upper bounds similar to (10) and (11) because each access point can allocate different powers to different users, and thereby better control the interference. Note that the downlink power control has \( MK \) tunable coefficients while uplink power control has only \( K \).

**E. Cell-Free with ZF Decoding**

Saving the best for last, we next consider cell-free Massive MIMO with ZF decoding, which has not been studied in the existing literature.

We shall first derive an expression for the uplink SINR.

1) Uplink Effective SINR: The ZF decoding matrix is
\[ A_{ZF} = (\hat{G}^* \hat{G})^{-1} \hat{G}^* \]

where \( \hat{G} \) is given by (2), and the superscript \(^*\) denotes conjugate transpose. Applying ZF decoding we have
\[ A_{ZF}y = \sqrt{\rho_u} A_{ZF}Gx + A_{ZF}w \]
\[ = \sqrt{\rho_u} A_{ZF}(\hat{G} + \hat{G})x + A_{ZF}w \]
\[ = \sqrt{\rho_u} x + \sqrt{\rho_u} A_{ZF}Gx + A_{ZF}w \],

where \( \hat{G} \) is given by (3).

The signal power for the \( k \)th terminal is given by
\[ \rho_u E \left( x_k^* x_k \right) = \rho_u \eta_k \]

The effective interference power of the system is contributed by the term
\[ \sqrt{\rho_u} A_{ZF} \hat{G} x + A_{ZF} w \]

which consists of interference due to channel estimation error and noise. To compute the effective interference power, we first compute the covariance
\[ \text{Cov}(\sqrt{\rho_u} A_{ZF} \hat{G} x + A_{ZF} w) = E(\sqrt{\rho_u} A_{ZF} \hat{G} x + A_{ZF} w)^* \]
\[ = \rho_u E(A_{ZF} \hat{G} x x^* \hat{G}^* A_{ZF}^*) + E(A_{ZF} w w^* A_{ZF}^*) \]
\[ = \rho_u E \left\{ A_{ZF} \left( \sum_{k'=1}^K (\bar{g}_{k'} \bar{g}_{k'}^*) \eta_{k'} \right) A_{ZF}^* \right\} + E(\hat{G}^* \hat{G})^{-1} \]

where \( \bar{g}_{k'} \) is the \( k' \)th column of the estimation error \( \hat{G} \).

The effective interference power for the \( k \)th terminal is the \( k \)th diagonal element of the covariance matrix
\[ \rho_u \left\{ \left[ A_{ZF} \left( \sum_{k'=1}^K (\bar{g}_{k'} \bar{g}_{k'}^*) \eta_{k'} \right) A_{ZF}^* \right] \right\}_{k,k} + [E(\hat{G}^* \hat{G})^{-1}]_{k,k} \]

Here \([A]_{k,k}\) is the \( k \)th diagonal element of the matrix \( A \).

2) Max-Min Power Control: Let \( \zeta \) be the common SINR achieved by the \( K \) terminals. From (12) we have
\[ \frac{\rho_u \eta_k}{\rho_u \sum_{k'=1}^K \eta_{k'} E \left( |b_{k',k}|^2 \right) + \left[ E(G^*G) - 1 \right]_{k,k} \} \equiv \zeta \]

We can rewrite (13) in matrix form as
\[ (I_K - \zeta E(B^* \circ B)) \eta = \frac{\zeta}{\rho_u} \text{diag}[E(\hat{G}^* \hat{G})^{-1}] \]
A pleasant surprise is that cell-free Massive MIMO with ZF decoding can easily support such applications in urban, suburban and rural morphologies. An important added advantage is that no power control is needed: every vehicle just transmits with full power. Employing cellular Massive MIMO with ZF decoding to support such applications is also possible if the cell size is small, such as in an urban morphology. Because high SINR is required, using Massive MIMO with MR decoding is in general not desirable. Indeed, our simulations show that MR decoding is not suitable for supporting such applications, either cellular or cell-free. A rather unpleasant surprise is that in terms of 99% likely user uplink throughput, cell-free Massive MIMO with MR decoding severely underperforms cellular due to strong self-interference.

By considering only the single cell case, we overestimate the cellular performance. Yet results still indicate that a cellular network is not suitable for supporting uplink-intensive applications. We only consider single-antenna terminals. Multiple antenna terminals can be deployed to further increase throughput.

Further investigations should include the performance of MMSE (minimum mean square error) type receivers and maximum-ratio combination with weights [11], and correlated and Ricean channels [12].

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