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Path Loss Study for Millimeter Wave Device-to-Device Communications In Urban Environment

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***Abstract*—In the recent years the millimeter wave spectrum is being explored as a prospective band for the next generation (5G) cellular communications. In this paper we study the propagation of the the millimetre wave spectrum using ray tracing model for an urban environment. We consider the ISM bands in 24GHz and 61GHz in particular and conduct ray tracing simulations to study the path loss behaviour in terms of the path loss exponent and the shadowing variance for both Line of Sight and Non Line of Sight conditions. As a potential application we examine the device to device (D2D) communication, which is currently being developed for LTE-A standard. The resulting pathloss exponents and the shadow variances are presented here based on ray tracing simulations for an ITU-R statistical urban model, moreover this paper shows that intelligent beam steering can significantly improve the throughput for the considered D2D scenarios.**

Device to Device Communication, Millimetric Waves, Channel Modeling, LTE-Advanced, ISM-Band, 24GHz, 61GHz, Radio Propagation.

I. Introduction

A recent report on key ICT facts and figures by the International Telecommunication Union (ITU) [1] suggests that the year 2013 holds an interesting new event in which the number of mobile-cellular subscriptions has almost equaled the population of the world. Since, the mobile network is no longer limited to simple mobile phones but rather includes tablets and other smart devices, there is an expectation that the mobile-cellular subscriptions will far exceed the human population.

Also it is anticipated that in 2017 an overwhelming increase of mobile data traffic of over than 7 times will occur [2], an alarming figure that is urging research centers and standardization bodies to find new and creative methods in enhancing wireless networks efficiency and performance. In fact, the Third Generation Partnership Project (3GPP) with its recent Release 10 of the Long Term Evolution (LTE-Advanced) is trying to target these challenges by introducing novel technologies such as Relay Nodes, Enhanced Intercell Interference Coordination (eICIC), Carrier Aggregation and several other improvements in the Heterogeneous Network concept (HetNet). More advanced techniques such as Device-to-Device (D2D) communication are still under development. Some of our previous work on D2D assume common wireless channel models known in the literature but are not specific to D2D [3], [4].

The challenge of implementing D2D resides in mitigating the harm caused by interference to the the cellular spectrum by the communicating devices due to spectrum reuse. Especially with the recent advancements in the areas of cognitive radio related wireless communications [5] the deployment of D2D is becoming more and more feasible. In order to resolve this issue, we are examining the utilization of millimetric-waves (mmWaves) for the D2D link as an outband means of communication, since mmWave spectrum has a number of key advantages such as spectrum availability, low interference and small antenna dimensions that allows the implementation of highly directive antenna arrays with small form factor. The interesting properties of mmWaves are discussed in more detail in section II illustrating the different impairments of such band, and how to turn such properties into advantages for Device-to-Device communication. In order to investigate the propagation behavior of mmWave spectrum, a ray tracing simulation was preformed inside an *urban environment* model that is based on ITU-R recommended statistical parameters, taking into consideration the D2D's devices heights conditions. These simulation results were further processed and analysed, so that both the *path loss exponent* and the shadowing *variation distribution* were obtained for two different cases (i) Line of Sight (LoS) and (ii) Non Line of Sight (NLoS). Also this paper presents D2D system level performance simulation when devices are deployed in the same urban environment. The obtained results show that mmWave D2D is feasible only when utilizing beam forming or beam switching techniques.

The rest of this paper is organized as the following, in section III an overview of Device-to-Device communication is provided, and the use case scenarios, Section IV explains the modeling approach of the urban environment implemented in the succeeding simulation and the antenna beam switching technique. In Section V two simulation scenarios are presented before concluding in Section VI.

