Outage Probability Analysis of UAV Assisted Mobile Communications in THz Channel

Sara Farrag
German University in Cairo
sarah.farrag@guc.edu.eg

Engy Maher
German University in Cairo
engy.maher@guc.edu.eg

Ahmed El-Mahdy
German University in Cairo
ahmed.elmahdy@guc.edu.eg

Falko Dressler
TU Berlin
dressler@ccs-labs.org

***Abstract*—THz Communications are attractive candidate for providing ultra high data rate required by 5G and beyond. Unmanned Aerial Vehicle (UAV) is an emerging facility which can be used to assist wireless communications. In this paper, we consider a single-cell cellular network with a UAV that works as a decode-and-forward (DF) relay in full-duplex (FD) mode to assist a base station (BS) and extend its coverage over THz channel. A number of underlay device-to-device (D2D) pairs that communicate with each other and reuse the cellular resources is also considered. The outage probability of the link between the BS and a mobile device (MD) is derived in the presence of the interference of the D2D devices that share the same frequency band. The transmit powers of the MD and the UAV that minimize the outage probability are derived and compared with that of fixed power allocation. Numerical results show that the outage probability obtained using the proposed optimum power allocation scheme is decreased by 20% from the outage probability obtained using fixed power allocation scheme.**

***Keywords*-Wireless, UAV, Terahertz, Relays, D2D, DF, Power Optimization, Outage Probability.**

I. Introduction

Over the past few years, wireless data traffic has been witnessing a drastic increase and expansion due to change in the way today's society creates, shares and consumes information [1]. Particularly, mobile data traffic is expected to reach 56.8 exabytes per month [2]. Concerning video traffic, it is expected to experience a three-time increase. This requires a wireless network that supports throughput up to terabits per second per device. This remarkable growth of wireless traffic has made it necessary to investigate gap regions in the radio spectrum to meet the users' accelerating demands [2], [3]. Frequency band of 0.1–10 THz is currently a new research avenue for telecommunication researchers and policy makers because of the huge bandwidth and data rate it provides as compared to the traditional RF communication bands [4]. In fact, the THz frequency band promises wide bandwidth which theoretically can reach up to some THz, which in return results in a potential capacity in terabit per second [5]. Therefore, the bandwidth supplied is found to be one order of magnitude above millimeter-wave (mmWave) systems [6]. In addition, THz signals can allow higher link directionality and offer low eavesdropping chances compared to their millimeter counterparts. The analysis of the THz band indicates that these frequencies have a set of advantages in comparison to optical frequencies. For example, the THz waves are good candidates for uplink communication. They allow non-line-of-sight (NLOS) propagation and act as reliable substitutes during inconvenient climate conditions such as rain, fog, turbulence and dust. Moreover, the THz frequency band is not affected by surrounding noise arising from optical sources and it is not associated with any safety limits or health restrictions [7]. Nevertheless, the huge available bandwidth advantage of the THz band communications comes always at the cost of substantial propagation loss [8]. In fact, this great loss is due to the electromagnetic wave as it propagates through the medium as well as the absorption loss due to the molecular absorption of the water vapor molecules in the atmosphere [9], [10].

Underlaying D2D is a promising technique to communicate among user equipment underlying a cellular network by reusing cellular resources within the cell. Although, this can help in uploading the main cellular network, one of the major challenges is to control the interference generated by reusing the same resources. As a matter of fact, D2D communication has been deeply investigated and widely studied in the RF as well as mmWave bands. Furthermore, there are numerous challenges arised when using it in THz band [11].

The deployment of flying platforms such as UAVs, or drones, is expeditiously growing [12]. UAVs are key to several potential applications in wireless systems such as aerial base stations to enhance coverage, reliability, energy efficiency and capacity of wireless networks. One of the various UAV applications is UAV relaying in which the UAV is deployed in the network to provide wireless connectivity between two nodes without direct communication link between them. This application is considered an effective technique for throughput increasing, reliability improvement as well as BS coverage extension [9], [13]. When compared to traditional static relays, the UAV-relay is found to be more cost-efficient with a higher degree of freedom that is highly needed in emergency situations and rescue operations [14]. Moreover, the high mobility of the UAV relay can improve the communication performance by dynamically

This work is supported by the DAAD with funds of the Federal ministry of education and research, in co-operation between the department of telecommunications systems at TU Berlin and German University in Cairo.

