Significant Parameters in the Study of Massive MIMO Systems

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***Abstract*—As the fifth generation of mobile telecommunications (5G) is rolling out, advanced antenna technology has been deployed in the massive multiple-input-multiple-output (mMIMO) systems. For example, the antenna array in the mMIMO systems can adjust its beam steering in response to the time-varying traffic and the radio propagation conditions. This makes the antenna pattern become dynamic and constantly change, which is not the case in the 4G networks. As a result, some conventional methods applied in the study of mMIMO may not be working as expected. Hence, an in-depth and up-to-date study on the mMIMO systems becomes necessary. The up-to-date study on the mMIMO systems can be split into two parts, one is assessing the radio frequency (RF) exposure of the mMIMO systems, the other is analyzing the interference in the mMIMO systems. This paper proposes some significant parameters of mMIMO systems in those two parts respectively. Those parameters are system utilization, actual maximum exposure, data throughput, channel state information, and real-time distance between the users and the base stations respectively. Including those parameters in the study of mMIMO systems can help researchers get more accurate RF exposure values and mitigate the interference in the systems simultaneously. Besides those five parameters, other parameters are definitely needed to be considered as well.**

Keywords—mMIMO, RF exposure, interference mitigation, interference analysis, 5G Network, base stations

I. Introduction

As the development of the 5G network is proceeding, some advanced antenna technology is being implemented on the 5G mMIMO base stations. This results in the radiation pattern of mMIMO system become dynamic and constantly changing. Consequently, some traditional methods applied in the study of mMIMO systems will not be performing as expected. In particular, some techniques applied to calculate the interference in mMIMO systems are no longer applicable. Therefore, some new methods that allow one to account for the effect of dynamic antenna patterns are urgently required to address this issue.

Unlike conventional MIMO systems, mMIMO systems have a great number of antennas and implement some cutting-edge techniques, such as beamforming, capacity enhancement, and millimeter wave. All of these techniques require dynamic antenna pattern. But with dynamic radiation pattern, the direction that the antenna pattern is pointing at becomes a probabilistic problem. This is a challenging problem for the national regulators, because this leads the calculations on RF exposure and interference to become more difficult. And all the telecommunication systems in Canada, must satisfy Safety Code 6 [1], and mitigating the interference in the mMIMO systems can avoid harmful effects to public safety [2]. This motivates the Innovation, Science and Economic Development Canada (ISED) to raise up a research topic, which is "As a regulator, what parameters would model the characteristics of MIMO and massive MIMO antennas."

For the RF exposure of the mMIMO systems, [3] specifies the root-mean-square (RMS) burst power can be used to analyze the exposure level. [4] uses a spectrum analyzer to reconstruct the RF signal and then calculates the average and maximum exposure. [5] takes time-division duplex (TDD) and power reduction factor into account and calculates the realistic maximum exposure. [6] uses a technique called Ray-tracing technique to track each radiated RF signal and calculate the realistic maximum exposure.

As for the interference in the mMIMO systems, [7] lists some conventional methods on interference analysis, which are mostly based on measuring the interference-to-noise ratio (I/N). [8] uses MIMO over-the-air (OTA) testing to measure the data throughput to identify the effects that interference brings to the system. [9] states a promising interference management technique called Interference Alignment (IA) to characterize the capacity of wireless networks. This technique converts the interference analysis question into the capacity analysis question. [10] shows two techniques to mitigate the interference in MIMO systems, which are Dirty Paper Coding (DPC) and Beamforming with Joint Decoding respectively. [11] proposes two algorithms to mitigate the pilot contamination, which causes inter-cell interference in a TDD-mode mMIMO system. Those two algorithms are Improved Path Loss for performing User Grouping (IPLUG) and utilizing pseudo-random code to assign orthogonal pilot sequences to different cells. However, the frequency-division duplex (FDD) mode is used more generally in the industry. Plus, the current cellular systems are mostly implemented in FDD, and most licensed frequency bands are assigned for FDD usage. Hence, [12] proposes a strategy to mitigate interference in an FDD-mode mMIMO system. The strategy is called User Cooperative Interference Cancellation

(UCIC) and is user-centric instead of the conventional cell-centric.

This paper proposes five significant parameters in the study of 5G mMIMO systems, which includes system utilization, actual maximum exposure, data throughput, channel state information, and real-time distance between the users and the base stations. All of these parameters will be discussed in Section IV.

