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ARTICLE

A generalised antenna correlation model for accurate performance evaluation of 2D massive MIMO communication systems

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ABSTRACT
Massive multiple-input multiple-output (MIMO) is considered as a key component of the new fifth-generation (5 G) communication systems and beyond to meet the rapid explosion of global wireless data traffic. However, antenna correlation is well known to have a direct impact on the capacity of practical MIMO schemes. Therefore, research and industrial communities are still looking for novel techniques to employ a large number of antennas with minimum correlation for compact mobile devices and base stations. In this paper, a realistic and generalised correlation matrix (GCM) model is developed for the accurate performance evaluation of two-dimensional (2D) massive MIMO systems. Based on the proposed GCM model, a closed-form expression of the channel capacity is derived for spatially correlated Rayleigh-fading MIMO environment to assess the acceptable range of antenna correlation. Over different 2D antenna configurations, simulation results validate the accuracy of derived capacity expression and demonstrate that the proposed GCM model tends to provide a more realistic performance compared with the existing methods. This may help to implement a large number of antennas in a constrained-size ground plane with an efficient tradeoff between 2D array designs and required system performance.

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1. Introduction

The new fifth-generation (5 G) wireless communication systems are developed to counter the rapid explosion of global data traffic, driven mainly by the massive use of smartphones, tablets, laptops, and other important smart devices for modern lifestyle. Mobile Internet, online gaming, massive machine-type-communications (mMTC), and Internet of things (IoT) is examples of the extensively deployed wireless services that poses vital requirements for 5 G networks such as massive connectivity, ultra-high rates, and wider coverage (Parkvall et al. 2017; Al-Hussaibi and Ali 2019). To satisfy these critical challenges, massive multiple-input multiple-output (MIMO) schemes of about tens to hundreds of antennas are considered as the key components for 5 G and beyond (Larsson et al. 2018; Huang et al. 2018). Currently, LTE–Advanced Pro (4.5 G) standards support a two-dimensional (2D) antenna array at the base station (BS) with up to 32 elements in Release 14. In addition, 5 G New Radio (NR) specifications under Release 15 have significantly enhanced the BS with 64 to hundreds of antennas (Parkvall et al. 2017; Al-Hussaibi and Ali 2019; Ji et al. 2017). Until now, research activities and practical system designs have shown the possibility of employing more than 128 antennas at the BS/access node (Gao, Vinck, and Kaiser 2018; Gao et al. 2015). However, for compact mobile devices (e.g. smartphones, tablets, and wireless sensors), intensive works are still on-going to implement a large number of miniaturised antennas with a minimum spatial correlation over a constrained-size ground plane (Mourtzios and Siakavara 2017; Lu et al. 2018; Haq and Koziel 2018; Ali et al. 2019; Zhai, Chen, and Qing 2015; Soltani and Murch 2015; Sipal, Abegaonkar, and Koul 2017; Shi et al. 2018; Wong et al. 2016).

In MIMO systems, the channel capacity scales linearly with the minimum number of transmitting and receive antennas assuming independent Rayleigh-fading environment under fixed bandwidth and power conditions (Al-Hussaibi and Ali 2018; Chiani, Win, and Zanella 2003; Shin and Lee 2003). However, antenna correlation (r) owing mainly to insufficient spacing can dramatically reduce the achievable capacity regardless of existing rich scattering environment (Kudathanthirige and Baduge 2017; Biswas, Masouros, and Ratnarajah 2016; Masouros and Matthaiou 2015; Masouros, Sellathurai, and Ratnarajah 2013). This challenging issue motivates the necessity for novel and efficient isolation techniques to fabricate closely spaced antennas with *less than* half wavelength of the carrier frequency (λ_c), particularly for compact mobile devices. For instance, several isolation methods have been proposed to reduce the resulting mutual coupling based on fragment structures (Lu et al. 2018), ground plane alterations (Haq and Koziel 2018), metamaterial structures (Ali et al. 2019; Zhai, Chen, and Qing 2015), coupling elements (Soltani and Murch 2015),

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and decoupling constructions (Wong et al. 2016). However, with the common belief that antenna correlation of $r < 0.5$ has a negligible effect on the capacity of MIMO schemes (Chiani, Win, and Zanella 2003), exploiting a large number of antennas in the modern mobile devices and BSs seems to be extremely constrained by the size factor and definitely represents a significant design challenge. For instance and to the best of our knowledge, the most compact MIMO antenna design for a mobile device includes 20 elements having a total size of $150 \times 80mm^2$ at 2.6 GHz, presenting a high density of 22 antennas per square wavelength (Soltani and Murch 2015).

