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System Performance Assessment in Dual-Band Device-to-Device MIMO Channels

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Abstract—Device-to-Device (D2D) communications has been embraced as a novel approach for extending coverage in fifth-generation (5G and beyond) wireless networks. Throughput and reliability assessment of such wireless networks are therefore of utmost importance for D2D communication systems design. In this paper, we consider the capacity results of wireless propagation channels in two 5G modes *namely* the sub-6 GHz centimeter-wave (cm-wave) and 60 GHz millimeter-wave (mm-wave) bands for a multiple-input-multiple-output (MIMO) D2D fading channel. Results presented in this paper were obtained from propagation channel measurements jointly conducted in both cm-wave (2-6 GHz) and mm-wave (59-63 GHz) bands using an 8×8 MIMO virtual array setup in an outdoor environment. These measurements were conducted at the exact same locations (with constituents unchanged) in both cm-wave and mm-wave bands for comparability of results. Capacity values were computed using two power policies (with and without channel state information (CSI)). We also investigated the eigenmode spectral structure to understand the *spatial correlatedness* of the channel and the Rician $\mathcal{K}$ -factor to analyze small-scale fading in the channel. The results presented in this paper can be used by wireless systems designer for assessing the performance of D2D systems operating in the cm-wave and/or mm-wave bands for this type of environment.

I. INTRODUCTION

Device-to-Device (D2D) communication has been motivated by the search for a complementary communication architecture to the infrastructure-based wireless communication (traditional cellular communication) so as to satisfy the increasing demands for higher data rate and improved overall wireless coverage by consumers. One way to increase the capacity of a cellular network system is by allowing direct communication between closely located user devices when they intend to communicate with each other instead of conveying data from one device to the other via the radio and core network. Organizations such as the Third Generation Partnership Project (3GPP) are actively pursuing the standardization of D2D communication [1]. An exhaustive reference list and detailed discussion on D2D related applications have been provided in [2].

The centimeter wave (cm-wave) and millimeter wave (mm-wave) bands have been proposed as complimentary frequency bands to be used for next-generation communication systems. Advantages afforded by the cm-wave band include; better coverage due to smaller pathloss and ability to penetrate

walls, while the mm-wave band allows higher data-rate due to large spectrum availability and less interference. An extensive discourse on the joint characterization of wireless propagation in both cm-wave and mm-wave bands has been provided in [3] and [4].

System performance assessment is generally very important for wireless system design and deployment. For example in cellular networks, cell capacity and coverage performance analysis are the driving metrics for determining possible subscriber population as well as governing the number of Access Points (AP) required to deliver a desired level of throughput with a certain reliability value. Similarly, such an analysis would be of great importance to D2D wireless communication system design. Recently, [5] even discussed a way of harnessing and using available systems information such as the correlation between two bands (cm-wave and mm-wave) to enhance communication if both bands are simultaneously available to the user. With all this in mind, quantifiable performance metrics of the propagation channels in which these D2D systems will be deployed will certainly be valuable to network planners and system designers alike.

A number of works [6]–[13] have tackled system performance in D2D networks while the band assignment problem in dual-band systems was discussed in [14]. These works such as [6]–[9] have discussed ways to improve system performance in cm-wave D2D networks while works such as [10], [11] have mainly focused on D2D simulation and performance evaluation in mm-wave bands. The performance of a mm-wave D2D system for the case of a picocell operating in the 60 GHz band was evaluated in [12] through simulation while the effect of power allocation on D2D and cellular user throughputs in mm-wave E-band 5G-underlay networks is discussed in [13]. Note that most of these works are based on D2D communication systems embedded (influenced or controlled) in traditional cellular networks. While a number of papers have compared mm-wave and cm-wave systems for cellular setups, D2D setups, which correspond to situations where Transmitter (TX) and Receiver (RX) are at the same height, have drawn less attention. We are unaware of any works which compared the performance of D2D communication systems in a *jointly* (multi-band) measured propagation channel with TX and RX at the same height.