II. mmWaves Propagation Characteristics

The spectrum range between 30 GHz and 300 GHz is referred as the mmWave spectrum since the wavelengths for these frequencies are in order of millimeters (less than 10mm) [6]. In general, the utilization of spectrum above 6 GHz has been greatly limited to highly directive Point-to-Point fixed communication systems, due to the fact that only longer wave-lengths (i.e. lower frequencies) can diffract around terrestrial terrain and obstacles more smoothly, and can penetrate more easily though buildings, in contrary to the shorter wavelengths (i.e. higher frequencies including mmWaves) that are usually impaired with strong reflections, refractions and scattering. Also mmWave radios were usually bulky and unsuitable for mobile or handheld communication. However there is recently an increasing interest in exploiting the vast available bandwidth in mmWave spectrum for NLoS communication and for mobile and cellular systems by exploiting mmWaves ability of strong reflections. Applications like Point-to-Multipoint PtMP are already in the market today, while other wireless applications are currently being developed. An example of the promising next generation mmWave wireless communication systems is the IEEE 802.11ad standard that is currently under development, proposing mmWaves as the carrier for the future Wireless LAN Technology (WLAN), along with several other standards that are already in place [7] such as WirelessHD, ECMA-387. These advancements are mainly facilitated by the new RFIC technology allowing low cost, low power electronics and antenna solutions [8]. This section is addressing the general propagation characteristics of mmWaves focusing on the newly allocated ISM bands within mmWaves spectrum.

A. *ISM Bands in mmWave Spectrum*

In spite of the original intention to use the Industrial Scientific Medical (ISM) spectrum band for non-telecommunication purposes, such as the "*operation of equipment and appliances locally generating and using radio frequency energy*" [9], this band has acquired a major focus and interest due to its availability for non-licensed and free use (with some minor exceptions). In fact, Wi-Fi/WLAN is a very famous example of ISM band utilization installed in most of the houses and enterprises around the world. Additionally, many other technologies like Zigbee and Bluetooth utilize ISM bands.

According to the ITU-R Radio Regulation Articles 5.138 and 5.150, both 24GHz and 61GHz bands are now defined for unlicensed used as ISM [9], if local radio regulation does not contradict. Table I is listing the most common applications of microwave ISM bands in addition to the two mmWave bands.

TABLE I. MICROWAVE & MMWAVE ISM BANDS

Frequency Range	Available Bandwidth	Main Applications
2,400-2.500 GHz	100 MHz	Wi-Fi IEEE 802.11b/g/n Bluetooth IEEE 802.15.1 Zegbee IEEE 802.15
5.725-5.875 GHz	150 MHz	WLAN IEEE802.11a/n
24.00-24.25 GHz	250 MHz	Point-to-Point Point-to-MultiPoint
61.0-61.5 GHz	500 MHz	WirelessHD (Overlapping) Point-to-Point IEEE 802.15.3c

In addition to the globally defined ISM bands, local and regional regulators have endorsed the use of mmWave spectrum for unlicensed communication as listed in table II which summarizes the available 60 GHz band for unlicensed use in different countries [10].

In this paper, we are proposing the use of the mmWave ISM bands for D2D communication that have their pros and cons; on one hand, since ISM is a license-free spectrum, commercial cellular operators could favor free-of-charge bands comparing to the tremendous spectrum license fees currently in place, that will allow the rapid growth of D2D market and the alleviation of the congested cellular networks. While on the other hand, special care and consideration needs to be taken when operating in unlicensed bands due to the major interference introduced by other unlicensed users and systems in the future, taking into consideration that the utilization of mmWaves is currently, to a far extent, very minimal. An additional merit of the mmWave spectrum is that high antenna directivity can be achieved using small form factor printed antennas [11]. This high directivity will allow the mitigation of interference received from other users sharing the same spectrum by steering the receiving beam towards the direction of the intended signal only, compared to omnidirectional antenna that receives power from all directions (including the interfering signal). On the other side of the link, the transmitter will focus the entire power towards the intended receiver. This important mechanism will help in avoiding UEs to become neither aggressors nor victims of co-tier interference.