For wireless systems, the effect of channel correlation on the MIMO capacity has been broadly investigated considering different impairments of the radio propagation environment. The main scenarios include spatial correlation (Al-Hussaibi and Ali 2018; Chiani, Win, and Zanella 2003) and rank deficiency of the channel matrix due to the considered number and distribution of scatterers (Shin and Lee 2003). To isolate the scattering impact, the Kronecker model is typically used to assess the performance of MIMO channels with spatial correlation at transmit and/or receive ends (Loyka 2001; Levin and Loyka 2011). In this model, constant or exponential correlation matrices are widely adopted to simulate the correlation among antennas (Chiani, Win, and Zanella 2003; Shin and Lee 2003; Loyka 2001; Levin and Loyka 2011). However, the basic assumption of equal coefficients in the constant correlation matrix (CCM) is unrealistic and can be used as a lower bound (worst-case analysis) of the system performance. On the other hand, the exponential correlation matrix (ECM) (Loyka 2001) may tend to exaggerate the performance of actual 2D antenna arrays where the realised correlation between adjacent elements is not always higher than that of the distant antennas (in term of antenna indices). In addition, other techniques such as successive colouring (Al-Hussaibi and Ali 2012) and iterative colouring (Al-Hussaibi and Ali 2011) channels are limited for the applications of 1D (i.e. linear) antenna array designs.

In this paper, we consider the performance evaluation of correlated 2D massive MIMO communication systems. The main contributions of this work are summarised as follows:

(1) A generalized correlation matrix (GCM) model is developed for the accurate performance evaluation of 2D antenna array designs. Based on this more realistic model, a closed-form expression of the upper bound capacity of spatially correlated Rayleigh fading MIMO channel is derived to assess the acceptable correlation factor between antenna elements which is a critical design objective over constrained-size ground planes.

(2) Considering the targets of new LTE releases towards massive MIMO systems, analytical results validated with numerical simulations show that the proposed model tends to predict sensible performance compared with the existing CCM and ECM forms. Most importantly, it demonstrates that the basic assumption of acceptable correlation range of less than 0.5 is not always proper choice under certain conditions of a large number of antennas at the correlated side and moderate to high signal-to-noise-ratio (SNR) settings.

(3) The achieved findings may help designers to accommodate a large number of MIMO antennas in a compact space with valuable tradeoff between different 2D array configurations and desired system performance. Furthermore, the proposed GCM model can be applied effectively for the evaluation of 2D array designs in diverse wireless applications such as mMTC (Al-Hussaibi and Ali 2019), sensors and wearable devices (Ali et al. 2019), multi-panel MIMO (Huang et al. 2018), Wi-Fi and WiMAX networks (Lu et al. 2014), radar systems (Guidi, Guerra, and Dardari 2016), unmanned aerial vehicular (UAV) communications (Chandhar and Larsson 2019), relay systems (Liu et al. 2017), and wireless power transfer (Kashyap, Bjornson, and Larsson 2016).

The rest of this paper is organised as follows. In Section 2, an analytical GCM model is presented. Section 3 investigates the capacity of correlated MIMO channel. Some important results and discussion are shown in Section 4. Finally, Section 5 concludes the paper.

Notations: throughout this paper, bold-face uppercase and lowercase letters denote matrices and vectors, respectively, while plain letters stand for scalars. $\mathcal{C}^{m\times n}$ denotes complex $m \times n$ matrix. The superscripts $[.]^*$ and $[.]^H$ stand for complex conjugate and conjugate transposition, respectively. $\mathbb{E}[.]$ is the expectation operator and $\mathbf{I}_m$ is $m \times m$ identity matrix. $\det[\mathbf{A}]$ and $\mathbf{A}^{1/2}$ denote the determinant and Hermitian square root of the matrix $\mathbf{A}$, respectively. $\mathbf{A}^{(k)}$ denotes $k \times k$ principal submatrix constructed from 1^{st} to k^{th} rows and columns of $\mathbf{A}$.

2. A generalised correlation matrix (GCM) model

Consider a point-to-point MIMO communication system with N transmit and M receive antennas. Based on the Kronecker model (Shin and Lee 2003; Levin and Loyka 2011), the correlated Rayleigh-fading MIMO channel $\mathbf{H} \in \mathcal{C}^{M\times N}$ whose entries h_{mn}; $m = 1,\ldots,M$; $n = 1,\ldots,N$ represent the complex gains from n^{th} transmit to m^{th} receive antennas can be represented as

$$\mathbf{H} = \mathbf{R}_r^{1/2}\mathbf{G}\ \mathbf{R}_t^{1/2} \tag{1}$$

where $\mathbf{R}_r \in \mathcal{C}^{M\times M}$ and $\mathbf{R}_t \in \mathcal{C}^{N\times N}$ denote positive definite correlation matrices at transmit and receive sides, respectively, and $\mathbf{G} \in \mathcal{C}^{M\times N}$ is spatially white (uncorrelated) channel matrix whose elements are i.i.d. complex Gaussian random variables with zero-mean and unit variance.