Fig. 1: Measurement points at the quad

In this paper, we fill this gap by investigating system performance parameters such as the channel capacity values at cm-wave and mm-wave bands in Line-of-sight (LOS) and Non-line-of-sight (NLOS) channels measured in an outdoor environment. We also investigated the eigenmode spectral structure of the propagation channel by providing the distribution of eigenvalues and corresponding spreads in both bands and scenario. This was done to understand the spatial correlatedness of the channel. The small-scale fading in the propagation channel was also investigated with the Rician K -factors obtained from both bands and scenarios presented in this paper.

The rest of the paper is organized as follows. A short description of the channel measurement campaign and corresponding data evaluation procedure is provided in Section II. The small-scale fading analysis is discussed in Section III. Eigenvalue characteristics of the propagation channel is discussed in Section IV. Results from the channel capacity evaluations is provided in Section VI while the summary and conclusion is inferred in Section VII.

II. MEASUREMENT CAMPAIGN

With the aid of a vector network analyzer, a dual-band channel sounder system, which uses an 8×8 virtual multiple-input-multiple-output (MIMO) antenna¹ array configuration and operates in both cm-wave (2 – 6 GHz) and mm-wave (59 – 63 GHz) frequency range was constructed and used for the measurement campaign. The channel measurements were performed for LOS and NLOS scenarios in and around an open-square i.e., a quadrangle (quad) in front of the Norris Medical Library on the Health science campus (HSC) of

the University of Southern California (USC) in Los Angeles. The quadrangle and the measurement locations are shown in Fig.1. The quad is a 33×33 m open space surrounded by buildings and trees. At the center of the quad is a 15×15 m demarcation, where trees and flowers were planted. Additional details about the channel measurement setup and environment have been provided in [3] and [4].

The measurements were conducted with TX-RX separation of 5, 10, 15, 24 and 27 m respectively. Multiple measurements were taken for each distance measured, by placing the TX and RX array at different positions (as shown in Fig. 1). For each TX-RX separation, four positions were selected, respectively for the LOS and NLOS scenarios. These positions provide different realization of shadowing (power-variations due to blockage) effects. We will hence refer to these positions as shadowing points in the rest of the paper. A total of 80 positions were measured in our campaign. The exact same locations (with constituents unchanged) were measured for both cm-wave and mm-wave bands for comparability of results.

The channel transfer function ($\mathbf{H}$) obtained from the measurements was transformed to the delay domain by using an inverse Fourier transform thereby resulting in an impulse response – with the square of its magnitude as the instantaneous power-delay-profile (PDP). For each shadowing location measured, the influence of small-scale fading was removed by averaging the instantaneous PDPs over the 8×8 TX/RX virtual antenna element positions in the array to obtain the average-power-delay-profile (APDP). A sample of the APDP plot at a selected distance for both cm-wave and mm-wave LOS measurements is shown in Fig. 2.

A noise thresholding filter was implemented such that all PDP samples with magnitudes below a certain threshold are set to zero. After this noise filtering, the impulse response

¹ Two vertically polarized Bicone antennas were used for the cm-wave and mm-wave measurements. The gain of these antennas were 2 dBi (at cm-wave) and 1 dBi gain (mm-wave) respectively.

Fig. 2: Sample plots of APDP from 10 m LOS scenario from measurement at both cm-wave and mm-wave bands. The delay was converted to meters as $\tau(s) \cdot c_0(\frac{m}{s})$.

is transferred back into the frequency domain for further processing. Further details about the noise thresholding filter can be found in [4].

We next proceed to the discussion of extracted channel parameters such as the Rician $\mathcal{K}$ -factor obtained from the small-scale fading analysis, channel eigenvalue computation with corresponding spreads and channel capacity values.