TABLE II. UNLICENSED LOCAL MMWAVE REGULATIONS

Country	Frequency Range	Available Bandwidth
Australia*	59.4-62.9 GHz	3.5 GHz
USA	57.0-64.0 GHz	7.0 GHz
Japan	59.0-66.0 GHz	7.0 GHz
Canada	59.0-64.0 GHz	5.0 GHz

*Under discussion

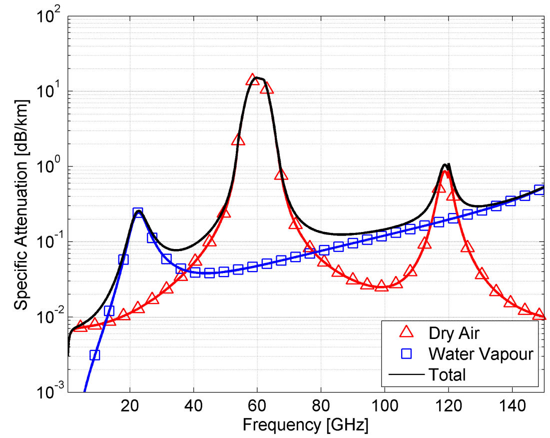

Fig. 1. Atmospheric Absorbtion due to Water Vapor and Gasses

B. *Atmospheric Attenuation*

Radio Frequency (RF) propagation in earth atmosphere is usually impaired with minor energy losses due to the atmospheric absorbtion caused by the resonance of water vapor molecules and oxygen gas molecules [12], peaking near certain frequencies such as 24 GHz, 60 GHz and 120 GHz as depicted in Figure 1, that was regenerated by curve approximation according to ITU guidelines in [12], showing a total atmospheric absorbtion of 0.23 dB/km and 13.55 dB/km for frequencies 24 GHz and 61 GHz respectively calculated at temperature 25°C , relative humidity 50% and pressure of 101.3 kPa. In general the signals using mmWave spectrum endure higher atmospheric absorbtion than signals using lower frequencies.

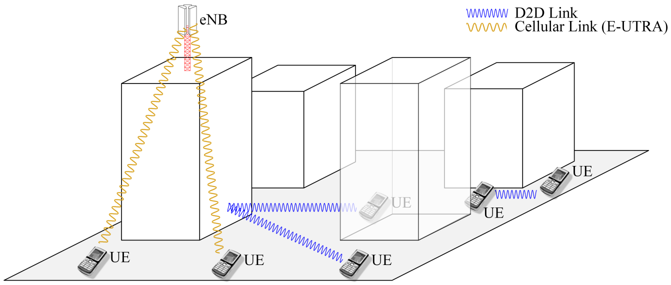

Fig. 2. Device to Device Communication Concept

Also, heavy rain can cause relatively higher attenuation in mmWave spectrum due to the comparable raindrop size with the mmWave wavelength. These impairments, for long time, limited the mmWaves communication to only LoS scenario, while NLoS was avoided. However for short range communication applications, as in the cellular networks, atmospheric and rain absorbtion are not playing a limiting factor since at distances around 250 meters these absorbtions are summing up to a less than 4dB in case of 61GHz links and 0.5dB in the case of 24GHz, which is rather considered as an advantage, since it can help limiting the signal propagating beyond its intended target UE(s) and causing a co-tier interference.

III. Device-to-Device Communication Under LTE-Advanced

Device-to-Device Communication is a promising technology that has gained a great interest from researchers and industry alike. This technique will allow peer-to-peer communication, adding numerous gains to LTE-Advanced; the (i) first gain is proximity gain [13], since short distance allows higher throughput and lower power consumption, (ii) secondly D2D can enhance cell edge throughput [14] by performing aggregation and forwarding i.e. acting as a decode and forward mobile Relay Node, the (iii) third benefit is the reuse gain, since the transmission range of D2D is distance-limited, a very short spectrum reuse-distance can be implemented, while utilizing mmWaves will further boost this feature. Figure 2 illustrates the general concept of D2D communication.

In some situations D2D is considered as a favoured or even a vital means of communication, these cases are listed below:

- Local source-sink type traffic between two nearby devices (such as local voice/video calls, file transfer, etc...)
- Extending Cell-edge coverage, by allowing devices to relay traffic towards eNB.
- Backup connection in case of poor cellular network coverage or during natural disasters during which the wireless cellular infrastructure is expected to be severely damaged. D2D can form a temporary ad-hoc network enabling basic communications.

In fact the lack of D2D communication in LTE Release 10, is one of the major issues that is inhibiting public safety from adopting LTE technology, due to the concerns regarding cellular network performance during natural disasters or in remote and at cell edge areas [3]. A prime demand for D2D technology by public safety authorities is being currently observed, while 3GPP is striving to include the basic guidelines of this feature in LTE Release 12 [15].