adjusting the UAV location according to the surroundings. As a matter of fact, the major feature of THz communications lies in its ability to enable mobile communications at both the access level and the device level in D2D and drone-to-drone communications [15]. There are few papers dealing with UAV communication over the THz channel [16]–[18]. In [16], the effects of mobility uncertainties on THz-band communications between flying drones were studied. Moreover, some field experiments were conducted in order to measure the mobility uncertainties of flying drones in various scales. The achievable capacity of the THz links in presence of mobile uncertainties was studied. The authors in [17] proposed an UAV-based interference management algorithm in order to optimize the in-band UAV-assisted integrated access and backhaul (IAB) networks performance. The authors utilized fixed-point method along with particle swarm optimization (PSO) in order to jointly optimize user-BS associations and down-link power allocations. In [18], the authors analyzed the orientation and position estimation capabilities of the THz multiple input multiple output MIMO-OFDM link between two UAVs based on both the position and the orientation error bound.

From the above discussions, it can be seen that the researchers did not yet focus on analyzing the overall outage probability of the uplink of MD to BS through a UAV in the THz channel, where a UAV is deployed as a relay in the presence of interference. In this paper, we tackle this point, where the total outage probability of the communication link from MD to UAV and from UAV to BS is derived in THz channel and in the existence of the UAV self-interference and D2D devices that share the same frequency resources. The UAV acts as a DF-FD relay between the MD and the BS to extend the coverage of the BS. We consider a fixed position for the UAV. The optimum transmit powers of the MD and the UAV that minimize the derived outage probability is obtained.

The rest of the paper is organized as follows. In Section II, THz channel and system models are described. In Section III, mathematical formulations are provided. In Section IV, the outage probability is derived. In Section V, the power allocation optimization problem is formulated to minimize the outage probability. Section VI provides the system performance evaluation and numerical results. Section VII provides the conclusion and suggests for future work.

II. System and Channel Model

A. System Model

Consider a single cell cellular network as shown in Fig. 1 which consists of one BS, one UAV, one MD and M D2D device pairs that coexist and share the same frequency resources with the MD and the UAV. The direct link between the MD and the BS is unattainable due to high loss resulting from long distances travelled or the existence of obstacles. Then, a UAV is employed to act as a DF relay to assist

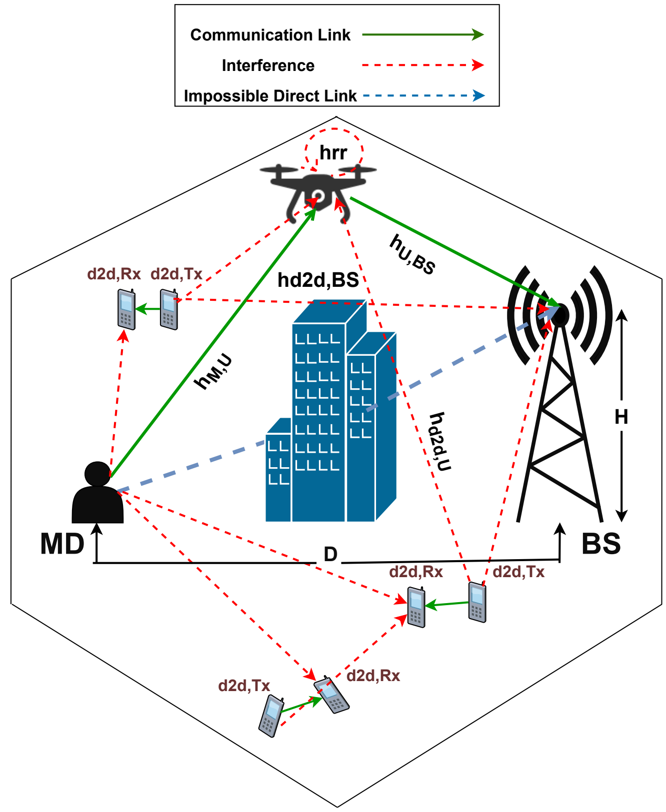

Fig. 1. Scenario under consideration where a UAV is serving as a DF-FD relay that assists the communication link between the MD and the BS with some D2D pairs coexist.

the communication link between the MD and the BS. The UAV is assumed to work in FD mode to increase the data rate. Therefore, the UAV is equipped with two antennas (one transmit antenna and one receive antenna), while the other devices in the network are equipped with a single antenna.