III. SMALL-SCALE FADING ANALYSIS

The variation in the received signal amplitude over the 8×8 MIMO channel can be attributed to the small-scale fading (SSF) in the environment. This variation stems from multipath components (MPCs) – due to radio wave – interaction with local scatterers. Since the dual-band measurements were conducted in the same environment with constituents unchanged, we intend to characterize and compare the small-scale fading occurring in both cm-wave and mm-wave bands in this environment.

Several channel measurement works such as [15], [16] have described the SSF statistics as either lognormal, Rician, Rayleigh or m -Nakagami distributed (with an analysis of the Nakagami fading in the same environment as this work provided in [3]), however in this work, the SSF statistics was modeled as Rician distribution with the $\mathcal{K}$ -factor parameter computed using the method of moments as described by Eqs.(1)-(9) in [17]. The $\mathcal{K}$ -factor will be used as a measure for quantifying fading in our analysis. We have provided the logarithmic equivalent (i.e., in dB) of the mean values (over an ensemble of shadowing points at each TX-RX separation measured) of the $\mathcal{K}$ -factor estimated from measurements conducted at the cm- and mm-wave bands for LOS and NLOS scenarios as summarized in Table I.

It can be observed in Table I that less severe fading is experienced in LOS than NLOS in both bands, however, a

LOS – $\mathcal{K}$ -factor (dB)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	7.8	6.7	5.3	3.9	3.5
mm-wave	6.6	5.7	5.1	2.9	2.2
NLOS – $\mathcal{K}$ -factor (dB)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	-5.2	-7.1	-4.4	-5.9	-5.5
mm-wave	-6.2	-7.7	-5.9	-7.1	-6.5

TABLE I: $\mathcal{K}$ -factor (dB) value for LOS and NLOS scenarios in both cm-wave and mm-wave bands

Fig. 3: CDF of $\mathcal{K}$ -factor (dB) in the LOS and NLOS scenario for both bands

more severe fading is experienced in mm-wave band than cm-wave band in both LOS and NLOS scenarios. This observation is intuitive in that although all MPCs are likely to undergo similar propagation mechanisms in both bands for the LOS case, MPCs in the mm-wave band are more susceptible to foliage i.e., trees and bushes in the vicinity of the TX/RX and could have suffered weaker penetration and diffraction in the NLOS case. A cumulative distribution function (CDF) of the $\mathcal{K}$ -factor (dB) using the ensemble of all the measured locations is provided in Fig. 3.

IV. CHANNEL EIGENVALUE CHARACTERISTICS

The eigenvalue or singular value distribution of the propagation channel matrices is a strong indicator of the correlatedness of the channels at different antenna elements. Correlation of the signals at different antenna elements can significantly increase the eigenvalue spread and reduce the capacity of a MIMO system, hence understanding the nature of the eigenvalue distribution could be crucial in system modeling.

The eigenvalues² and corresponding spreads of the propagation channel in both bands and scenarios are presented in this work with a CDF plot of eigenvalues extracted shown

²Note that the eigenvalue (λ) was computed from the spectral decomposition of the Gramian ($(\mathbf{H}(f_k)\mathbf{H}(f_k)^\dagger)$) of the channel transfer function matrix $\mathbf{H}(f_k)$ such that $\lambda(\text{dB}) = 10 \cdot \log_{10}(\text{Eig}\{\mathbf{H}(f_k)\mathbf{H}(f_k)^\dagger\})$, where $\text{Eig}\{\cdot\}$ is the eigen/spectral decomposition operator.

in Fig. 4 while the eigenvalue spreads have been provided in Table II. It is important to note that the CDFs shown in Fig. 4 are derived from all eigenvalues across all frequencies at all measured locations while the spread values in Table II are those from different measurement points and frequencies.

$$\lambda_{\text{spread}}(\text{dB}) = \lambda_{\text{max}}(\text{dB}) - \lambda_{\text{min}}(\text{dB}) \quad (1)$$

Fig. 4: CDF of Eigenvalues (dB) in the LOS and NLOS scenarios for both bands across all frequencies and measured locations.