When the ECM model is utilised for a regular antenna array of N_a elements, the entries of $N_a \times N_a$ correlation matrix $\mathbf{R}$ are given in (Al-Hussaibi and Ali 2018; Chiani, Win, and Zanella 2003; Loyka 2001; Levin and Loyka 2011) as

$$R_{ij} = \begin{cases} r^{|j-i|}, & i \le j \\ (r^*)^{|i-j|}, & i > j \end{cases} ; \quad |r| < 1 \tag{2}$$

where R_{ij} ; $i,j = 1,\ldots,N_a$ denotes complex correlation coefficient between i^{th} and j^{th} antennas, and the factor r is determined by the correlation between any pair of nearest antennas. While this model predicts good performance results for 1D antenna arrays, it has a serious shortcoming when applied for 2D arrangements. For instance, the achieved correlation between adjacent antenna pairs is not always higher than that of the far elements. Therefore, a generalised correlation matrix (GCM) model is developed in this section for any 2D antenna array design to mitigate the aforesaid limitations of CCM and ECM techniques.

To clarify the principles of GCM method, consider a 2D massive MIMO antenna array configuration of N_a elements as shown in Figure 1. The antenna elements $A_i; i = 1,\ldots,N_a$ are placed in the $x = \{1,2,\ldots,U_x\}$ and $y = \{1,2,\ldots,U_y\}$ directions with normalised length units based on the minimum centre-to-centre spacing of $d_{min} = \alpha\lambda_c < \lambda_c/2$, where $N_a \le U_xU_y$ and the required size for antenna array ground plane can be found as $S_a > (U_x - 1)(U_y - 1)\alpha^2\lambda_c^2$. The factor $\alpha < 1/2$ is used since the correlation between adjacent antennas is theoretically zero for $d_{min} = \lambda_c/2$. For correlation factor r between any pair of nearest antennas in the x-direction or y-direction with $d_{min} < \lambda_c/2$ spacing, the coefficients of GCM are given in terms of the Euclidean distance $d(A_i, A_j)$ between i^{th} and j^{th} antennas as

$$R_{ij} = \begin{cases} r^{d(A_i,A_j)}, & i \le j \\ (r^*)^{d(A_i,A_j)}, & i > j \end{cases} ; \quad |r| < 1 \ ; \ N_a \le U_xU_y;$$
$$d(A_i, A_j) = \left[(x_j - x_i)^2 + (y_j - y_i)^2\right]^{1/2}. \tag{3}$$

In this case, we have replaced the simple exponential terms in ECM model (2) represented by the associated antenna indices (i and j) (Loyka 2001) by the real distances between antenna elements $d(A_i, A_j)$ for more precise results. To the best of our knowledge, this issue has not been considered before and requires critical analysis and validation for more insight towards effective 2D antenna array designs.

In Figure 2, a representative example of $N_a = 12$ antennas for MIMO system is shown with two possible configurations (A and B) over the constrained-size ground plane. In configuration (A), $U_x = 4$ and $U_y = 3$ are utilised to attain $U_xU_y = N_a = 12$ without any empty places on the ground plane. In contrast, configuration (B) has three unoccupied places where $U_x = 5$, $U_y = 3$, and $U_xU_y = 15 > N_a$.

The above formulations demonstrate that GCM model is physically sensible where the spatial correlation always decreases as the distance between any pair of antenna increases. Furthermore, owing to its flexibility, it can be applied efficiently in diverse practical 2D antenna arrays. For a fixed number of antennas N_a, different design arrangements will produce different correlation matrices which have a direct impact on the system performance.

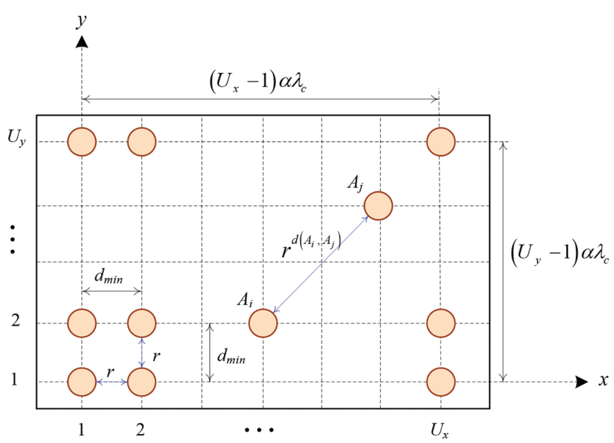

Figure 1. 2D massive MIMO antenna array configuration of N_a elements.