The PHY of D2D link could be modulated by either using Orthogonal Frequency Division Multiplexing (OFDM) or Single Carrier modulation (SC), the former will give the ability of coordinated resource sharing with the cellular network and will allow the possibility of multiDevice-to-multiDevice (mD2mD) by using OFDMA. However SC, on the other hand, will allow power saving on terminals and lighter signalling overhead, but gives limited multiplexing capabilities.

IV. Simulation Model

A. Modeling Urban Environment

When studying a wireless system performance, it is required to develop an accurate definition of the radio propagation conditions and constraints; one of the most important conditions inside a city is the layout of the buildings that determines the behavior of the propagating radio signals. ITU-R in its recommendation document [16], is suggesting a standardized model for urban areas, based on three statistical parameters α_o, β and γ, that describe to a fair extend the general geometrical statistics of a certain area. These parameters are explained below:

- Parameter α_o: Represents the ratio of the built-up land area to the total land area (dimensionless).
- Parameter β: Represents the mean number of buildings per unit area (buildings/km2).
- Parameter γ: A statistical variable that describes the building heights distribution according to Rayleigh probability density function:

$$P(h) = \frac{e^{\frac{-h^2}{2\gamma^2}}}{\gamma^2} h \tag{1}$$

where (h) is the building height in meters.

Accordingly for simulating urban environment we have selected $\alpha_o = 0.3$, $\beta = 500$ and $\gamma = 15$, [17] although the latter is irrelevant for our study since the assumed User Equipments' (UE) heights is limited to 1.5m. In this paper it has been selected to reproduce the virtual-city environment according to Figure 3; an array of structures (buildings or houses) of an assumed square plot of width (W), and inter-building spacing (S), that are linked to the ITU-R statistical parameters as per the following formulas:

$$W = 1000\sqrt{\frac{\alpha_o}{\beta}} \tag{2}$$

$$S = \frac{1000}{\sqrt{\beta}} - W \tag{3}$$

While the buildings material is considered concrete, and the ground waves reflections were neglected. The selected transmitter location is shown in the same figure, as well as the locations of the distributed receivers (a total of 114 receivers). As it is clear from the figure, some of the receivers can favor an LoS condition while others do not. The simulated patch area is 275m X 275m that includes 36 building blocks.

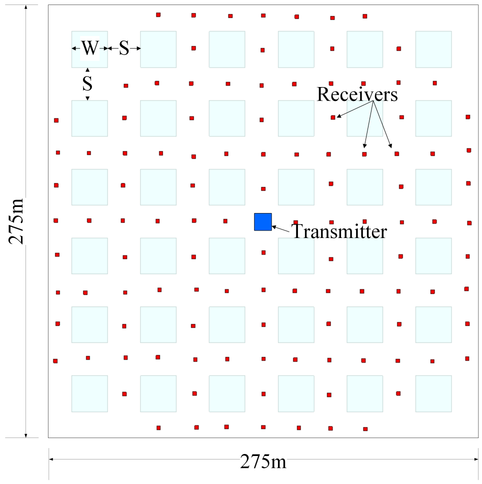

Fig. 3. Building Layout, and Simulation Setup

B. Antenna Beam Switching

Directional antennas transform the propagation impairments associated with mmWave links into a great advantage by leveraging the high reflections and refractions caused by urban structures as an alternative to the LoS communication. Current mobile systems (working in the range of 300MHz-3GHz) depend largely on omni-directional antennas for the UE, while the base station usually exploits directive antennas (of half power beam width 60° to 70°) forming the conventional three sectors cellular site. The uplink of the UE is suffering a huge energy waste, since the RF power is transmitted in all directions, not only draining the battery energy, but also raising the level of interference in the neighboring cells, and accordingly reducing the cellular spectral efficiency. The reason of adopting omni antennas in the current UEs is mainly related to antenna dimensions, since the latter is inversely proportional to system's frequency, and implementing directional antennas would occupy a huge space at the current standard cellular frequencies, in the contrary to mmWave frequencies, very small, highly directional antennas could be fabricated [11]. Beam switching (i.e. using RF switches) is selected for the simulation setup, rather than beam forming (i.e. using RF phase shifters), as the Switched Beam Array would be more feasible and easier to implement in future UEs [18]. The utilized antenna array in this paper is based on the generic formula in [19] which relate the Directivity (G) of a planar antenna array to the half power beamwidth as per the following:

$$G = \frac{32400}{\theta_E \theta_H} \tag{4}$$

where θ_E and θ_H are the half power beamwidth in E-Plane and H-Plane respectively. In the performed simulation we have selected the following for 24GHz: (G=24dBi, $\theta_E = 22.5°$, $\theta_H = 60°$). And for 61GHz: (G=32dBi, $\theta_E = 22.5°$, $\theta_H = 45°$). Aiming to form a set of 16 antennas, noticing that only one antenna at a time will be active.

V. D2D Simulation in mmWave Spectrum

Two main simulation scenarios are presented in this paper; the (i) first scenario is for illustrating the path loss (PL) exponent behavior in urban environment assuming isotropic

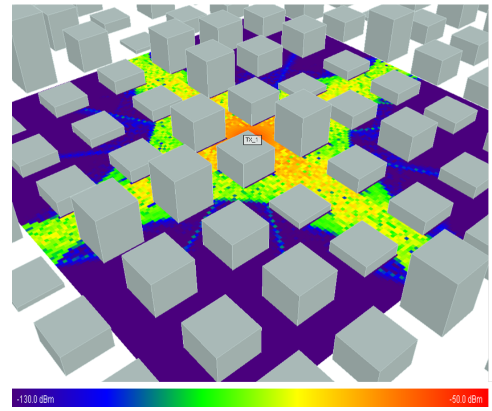

Fig. 4. RSRP Level due to a D2D transmitter at 60GHz

antennas on both the transmitter and the receiver, while in the (ii) second scenario is performed using a limited number of receivers distributed according to Figure 3. The second scenario is addressing three situations; (a) where all antennas are isotropic, (b) using directional antennas for the receivers (c) using directional antennas for both the transmitter and the receivers, so the results of these three cases will allow benchmarking the possible throughput enhancement when embracing the antenna beam switching technique. Ray tracing simulation were performed using Wireless InSite®, and the postprocessing of results were performed using MATLAB®, including the system level throughput estimation. The main simulation and the post processing parameters are listed in Table III.

TABLE III. Simulation Parameters

Parameter	Value
Simulation Frequency	24 GHz, 61GHz
Channel Bandwidth	20 MHz
Number of Simulated Reflections	2
Number of Simulated Diffractions	1
Number of Simulated Transmissions	Not Simulated (No penetration)
Ambient Temperature	25°C
Atmospheric Pressure	101.3 kpa
Water Vapor Density	11.5 g/m^3
TX/RX Hight from Ground	1.5 m
Transmitter TX Power	23 dBm [20]
Receiver Noise Figure	9 dB [20]
Noise	Additive White Gaussian Noise

A. Path Loss Exponent in Urban Environment

The first scenario simulation was performed in order to get a general sense of the D2D Path Loss behavior in built-up areas when utilizing mmWave ISM bands. Large number of receivers were deployed in the simulation environment (above 20,000 Receivers) allowing more accurate Path Loss Exponent estimation. The Reference Signal Received Power (RSRP) is shown Figure 4, where it can be clearly noticed that the signal level deteriorates rapidly for NLoS receivers.

The received power due to an isotropic transmitter can be

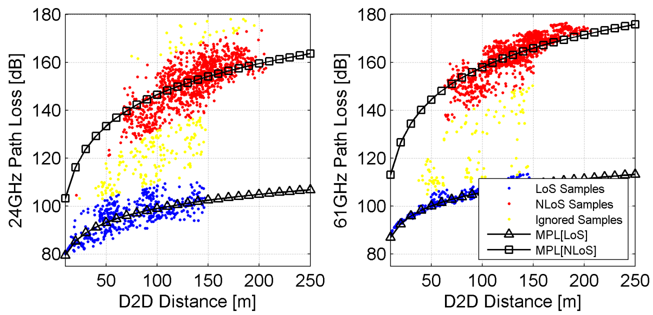

Fig. 5. Device-to-Device Path Loss in Urban Environment

calculated as:

$$P_r = \frac{P_t}{4\pi D^\alpha} A_r \quad (5)$$

where P_t is the transmitted power, α is the path loss exponent (which is equal to 2 in case of free space transmission), D is the distance between the transmitter and the receiver, and A_r is the aperture area of the receiver defined as:

$$A_r = G_r \frac{\lambda^2}{4\pi} \quad (6)$$

where $\lambda = C/f$ is the wavelength and G_r is the receiver antenna gain and it is equal to 1 in case of an isotropic receiver. Accordingly equation (5) can be rewritten to represent the incurred path loss in decibel form as:

$$PL = P_t[dB] - P_r[dB] = 20log\left(\frac{4\pi f}{C}\right) + 10\alpha log(D) \quad (7)$$

As it can be noticed from Figure 5 that the simulated Path Loss samples have a clear tendency towards two specular modes; one corresponds to LoS and another corresponds to NLoS. Accordingly the Mean Path Loss (MPL), representing the highest PL expectancy, was obtained using curve fitting (for LoS and NLoS samples separately) following equation 7. The samples with large deviation from the specular modes were ignored during the fitting process, that is because of two reasons; (i) In order to simplify the Path Loss model, (ii) the contribution of these samples is less than 15% of the total samples set. The resulting MPL(s) are listed in Table IV

TABLE IV. D2D Mean Path Loss

Frequency	Condition	Path Loss
24 GHz	LoS	60.05 + 1.95 * 10log(D)
	NLoS	60.05 + 4.32 * 10log(D)
61 GHz	LoS	68.15 + 1.88 * 10log(D)
	NLoS	68.15 + 4.49 * 10log(D)

Another important path loss behavior aspect is the samples deviation from the MPL value. This deviation is usually caused by multiple effects; such as small-scale fading, doppler effect and large-scale fading. However, since the simulation is performed for static receiver locations with interspacing of 2m (much larger than λ), the only relevant fading deviation that can be obtained from this simulation is the large-scale fading. For a receiver (n) we define the PL deviation for each specular mode as $D_n = PL_n - MPL$, where PL_n is receiver(n) incurred path loss. Accordingly we can obtain PL

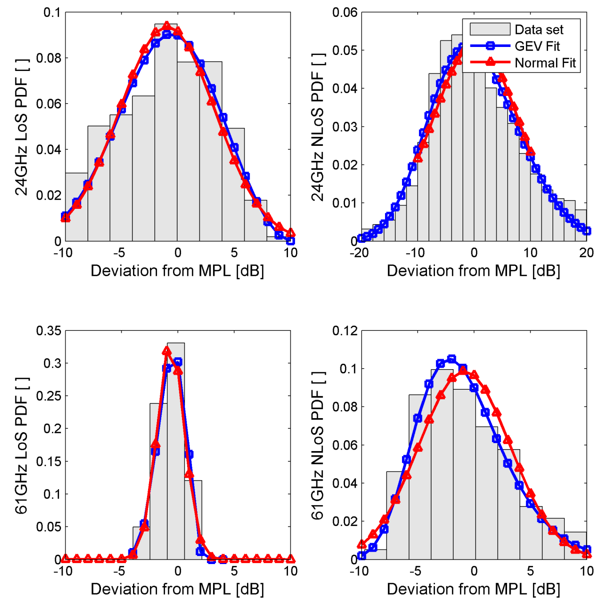

Fig. 6. Device-to-Device Deviation from MPL Distribution

deviation distribution as plotted in Figure 6. Multiple statistical distribution fitting has been compared with respect to their Bayesian Information Criteria (BIC) and it has been found that the best fit for this variation distribution is the General Extreme Value (GEV) as depicted in the same figure. However Gaussian Distribution showed a very close BIC score to GEV, and since it is a much easier way to represent a distribution, we have opted to use it for modeling the path loss variation distribution. Accordingly the best fit gaussian standard deviation values are listed Table V.