Firstly, from the results shown in the CDF plot in Fig. 4, it can be observed that eigenvalues are generally larger in the cm-wave than mm-wave frequency bands. The difference in magnitude of eigenvalues between LOS and NLOS scenarios can be explained by the increase in pathloss at the latter scenario. An extensive discourse on pathloss values obtained in both bands for this environment can be found in [3].

Secondly, eigenvalue spreads as shown in Table II were larger in LOS than NLOS at both cm-wave and mm-wave bands. This observation agrees with intuition since a larger spread would inform on the correlatedness of the channel, which is expected in the LOS as compared to NLOS irrespective of the frequency band.

LOS – Eigenvalue spread (dB)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	54.3	62.6	49.6	50.8	49.2
mm-wave	53.1	50.2	51.7	48.0	44.3
NLOS – Eigenvalue spread (dB)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	40.2	40.6	40.9	45.6	38.6
mm-wave	36.1	42.3	38.7	37.2	38.4

TABLE II: Eigenvalue spread (dB) for LOS and NLOS scenarios in both cm-wave and mm-wave bands. The spread is averaged over frequencies and locations.

V. CAPACITY EVALUATIONS

In this section, we analyze the ergodic capacity for the MIMO channels for the LOS and NLOS scenarios in both cm-

wave and mm-wave bands. These capacities were computed by using two different power allocation policies:

- POLICY 1:** Constant TX power (this would be used, e.g., when the TX does not have channel state information (CSI)).
- POLICY 2:** Distribute TX power based on SNR values of sub-channels, i.e., the *waterfilling* concept [18]. This assumes TX does have channel state information and could incur a significant feedback overhead as a consequence. We assume, however, that the transmit power spectrum (i.e., distribution over frequency) is flat.

As presented in this work, the capacity results from these power allocation schemes will serve a readily available quantifiable measure, which will be useful for system design and analysis. Note that in both cases we consider constant TX power, not constant SNR. Consequently, we can expect that LOS will provide *higher* capacity than NLOS, in reversal of the well-known constant-SNR results [18].

The normalized (per unit bandwidth) channel capacity in frequency-selective channels is given by

$$C = \frac{1}{N_F} \sum_k \log_2 |I_{N_R} + \frac{\gamma}{N_T} \mathbf{H}(f_k) \mathbf{H}(f_k)^\dagger| \quad (2)$$

where $\mathbf{H}(f_k)$ is an $N_R \times N_T$ un-normalized transfer function of the channel under consideration (N_R – number of RX antenna array element, N_T – number of TX antenna array element), I_{N_R} represents an identity matrix with size $N_R \times N_R$, the transmit SNR, $\gamma = 88$ dB is calculated from $\frac{P_{TX}}{N_0}$ where P_{TX} is the transmitted power and N_0 is the noise power per sub-carrier, while N_F is the number of sub-carriers. Results of channel capacities obtained from the two power allocation policies are discussed next.

A. Channel capacity using policy 1

We computed the ergodic (average over an ensemble of shadowing positions) capacity with adherence to power policy 1, i.e., with the assumption that there is no CSI at TX hence equal power has been transmitted to all sub-channels. Results from our analysis are shown in Table III). Inter-band and scenario capacity difference can mostly be attributed to pathloss. The empirical CDFs (and distribution fit) of channel capacity using an ensemble of shadowing points and measured distances for both bands in the LOS and NLOS scenarios from power policy 1 is provided in Figs. 5 and 6. Note that the gains of the measurement antennas for the cm-wave and mm-wave bands are essentially the same (differed by only 1 dB). Thus, the free-space pathloss follows an f^2 law, so that we can expect approximately 26 dB pathloss difference in the two bands. Obviously, a practical mm-wave system would have to compensate this through a higher antenna gain.