3. Capacity analysis of correlated MIMO channel

For the considered $M \times N$ MIMO system of constrained transmit power $\mathcal{P}$, equal power allocation strategy $(\mathcal{P}/N)$ is commonly used for each transmit antenna when the channel is perfectly known at the receiver. The received signal model is described by

$$\mathbf{r} = \mathbf{H}\mathbf{v} + \mathbf{n} \tag{4}$$

where $\mathbf{r} \in \mathcal{C}^{M\times 1}$ is the received signal vector,$\mathbf{v} \in \mathcal{C}^{N\times 1}$ is the transmitted signal vector of zero-mean and covariance matrix $\mathbb{E}[\mathbf{v}\mathbf{v}^H] = (\mathcal{P}/N)\mathbf{I}_N$, and $\mathbf{n} \in \mathcal{C}^{M\times 1}$ is i.i.d. additive white Gaussian noise (AWGN) vector of elements having zero-mean and variance σ_n^2.

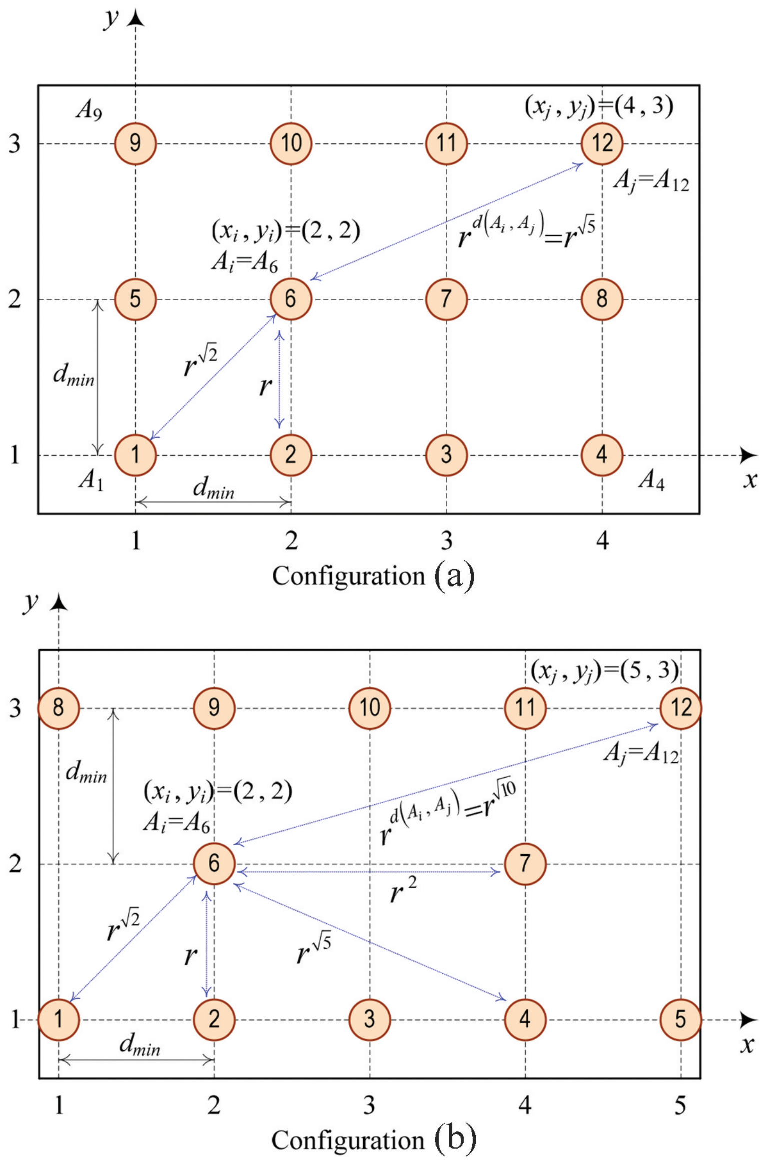

Figure 2. A representative example of 2D antenna array configurations for MIMO system with $N_a = 12$ antennas over constrained-size ground plane. (a): $U_x = 4$ and $U_y = 3$, (b) $U_x = 5$and $U_y = 3$.

For fixed channel realisation $\mathbf{H}$, the channel capacity C is given in bit/s/Hz as (Chiani, Win, and Zanella 2003)

$$C = \log_2 \det\left(\mathbf{I}_L + \frac{\rho}{N}\mathbf{W}\right) = \sum_{l=1}^{L} \log_2\left(1 + \frac{\rho}{N}\lambda_l\right) \quad (5)$$

where $\rho = \mathcal{P}/\sigma_n^2$ is the average SNR at each receive antenna, $L = \min\{N, M\}$ is the channel rank, $\mathbf{W} \in \mathcal{C}^{L\times L}$ is defined as $\mathbf{W} = \mathbf{H}\mathbf{H}^H = \mathbf{R}_r\mathbf{G}\mathbf{R}_t\mathbf{G}^H$ for $M \le N$ and $\mathbf{W} = \mathbf{H}^H\mathbf{H} = \mathbf{G}^H\mathbf{R}_r\mathbf{G}\mathbf{R}_t$ for $M>N$, and $\lambda_l; l = 1,\ldots,L$ denote the nonzero eigenvalues of $\mathbf{W}$.