TABLE V. Path Loss Deviation from MPL

Frequency	Condition	σ
24 GHz	LoS	4.3 dB
	NLoS	7.8 dB
61 GHz	LoS	1.2 dB
	NLoS	4.0 dB

B. D2D Link with Beam Steering

The second scenario simulation is mainly aiming to illustrate the enhancement in system level (MAC) throughput that can be achieved when utilizing antenna beam switching. The D2D transmitter is assumed to behave in a similar manner to an LTE eNodeB, and accordingly the link level and system level overhead were utilised inline with the bandwidth efficiency assumptions obtained in [21]. The maximum Modulation and Coding Scheme is assumed to be QAM512, 4/5, to show the allowed additional gains of the setup, and hence the data throughput was linked to the SNR using the following:

$$TP = BW.BW_{eff}.\eta.log_2\left(1 + 10^{\frac{SNR - SNR_{eff}}{10}}\right) \quad (8)$$

where BW is the system bandwidth 20MHz, BW_{eff} is the system level Bandwidth Efficiency, η is a correction factor

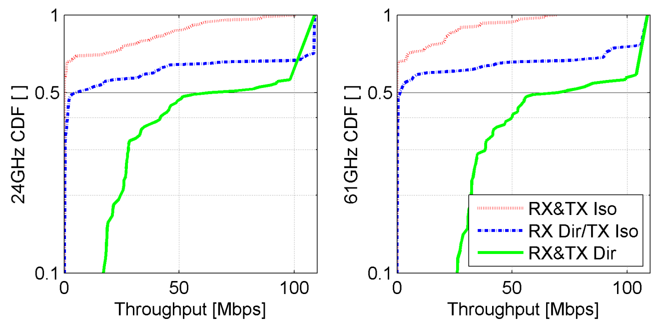

Fig. 7. System Level Throughput at 24GHz and 61GHz

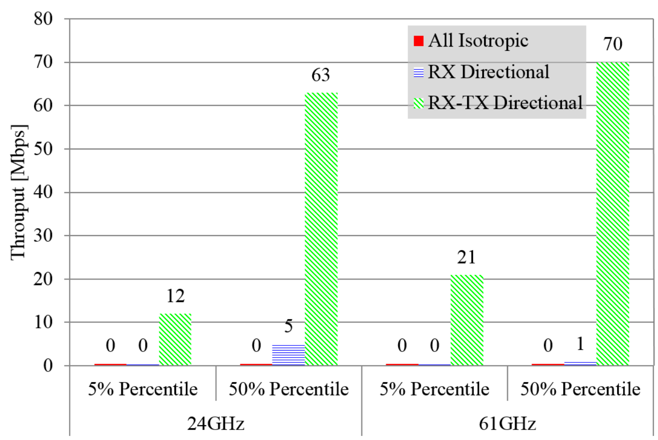

Fig. 8. Performance Benchmarking at 5% and 50% Percentile

and SNR_{eff} is the SNR implementation efficiency. These parameters are given in [21], and listed in table VI.

TABLE VI. D2D PATH LOSS

Correction Parameter	Value
BW_{eff}	0.57
η	0.9
SNR_{eff}	1.25 dB

The Cumulative Distribution Function of the D2D throughputs are depicted in Figure 7, showing limited enhancement when adopting the one sided beam switching, while a major improvement can be witnessed when both the transmitter and the receivers utilize the beam switching technique giving a significant throughput increase in the lower (5%) percentiles and in also the median (50%) percentile , these enhancements are depicted in Figure 8, showing that for both 24GHz and 61GHz bands, more than 95% of the receivers in the simulated patch were able to attain a usable OFDM link.

VI. CONCLUSION

This paper has studied the path loss behavior in urban environment for mmWave D2D link and demonstrated the feasibility of utilizing the mmWave spectrum for conducting LTE-A D2D communication over ISM bands, however this can only be achieved by adopting techniques such as beam switching and beam forming, leveraging the reflections and refractions in the radio path caused by urban structures. Future work shall focus on additional analysing and understanding of the D2D link in mmWave spectrum, and also in the experimental verification of beam switching technique that include the physical realization of the antenna arrays. In general the concept of using mmWave for cellular communication is still in its early stages with more work to be done.

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