B. Channel capacity using policy 2

In this case, channel capacity is computed by using the *water-filling* technique [18], which distributes the TX power optimally over sub-channels based on their SNR values. Similarly to the power policy 1 case, our analysis (see Table IV)

LOS – (normalized) Capacity (b/s/Hz)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	37.4	27.6	25.4	19.9	18.8
mm-wave	3.8	2.8	1.8	1.1	0.4
NLOS – (normalized) Capacity (b/s/Hz)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	24.0	14.6	10.0	7.4	5.5
mm-wave	0.5	0.2	0.1	0.06	0.03

TABLE III: Normalized capacity for LOS and NLOS scenarios in both cm-wave and mm-wave bands using policy 1

Fig. 5: CDF of normalized capacity over an ensemble of measured locations and shadowing points in LOS scenario for cm-wave and mm-wave using power policy 1

Fig. 6: CDF of normalized capacity over an ensemble of measured locations and shadowing points in NLOS scenario for cm-wave and mm-wave using power policy 1

shows inter-band and scenario capacity difference that can be mostly attributed to pathloss increase at higher frequencies and in NLOS cases.

The empirical CDFs (and distribution fit) of channel capacity using an ensemble of shadowing points and measured distances for both bands in the LOS and NLOS scenarios from power policy 2 is provided in Figs. 7 and 8.

LOS – (normalized) Capacity (b/s/Hz)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	38.6	29.2	27.1	21.8	20.7
mm-wave	6.2	4.8	3.6	2.6	1.1
NLOS – (normalized) Capacity (b/s/Hz)					
	5 m	10 m	15 m	24 m	27 m
cm-wave	25.4	16.4	11.9	9.3	7.4
mm-wave	1.2	0.7	0.3	0.2	0.1

TABLE IV: Normalized capacity for LOS and NLOS scenarios in both cm-wave and mm-wave bands using policy 2

Fig. 7: CDF of normalized capacity over an ensemble of measured locations and shadowing points in LOS scenario for cm-wave and mm-wave using power policy 2

Fig. 8: CDF of normalized capacity over an ensemble of measured locations and shadowing points in NLOS scenario for cm-wave and mm-wave using power policy 2

VI. SUMMARY AND CONCLUSION

In this work, we embarked on a system performance evaluation of a multi-band (cm-wave and mm-wave) D2D MIMO propagation channel measurements jointly (both bands) conducted in an outdoor environment. The small-scale fading in the propagation channel was modeled using a Rician distribution. The $\mathcal{K}$ -factor (dB) parameter of the Rician distribution re-

vealed a severe fading in mm-wave band than cm-wave band in both LOS and NLOS scenarios. Since the eigenvalue spreads in a propagation channel usually informs on correlatedness of the propagation channel, we also quantified eigenvalues and corresponding eigenvalue spreads in the propagation channels for both cm-wave and mm-wave bands. We observed that eigenvalues were generally larger in the cm-wave band than mm-wave band while the spreads were larger in LOS than NLOS scenarios in both cm-wave and mm-wave bands with higher spreads observed at cm-wave than mm-wave band. Using two power allocation policies (equal power allocation and water-filling approach) we computed channel capacity values. We also found capacity to be higher in the cm-wave band than in the mm-wave band with inter-band capacity difference attributed to higher pathloss typically experience at higher frequencies.

Although system performance analysis like this cannot be generalized to all D2D wireless networks, the quantification of capacity results as done in this work provides a useful example for D2D systems design and prototyping in this type of environment.