The rest of the paper is organized as follows: Section II describes the detailed information of the previous work. Section III presents the limitations and shortcomings of each previous work. Section IV provides some options to overcome the limitations of those previous work. Section V concludes the paper along with an outlook on the future work.

II. Details of Previous Work

As being discussed in Section I, the study of mMIMO systems can be separated into two sectors, which include RF exposure and interference analysis. Both of those subsections are being studied for protecting public health safety and preserving the performance of the mMIMO systems. This section not only provides some essential background information for those two sectors, but describes the details of previous work on those two sectors.

A. RF Exposure Standards

Different countries in the world have different reference levels for the general public RF exposure. The reference levels are set in terms of the electrical field strength (V/m) or its equivalent plane wave power flux density (W/m^2). For example, when talking about the RF signal in the frequency of 1.8 GHz, according to Health Safety Code 6, the RF reference level in Canada is 61.5 V/m or 10 W/m^2 [1]. But the reference levels in the UK and Australia are 58.3 V/m or 9 W/m^2 and 58.1 V/m or 9 W/m^2 respectively, according to [13] and [14]. Some other European countries set the limiting exposure of RF fields by following the recommendation of the International Commission on Non-Ionizing Protection (ICNIRP) [15]. This leads the majority of European countries to share the same reference level of RF exposure.

Table I, which is partially extracted from [16], demonstrates the limiting exposure of RF fields for the general public in some countries around the world including Canada. The reference levels are shown in terms of power flux density, which is in the unit of W/m^2. The RF frequency in Table I includes 900 MHz (e.g. mobile phones, base stations), 1.8 GHz (e.g. cordless phones), and 2.45 GHz (e.g. microwave oven, Bluetooth).

From Table I, we can conclude that, although the RF reference level in Canada is a bit different from other European countries or ICNIRP, it is still generally comparable with the RF exposure standards in other countries. But how to measure an accurate RF exposure on mMIMO systems deserves some further study and discussion.

B. RF Exposure Measurement

The dynamic antenna pattern makes the RF exposure measurement on mMIMO systems become different from other kinds of systems. In particular, the method on deciding the compliance boundary of mMIMO systems needs to be updated urgently.

TABLE I. RF Exposure Limits for General Public in Differnet Countries (Unit: W/m^2) (from [16])

Country	Frequency		
	900 MHz	***1.8 GHz***	***2.45 GHz***
ICNIRP	4.5	9	10
Canada	6	10	10
USA	6	10	10
Australia	4.5	9	10
UK	4.5	9	10
Germany	4.5	9	10
France	4.5	9	10
Spain	4.5	9	10

Most of the RF exposure measurements are based on assessing the time-averaged instantaneous exposure level E_{avg} and comparing the E_{avg} with the RF exposure reference levels. Alternately, E_{avg} can be converted into the equivalent plane wave power density and compared with the reference levels. The assessment of E_{avg} of an RF signal means measuring the actual, instantaneous electric field strength over a certain amount of time and subsequently taking the average.

[4] utilizes a spectrum analyzer to measure the electric field intensity at a designated point with a sampling frequency. The measurement takes around six minutes. After the six minutes are finished, the researcher applies the following formula to calculate the average intensity:

$$E_{avg} = \sqrt{\sum_{j=1}^{N} \frac{E_j^2}{N}} \tag{1}$$

After that, the researcher compares the computed value with the standard value of RF exposure. This method still applies smoothly to the 5G mMIMO systems.

In [4], the researcher also points out that the RF exposure at an evaluation point, which is in the line of sight (LOS), can reach its theoretical maximum if the system is fully loaded (100% utilized). One can use the theoretical maximum exposure value to analyze the RF exposure of the systems. But this methodology has some significant drawbacks when it is applied to the mMIMO systems. The drawbacks will be discussed specifically in Section III. In addition, [4] raises up another terminology called actual maximum exposure, which takes time-division duplex factor, system utilization, spatial distribution of energy into account.

In [5] researcher provides a case study about computing the actual maximum exposure of a 5G base station. Since the theoretical maximum exposure of a base station is a rated value, [5] multiplies the rated value with the TDD factor and power reduction factor. This results in a much more realistic RF exposure value, which is only around 25% of the theoretical maximum exposure. Then [5] utilizes the actual maximum exposure value to analyze the RF exposure of the 5G base station, and compute the compliance boundaries for the general public and workers.