Since the channel $\mathbf{H}$ is randomly varying, the performance measure of ergodic (mean) capacity $\bar{C}$ over many channel realisations can be evaluated as (Shin and Lee 2003)

$$\bar{C} = \mathbb{E}\left[\log_2 \det\left(\mathbf{I}_L + \frac{\rho}{N}\mathbf{W}\right)\right]. \quad (6)$$

Thus, the upper bound approximation of (6) can be found by applying Jensen's inequality as

$$\bar{C} \le \log_2\left[\mathbb{E}\left\{\det\left(\mathbf{I}_L + \frac{\rho}{N}\mathbf{W}\right)\right\}\right]. \quad (7)$$

Besides, the term under expectation in (7) can be written in terms of all principal minor determinants as (Horn and Johnson 2013) and [19, Theorem II.3]

$$\det\left(\mathbf{I}_L + \frac{\rho}{N}\mathbf{W}\right) = 1 + \sum_{u=1}^{L}\sum_{k=1}^{u} \det\left(\frac{\rho}{N}\mathbf{W}^{(k)}\right) \quad (8)$$

where $\mathbf{W}^{(k)}; k = 1,\ldots,u \le L$ is $k\times k$ principal submatrix constructed from the 1^{st} to k^{th} rows and columns of $\mathbf{W}$. The mean of the above equation can be found as

$$\mathbb{E}\left\{\det\left(\mathbf{I}_L + \frac{\rho}{N}\mathbf{W}\right)\right\} = 1 + \sum_{u=1}^{L}\left(\frac{\rho}{N}\right)^u \sum_{k=1}^{u} \mathbb{E}\left\{\det\left(\mathbf{W}^{(k)}\right)\right\}$$
$$= 1 + \sum_{u=1}^{L}\left\{\left(\frac{\rho}{N}\right)^u \binom{M}{u}\binom{N}{u} u!\ \det\left(\mathbf{R}_r^{(u)}\right)\ \det\left(\mathbf{R}_t^{(u)}\right)\right\} \quad (9)$$

where $\mathbf{R}_r^{(u)}$ and $\mathbf{R}_t^{(u)}$ are $u \times u$ principal submatrices of $\mathbf{R}_r$ and $\mathbf{R}_t$ matrices, respectively.

Therefore, a closed-form expression of the upper bound capacity (7) can be written as

$$\bar{C} \leq \log_2\left[1 + \sum_{u=1}^{L}\left\{\left(\frac{\rho}{N}\right)^u \binom{M}{u}\binom{N}{u} u!\ \Phi_u \Psi_u\right\}\right] \quad (10)$$

where $\Phi_u = \prod_{k=1}^{u} \phi_k$ is the product of all eigenvalues $\phi_k; k = 1, \ldots, u$ of submatrix $\mathbf{R}_r^{(u)}$ and $\Psi_u = \prod_{k=1}^{u} \psi_k$ denote the product of all eigenvalues $\psi_k; k = 1, \ldots, u$ of $\mathbf{R}_t^{(u)}$.

From (10), it is clear that the maximum capacity is achieved for the uncorrelated channel with a full degree of freedom (DoF) of L where $\Phi_u = \Psi_u = 1$ for all $u = 1, \ldots, L$. As the correlation increases, the values of Φ_u and Ψ_u are decreased from 1 towards zero for $2 \leq u \leq L$, and hence, less DoF can be realised and the capacity degradation depends mainly on the distribution of dominant eigenvalues of utilised correlation matrix model.

4. Simulation results and discussion

In this section, numerical results of the upper bound capacity (10) and Monte Carlo simulations of (6) over spatially correlated Rayleigh-fading channel are shown using MATLAB environment to investigate the impact of antenna correlation on the performance of $M \times N$ MIMO system using proposed GCM model compared with the existing CCM (Shin and Lee 2003) and ECM (2) models. To demonstrate the effectiveness of the proposed model from a theoretical perspective, different moderate/large scale MIMO configurations are investigated. All conducted numerical results are averaged over 10^4 channel realisations.