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REFERENCES

- [1] X. Lin, J. G. Andrews, A. Ghosh, and R. Ratasuk, "An overview of 3GPP device-to-device proximity services," *IEEE Communications Magazine*, vol. 52, no. 4, pp. 40–48, April 2014.
- [2] A. Asadi, Q. Wang, and V. Mancuso, "A survey on device-to-device communication in cellular networks," *IEEE Communications Surveys Tutorials*, vol. 16, no. 4, pp. 1801–1819, Fourthquarter 2014.
- [3] S. Sangodoyin, U. Virk, D. Burghal, K. Haneda, and A. F. Molisch, "Joint Characterization of mm-wave and cm-wave Device-to-Device Fading Channel," *presented at IEEE Military communication conference (MILCOM) 2018*.
- [4] —, "Mm-wave and cm-wave Device-to-Device MIMO Channel Characterization and Performance Evaluation for 5G Systems," *to be submitted*.
- [5] D. Burghal and A. F. Molisch, "Rate and outage probability in dual band systems with prediction-based band switching," *IEEE Wireless Communications Letters*, pp. 1–1, 2018.
- [6] C. H. Yu and O. Tirkkonen, "Device-to-device underlay cellular network based on rate splitting," in *2012 IEEE Wireless Communications and Networking Conference (WCNC)*, April 2012, pp. 262–266.
- [7] K. Doppler and C. H. Yu and C. B. Ribeiro and P. Janis, "Mode Selection for Device-To-Device Communication Underlaying an LTE-Advanced Network," in *2010 IEEE Wireless Communication and Networking Conference*, April 2010, pp. 1–6.
- [8] M. Zulhasnine and C. Huang and A. Srinivasan, "Efficient resource allocation for device-to-device communication underlaying LTE network," in *2010 IEEE 6th International Conference on Wireless and Mobile Computing, Networking and Communications*, Oct 2010, pp. 368–375.
- [9] Z. Liu and T. Peng and Hao Chen and Wenbo Wang, "Optimal D2D user allocation over multi-bands under heterogeneous networks," in *2012 IEEE Global Communications Conference (GLOBECOM)*, Dec 2012, pp. 1339–1344.
- [10] K. Venugopal and M. C. Valenti and R. W. Heath, "Device-to-Device Millimeter Wave Communications: Interference, Coverage, Rate, and Finite Topologies," *IEEE Transactions on Wireless Communications*, vol. 15, no. 9, pp. 6175–6188, Sept 2016.
- [11] W. Yi and Y. Liu and A. Nallanathan, "Modeling and Analysis of D2D Millimeter-Wave Networks With Poisson Cluster Processes," *IEEE Transactions on Communications*, vol. 65, no. 12, pp. 5574–5588, Dec 2017.
- [12] G. H. Sim and A. Loch and A. Asadi and V. Mancuso and J. Widmer, "5G Millimeter-Wave and D2D Symbiosis: 60 GHz for Proximity-Based Services," *IEEE Wireless Communications*, vol. 24, no. 4, pp. 140–145, Aug 2017.
- [13] Z. Guizani and N. Hamdi, "mmWave E-band D2D communications for 5G-underlay networks: Effect of power allocation on D2D and cellular users throughputs," in *2016 IEEE Symposium on Computers and Communication (ISCC)*, June 2016, pp. 114–118.
- [14] D. Burghal, R. Wang, and A. F. Molisch, "Band Assignment in Dual Band Systems: A Learning-based Approach," *presented at IEEE Military communication conference (MILCOM) 2018*.
- [15] S. Sangodoyin and R. He and A. F. Molisch and V. Kristem and F. Tufvesson, "Ultrawideband MIMO Channel Measurements and Modeling in a Warehouse Environment," in *2015 IEEE International Conference on Communications (ICC)*, June 2015, pp. 2277–2282.
- [16] S. Sangodoyin, S. Niranjayan, and A. F. Molisch, "A Measurement-Based Model for Outdoor Near-Ground Ultrawideband Channels," *IEEE Transactions on Antennas and Propagation*, vol. 64, no. 2, pp. 740–751, Feb 2016.
- [17] L. J. Greenstein and S. S. Ghassemzadeh and V. Erceg and D. G. Michelson, "Rician K-Factors in Narrow-Band Fixed Wireless Channels: Theory, Experiments, and Statistical Models," *IEEE Transactions on Vehicular Technology*, vol. 58, no. 8, pp. 4000–4012, Oct 2009.
- [18] A. Molisch, *Wireless Communications*, ser. Wiley - IEEE. Wiley, 2010.