C. Interference between Non-cooperaitve mMIMO Systems

One of the reasons that the mMIMO system is gaining more and more attention is due to its potential to increase the capacity of communication systems. But the presence of interference in the systems degrades the channel performance. In particular, the frequency reuse technique by nature increases the number of interfering sources and hinders the channel capacity. This is because of the increasing waiting time when the same channel is used by different user equipment (UE). Therefore, the interference in the mMIMO systems needs to be analyzed and mitigated moderately. However, in 5G mMIMO systems, there are a lot of coordination between the UE and the base stations, which is not the case in the previous communication systems. That coordination actively reduces the amount of the intra-cell interference existing in the systems and increases the channel capacity. But the inter-cell interference is still unpredictable.

[7] points out analyzing the interference in the systems can be accomplished by measure the interference-to-noise power ratio (I/N) or (I+N)/N. The (I+N)/N of 3dB and 10dB are considered as two essential threshold values. 3dB represents a moderate likelihood of interference in the system and 10dB represents a high likelihood of interference is involved. But the dynamic antenna pattern makes this method no longer applicable to the mMIMO systems. Since in the mMIMO systems, the signal intensity at an evaluation point is a random variable and hard to predict. Moreover, the interference channel in the mMIMO systems is much more complicated. [17] draws out the interference channel in the mMIMO systems, which is shown in Fig. 1

D. Interference between Cooperative mMIMO Systems

Besides measuring the interference-to-noise power ratio to do the interference analysis, [11] provides two ways to mitigate the pilot contamination in the mMIMO systems. The presence of the pilot contamination can cause inter-cell interference in a TDD-mode mMIMO system. The first algorithm, IPLUG, dynamically classifies users as edge users and central users depending on the distance between the users and the base station. If a user is far away from the base station, then the user is considered as an edge user, otherwise the user will be thought as a central user. Two orthogonal user pilot sequences are sent to the edge users and central users respectively, which helps the edge users avoid pilot contamination. Consequently, the central users and the edge users can be less annoyed by the inter-cell interference. The second algorithm is about utilizing the pseudo-random code to assign orthogonal pilot sequences to different cells, and each cell is receiving the sequence with different delays. The original pilot sequence of each user is multiplied with the pseudo-random sequence, which yields a new pilot sequence. The new pilot sequence will be sent to the base station for acquiring the channel state information (CSI) in the systems. In this algorithm, the inter-cell interference is mitigated by the pseudo-random sequence and the CSI.

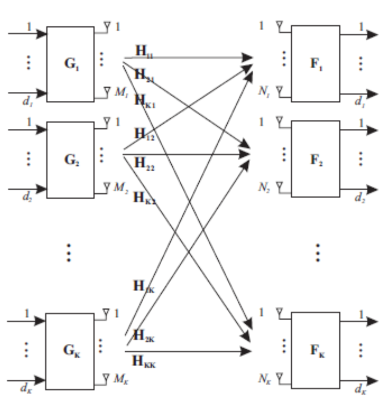

Fig. 1. mMIMO interference channel (from [17])

[12] proposes a method to mitigate the interference in FDD-mode mMIMO systems. A UE estimates its downlink channel and broadcasts the channel characteristic with other vicinity UE. Then, all the UE jointly set their antennas' receiving weight vectors to maximize effective channel gains, so that they can have similar channel characteristics. All the UE with similar channel characteristics will be grouped into a cluster, and the head of the clustered UE (H-UE) will be selected. The H-UE sends channel quality indicator (CQI), and other UEs send channel direction indicator (CDI). The CQI is used for UE-scheduling, power allocation, signal modulation, and coding-rate adaption, whereas the CDI is used for computing precoder matrix. The base station receives both CQI and CDI to mitigate the interference amongst all the UE.

III. Critique of Previous Work

This section lists out the limitations of some previous work discussed in Section I and Section II. The first two limitations are in the area of RF exposure measurement on mMIMO systems. The rest three limitations are in the field of interference mitigation on mMIMO systems.

A. Conservative Results by Theoretical Maximum Exposure

Due to the dynamic antenna pattern, the 5G mMIMO systems cannot focus the beams to an evaluation point for a long-standing time, let alone focusing all the signal power to one point. In this way, it is impossible for an evaluation point to reach the theoretical maximum RF exposure. [18] points out that the actual maximum exposure a mMIMO system is significantly lower than the theoretical maximum value. [19] states that the actual maximum exposure is just around 30% of the theoretical maximum exposure value. Hence, using the theoretical maximum exposure to analyze the RF exposure of a system will lead to an overestimation. [20] proves that this overestimation is much more visible when it comes to determining the compliance boundary of the mMIMO systems. Fig. 2, extracted from [21], shows the compliance boundaries based on theoretical maximum exposure and actual maximum exposure respectively. Obviously, the compliance boundary determined by the actual maximum exposure is much smaller than that determined by the theoretical maximum exposure. But this result still assumes the system utilization of the mMIMO system is 100%. This limitation cannot afford to ignore.