In Figure 3, the capacity of 12×12 MIMO system is shown assuming a correlation factor of $r = 0.6$ at the transmitter and $r = 0.8$ at the receiver side. GCM model (3) is utilised for the presented antenna configurations (A) and (B) in Figure 2 compared with CCM and ECM methods. It can be seen that the upper bound results are quite tight with the simulation outcomes and for all correlation matrix models. Moreover, GCM shows a realistic and fair performance based on the considered 2D antenna array arrangements as anticipated. For example at SNR of 30dB, the given arrangement in (B) provides extra 5 bit/s/Hz compared with (A) of 72.3 bit/s/Hz due to the unoccupied places on the ground plane (i.e. less correlation impact). In addition, the CCM model of 62.3 bit/s/Hz shows the worst capacity performance less than GCM of design (A) by valuable 10 bit/s/Hz. On the other hand, ECM demonstrates a rather exaggerated performance of 82.2 bit/s/Hz as expected. Similar overall performance of GCM is achieved for 128×64MIMO system as shown in Figure 4 where $(U_x = U_y = 8)$ is used at the transmitter while $(U_x = 16, U_y = 8)$ and $(U_x = 32, U_y = 4)$ are used at the receiver for two possible configurations (A) and (B), respectively.

In Figures 5 and 6, the capacity of considered 12×12 and 128×64 MIMO systems is investigated at SNR of 25dB as a function of receive correlation parameter $(0 \leq r \leq 0.9)$, respectively. In this scenario, the transmitter correlation parameter is assumed to be zero. Summary of the achieved results is presented in Table 1 where it can be seen that 90% of the maximum capacity of

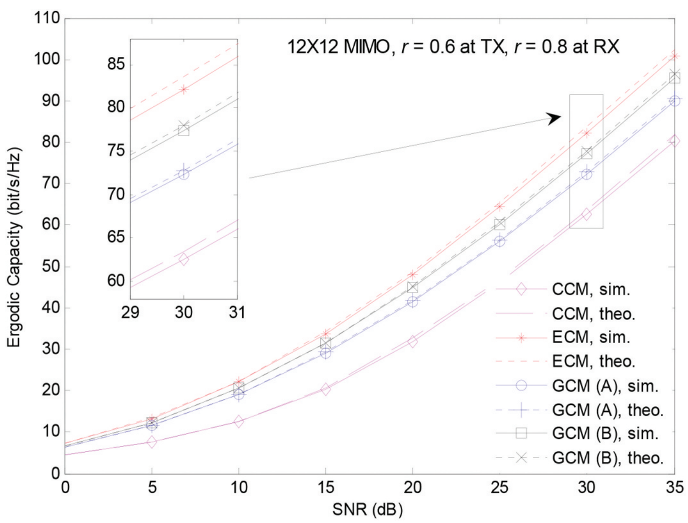

Figure 3. Ergodic capacity of 12×12 MIMO over correlated Rayleigh-fading channel using GCM compared with CCM and ECM models where $r = 0.6$ at the transmitter and $r = 0.8$ at the receiver.

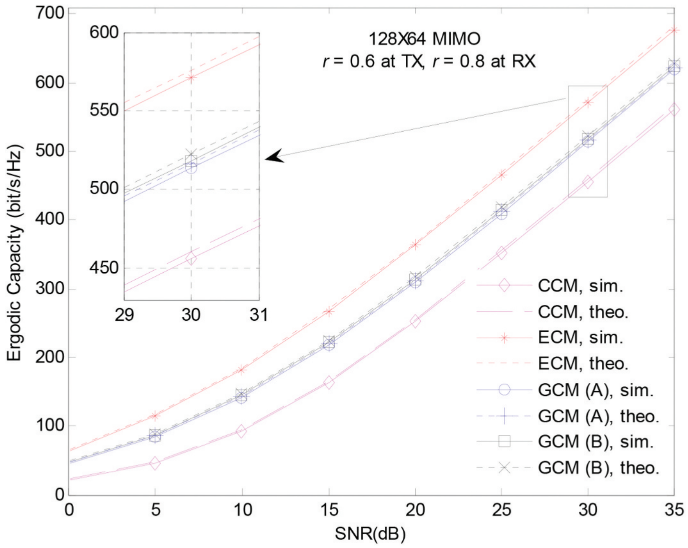

Figure 4. Ergodic capacity of 128 × 64 MIMO over correlated Rayleigh-fading channel using GCM compared with CCM and ECM models where $r = 0.6$ at the transmitter and $r = 0.8$ at the receiver.

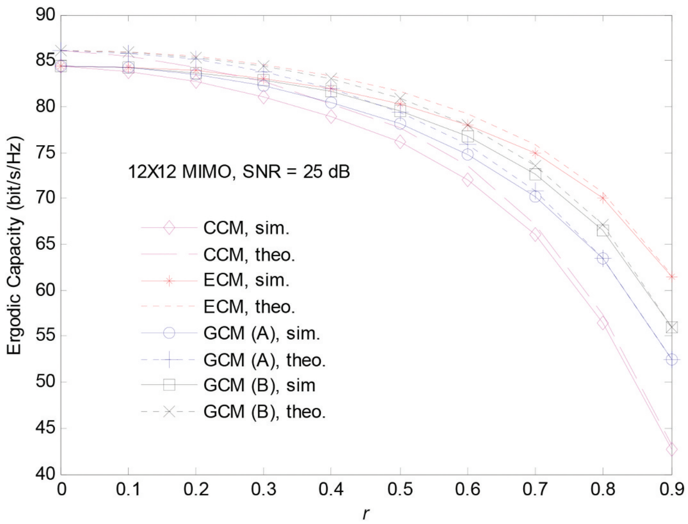

Figure 5. Ergodic capacity of 12 × 12 MIMO over correlated Rayleigh-fading channel as a function of receive correlation r and SNR of 25dB. GCM model is employed compared with CCM and ECM.

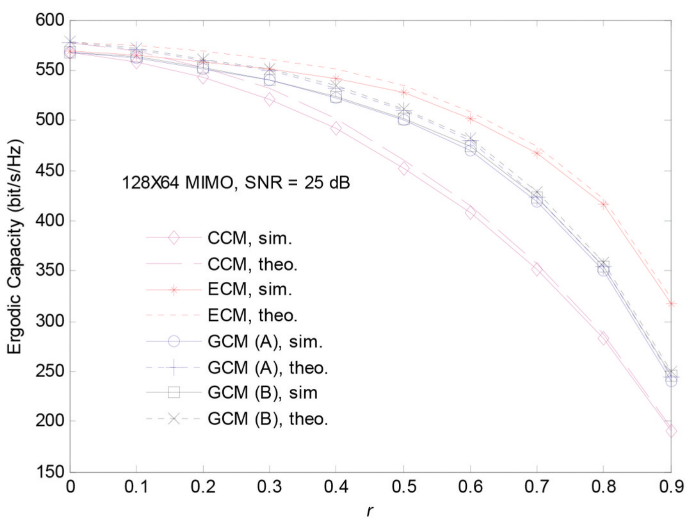

Figure 6. Ergodic capacity of 128 × 64 MIMO over correlated Rayleigh-fading channel as a function of receive correlation r and SNR of 25dB. GCM model is employed compared with CCM and ECM.

Table 1. Correlation factor (r) to achieve 90% of the maximum capacity of 12×12 and 128×64 MIMO systems at SNR of 25dB assuming only receive correlation using CCM, ECM, and GCM models.

	Correlation Factor (r)			
			GCM	
MIMO System	CCM	ECM	Configuration (A)	Configuration (B)
12×12	0.53	0.67	0.60	0.62
128×64	0.37	0.59	0.50	0.51

12×12 system (i.e. for $r = 0$) is achieved at correlation factors of 0.53, 0.67, 0.6, and 0.62 using CCM, ECM, GCM (config. A), and GCM (config. B), respectively. These results clearly indicate negligible correlation effect on the capacity for correlation factors beyond the well-known limit of $r < 0.5$, with a noticeable difference between the considered models. However, as the number of antennas increased, fewer values of antenna correlation parameter should be accepted to sustain the capacity of massive MIMO systems. For instance, $r = 0.37$ and $r = 0.51$ are required for 128×64 system using CCM and GCM (config. B), respectively.

In Figure 7, the capacity of different $M \times N$ MIMO systems is shown at SNR of 10and 25dB as a function of receiver correlation parameter (i.e. zero correlation at the transmitter). GCM model is employed for the considered 16, 32, and 64 receive antennas with $(U_x = U_y = 4)$, $(U_x = 8, U_y = 4)$ and $(U_x = U_y = 8)$, respectively. Summary of the obtained correlation factors to achieved 90% of the maximum capacity is presented in Table 2. It can be seen that as the SNR increases, r is increased for all schemes as expected. Besides, as the number of antennas at the correlated side M is enlarged for a fixed number N, the range of acceptable r is increased considerably. For example, when $N = 16$ and M is enlarged from 16 to 64, r is enhanced from 0.47 to 0.65 at SNR of 10dB, and further increased from 0.59 to 0.78 at SNR of 25dB. Note that for $M = N$, r is slightly decreased for a large increase of utilised antennas. For instance, the difference in r is just about 0.03 between 16×16 and 64×64 MIMO systems for both considered SNR values. From the above outcomes, it can be concluded that MIMO systems may pose different ranges of acceptable antenna correlation under certain conditions such as the use of a large number of antennas at the correlated side and moderate to high operating SNR levels.

Table 2. Correlation factor (r) to achieve 90% of the maximum capacity of $M \times N$ MIMO system at SNR of 10 and 25dB assuming only receive correlation with GCM model.