B. *Assumption on 100% System Utilization*

In the real world, an 100% system utilization in a communication system doesn't sound realistic. Fig. 3, extracted from [22], shows the time variation in physical resource block utilization on a mMIMO system, which is operating in 4G LTE TDD mode. The measurement was conducted over four days, and Fig. 3 shows that the system utilization during the four days between 8 a.m and 6 p.m. During the four-day measurement the maximum system utilization measurement is even below 50%, and most of time the system utilization doesn't even reach 30%. Therefore, assuming 100% system utilization is not reasonable, and using the 100% system utilization to anlayze the RF exposure of a mMIMO system definitely leads to a conservative result.

C. *Sensitivity to Channel State Information*

As for the interference mitigation methods on mMIMO systems, [9] utilizes interference alignment and [10] implements dirty paper coding to mitigate the interference in the mMIMO systems. But both of these methods highly depend on the quality of the channel state information, because one can tell which signal is the desired transmitting signal and which signals are the interference signals from the channel state information. In other words, if the accuracy of the channel state information is below expectation, those two methods in [9] and [10] cannot be working as expected, and the interference in the mMIMO systems cannot be mitigated moderately. In this way, we conclude that the interference alignment and dirty paper coding methods are highly sensitive to the channel state information in a mMIMO system, which is a limitation that is not negligible.

D. *High Computational Complexity*

Another limitation of the dirty paper coding on [10] is the high computational complexity. This is especially the case when it comes to the mMIMO systems, since mMIMO systems have a great number of antennas at both transmitters and receivers. The dirty paper coding has to store and transmit all the channel state information to the receivers. Only in this case, the receivers can filter out the interference signals and mainly receive the desired signal. But in 5G mMIMO systems, especially for the system with dynamic radiation pattern, the large number of antennas leads the method to have high computational complexity. The high computational complexity makes the method become inappropriate, because the method cannot adapt to the rapidly changing speed of radiation pattern. The method can even drag out the system operating speed, which will highly degrade the interference mitigation and user experience simultaneously.

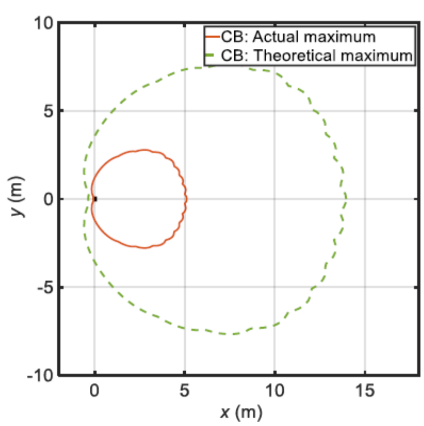

Fig. 2. Compliance boundary determined by theoretical maximum exposure and actual maximum exposure (from [21])

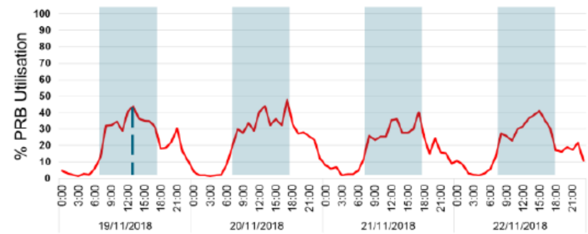

Fig. 3. System utilization over a four-day measurement (from [22])

E. *Only Applicable to Omnidirectional Antenna*

The IPLUG, which is another interference mitigation method discussed in [11], only focuses on the cells of omnidirectional antenna. However, this is not the case in 5G mMIMO systems, since all the antennas in the 5G mMIMO systems can adjust their weight vectors to have dynamic radiation patterns. Therefore, the IPLUG method discussed in [11] cannot be utilized to mitigate the interference in 5G mMIMO systems anyone.