$M \times N$MIMO	16×16	32×16	64×16	16×32	32×32	64×64
$r(10dB)$	0.47	0.55	0.65	0.44	0.45	0.44
$r(25dB)$	0.59	0.69	0.78	0.59	0.57	0.56

From the conducted capacity simulations of correlated MIMO channel, it can be seen clearly that the proposed GCM tends to offer more sensible results for 2D antenna arrays compared with the existing CCM and ECM models. The impact of actual antenna designs (e.g. patch antennas) (Sipal, Abegaonkar, and Koul 2017; Shi et al. 2018; Wong et al. 2016) and isolation techniques to mitigate the mutual coupling (Lu et al. 2018; Haq and Koziel 2018; Ali et al. 2019; Zhai, Chen, and Qing 2015; Soltani and Murch 2015) on the performance of considered correlation models are isolated for fair theoretical comparisons as in (Loyka 2001). This is very important in the research community of communication systems to provide the key results for the next steps of practical designs, measurements, evaluations, and field tests. Note that the comparison between the correlation results of 2D antenna arrays using analytical models (GCM (3), CCM, and ECM) and other commercial electromagnetic software (e.g. high-frequency structure simulator (HFSS) and computer simulation technology (CST)) is very interesting. However, it requires careful considerations of the aforementioned issues of antenna designs and isolation methods to achieve fair and accurate comparisons. This is beyond the scope of this work but will be considered in the future work.

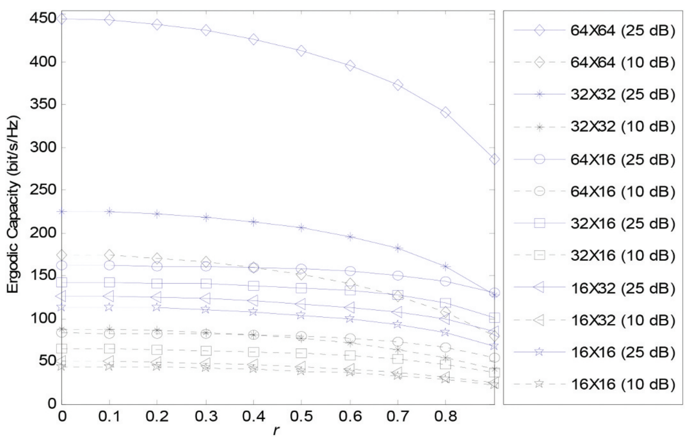

Figure 7. Ergodic capacity of $M \times N$ MIMO over correlated Rayleigh-fading channel as a function of correlation factor r and SNR of 10 and 25dB. GCM model is used.

5. Conclusions

In this paper, a GCM model has been proposed for 2D massive MIMO communication systems to achieve precise performance results for varied antenna array designs. An analytical expression of the upper bound capacity of correlated Rayleigh-fading MIMO channel has been derived based on the GCM model and presented in terms of the eigenvalues of correlation matrices at transmit and receive ends. The analytical capacity results are shown to be in a good agreement with the simulation outcomes of different moderate and large-scale MIMO systems over the entire range of correlation parameters and SNRs. It has been demonstrated that the proposed GCM is very flexible to be used for any 2D antenna array design and enables reasonable performance compared with the existing CCM and ECM models. Furthermore, it has been shown that most of the channel capacity can be achieved even for $r > 0.5$ based on the utilised number of antennas and operating SNR. For instance, when $N = 16$ and M is increased from 16 to 64, r is considerably enhanced from 0.59 to 0.78 at SNR of 25dB. Therefore, a large number of antenna elements can be realised in a compact size to capture most of the promised massive MIMO gains for 5 G and beyond wireless communication systems. In the future work, the impact of different antenna designs and isolation techniques in 2D antenna arrays will be considered for the performance evaluation of analytical correlation models (GCM, CCM, and ECM) compared with that from electromagnetic software simulators and field measurements.

Disclosure statement

No potential conflict of interest was reported by the author.

Notes on contributor

Walid A. Al-Hussaibi (S'07-M'12-SM'17) received the BSc and MSc degrees in Electronics and Communications from the University of Basrah, Iraq, in 1991, and from the University of Science and Technology (JUST), Jordan, in 2000, respectively. From 2001 to 2006, he was a lecturer at the EE Department, BETC, FTE. In 2007, he joined the CRG at Sussex University, UK, as a researcher, where he received his Ph.D. in Wireless and Mobile Communications, in 2011. In 2012, he joined the Southern Technical University (STU), Iraq, as a faculty member, where he is currently an Assist. Prof. with the Department of ET, BTI. His research interests include massive MIMO, multiuser MIMO-NOMA, chaotic communications, channel capacity, performance evaluation, and multiple access techniques for future wireless systems. He is an Associate Editor of the IEEE Access and IEEE TechRxiv moderator.

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