IV. Future Options

This section lists out all the parameters that is significant in the study of mMIMO systems, some of these parameters can also help overcome the limitations of previous work, which is talked about in Section III

A. *Actual Maximum Exposure*

As discussed in Section III, using the theoretical maximum exposure to analyze the RF exposure of a system leads to an overestimation. This is especially the case in the 5G mMIMO systems. Theoretical maximum exposure requires the systems to focus all the power to one evaluation point for a long-standing time. But all the antennas in the mMIMO systems are smart antennas, which can modify the weights to adjust the antenna patterns. This makes focusing all the beams with 100% power to a point become impossible. Plus, using the theoretical maximum exposure value to determine the compliance boundary leads to an overestimation as well. Hence, one needs to include the actual maximum exposure in the study of mMIMO systems, and use the actual maximum exposure to analyze the RF exposure level and determine the compliance boundary of the systems.

B. *System Utilization*

As discussed in Section III, assuming 100% system utilization can lead to a conservative result on RF exposure analysis. Therefore, one must measure the system utilization of a 5G mMIMO system accurately and include this statistic in the study of mMIMO systems. One can measure the system utilization during a certain amount of time, like [22] did. Then calculating the mean value of the measurement dataset. After that, one can include the average system utilization to get a more realistic actual maximum exposure. To be specific, one can multiply the theoretical maximum exposure value with the TDD factor, power reduction factor, and the calculated average system utilization, this multiplication yields a more realistic maximum exposure. A more realistic actual maximum exposure value leads to a more accurate compliance boundary.

C. Data Throughput

As [23] states, the throughput is considered as a KPI (Key Performance Indicator) of a communication system. Including the data throughput into the study of 5G mMIMO systems can help one monitor the performance of the systems. The data throughput can be acquired through MIMO OTA testing, which is specifically discussed in [8]. If the data throughput is high, that means the system performance and the user experience in the system reach the expectation. Moreover, the high data throughput shows that the system is less affected by the interference signals. If the data throughput is relatively low, that means the users in the system are largely annoyed by the interference signals. In this situation, some methods on mitigating the interference signals are urgently required.

D. Channel State Information

Including the channel state information in the study of mMIMO systems can help one mitigate the interference signals in the systems, especially the channel state information of transmitter (CSIT). Since the smart antenna in 5G mMIMO systems can identify which is signal is the desired signal, and which signals are the interference signals, as long as all the parameters and designs are set properly. Knowing the information of the interference signal in CSIT, one can monitor and modify the channel state information of receiver (CSIR) to mitigate the effects that the interference signals would bring to the receiver, and improve user experience eventually. Plus, the channel state information can also help one model the system, especially modeling the communication channel precisely.

E. Real-time Distance between Users and Base Stations

Since the users are moving all the time and the antenna patterns are changing dynamically, it is worthwhile including some real-time parameters when studying the mMIMO systems. Including the real-time distance between the users and base stations in the study of 5G mMIMO systems has two advantages. One is to monitor whether the users get into the compliance boundary of the mMIMO systems accidentally. In such a way, the public safety can be further protected. The other one is to identify the users as edge users or central users. In this way, the antennas in the base stations can modify the weights inside so that the signals transmitted to the edge users are less intensive, and almost all the desired signals are transmitted to the central users. As a result, the user experience is improved and the interference mitigation is proceeding to be accomplished.

V. SUMMARY AND CONCLUSIONS

As the 5G communication is developing around the world, the demands for cutting-edge communication technologies and the corresponding study are becoming necessary. Additionally, some previous work and methods need to be urgently updated because they may not be applicable for the 5G mMIMO systems. For instance, using the theoretical maximum exposure to do RF exposure analysis on mMIMO systems leads to an overestimation. Assuming the system utilization to be 100% yields a conservative result as well. Identifying the interference level by measuring the interference-to-noise power ratio is no longer applicable in mMIMO systems. All the interference mitigation methods on omnidirectional antennas cannot be implemented in the mMIMO systems either. Under this circumstance, some updated study on the mMIMO systems needs to be conducted, and some new parameters need to be included in the study on mMIMO systems.

This paper proposes five parameters, which are significant in the study of mMIMO systems. Those parameters are actual maximum exposure, system utilization, data throughput, channel state information, and the real-time distance between users and base stations. Including these parameters in the study of mMIMO systems can overcome the shortcomings of previous work or methods. Some of the parameters can also help one model the communication systems, especially modeling the communication channels. However, including these five parameters in the study of mMIMO systems only is definitely inadequate. Some in-depth study on the 5G mMIMO systems is further required. And some new significant parameters, excluding the five proposed on this paper, are further required in the study of mMIMO systems as well.

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