In fact, the interference from the UAV-transmit antenna can not be neglected even with the deploying of advanced self-interference cancellation techniques.

Without loss of generality, consider an MD is located at (D,0,0) in a Cartesian coordinate system, where D is the distance from the MD to the BS as shown in Fig.1. The BS is located at (0,0,H), where H is its height as indicated. The UAV's location is predetermined and is assumed to be (x_o,y_o,z_o). Therefore, the distance from the MD to the UAV (i.e. $D_{m,u}$) and the distance from the UAV to the BS (i.e. $D_{u,bs}$) are given respectively by:

$$D_{m,u} = \sqrt{(x_o - D)^2 + y_o^2 + z_o^2}, \quad (1)$$

$$D_{u,bs} = \sqrt{x_o^2 + y_o^2 + (z_o - H)^2}. \quad (2)$$

Let M denotes the number of D2D pairs. The transmit power of the MD, the UAV, the i_{th} D2D transmitter and the self-interference power at the UAV are denoted as: P_M, P_U, P_{d2d_i} and P_{rr} respectively. The communication channels between the nodes in the network are assumed to be THz channels.

All the channels between the nodes are assumed to be known or perfectly estimated. The description of this channel is described in the next subsection.

B. Channel Model

In the following, we introduce the channel model of THz band that was developed using THz wave atmospheric transmission attenuation model as well as water vapour absorption. Following the channel model provided in [19], the channel gain can be formulated as:

$$h = \sqrt{N_T}\sqrt{\frac{1}{PL(f,d)}G\alpha(\phi)}, \tag{3}$$

where N_T is the number of antennas of the transmitting node, $PL(f,d)$ is the pathloss that frequency f suffers when traveling a distance d, G is the antenna gain and $\alpha(\phi)$ is the array steering vector that can be expressed for uniform linear array as:

$$\alpha(\phi) = \frac{1}{\sqrt{N_T}}[1, ..., e^{j\pi[nsin\phi]}, ..., e^{j\pi(N_T sin\phi)}]^T. \tag{4}$$

Particularly, $PL(f,d)$ consists of spreading loss L_{sl} as well as molecular absorption L_{mal} that must be highly considered in the THz band. In fact, the spreading loss L_{sl} is caused due to the expansion of the electromagnetic wave as it propagates through different mediums, whereas the molecular absorption L_{mal} is a result of the collisions initiated by atmospheric gas or water molecules. Intensive research on the effect of atmospheric attenuation was conducted in [19].

The pathloss at frequency f after travelling a distance d can be given as

$$\begin{aligned} PL_{f,d} &= \frac{1}{\sigma^2} = L_{sl}(f,d)L_{mal}(f,d), \\ &= \frac{1}{G_{Tx}G_{Rx}}(\frac{4\pi fd}{c})^2 e^{k(f)d}, \end{aligned} \tag{5}$$

where σ^2 is the variance of the THz channel with zero mean and hence, $h \sim CN(0,\sigma^2)$. G_{Tx} and G_{Rx} are the transmitter and the receiver gains, c is the speed of light in free space and $k(f)$ is the frequency dependent medium absorption coefficient that is provided in [20].

III. Mathematical Formulation

The received signal at the UAV can be expressed as

$$\begin{aligned} Y_U = &\underbrace{\sqrt{P_M}h_{M,U}X_M}_{\text{transmitting signal of MD}} + \underbrace{\gamma_r\sqrt{P_{rr}}h_{rr}}_{\text{self-interference signal}} \\ &+ \underbrace{\sum_{i=1}^{M}\sqrt{P_{d2d_i}}h_{d2d_i,U}}_{\text{interference signal from D2D transmitting devices}} + \underbrace{n_U}_{\text{noise}}, \end{aligned} \tag{6}$$

where P_M is the transmitting power of the MD, $h_{M,U}$ is the channel gain from the MD to the UAV, X_M is the transmitting signal of the MD and has unit energy, γ_r is the UAV self-interference factor, P_{rr} is the self-interference power of the UAV, h_{rr} is the self-interference channel experienced at the UAV, P_{d2d_i} is the transmitting power of the i_{th} D2D device, $h_{d2d_i,U}$ is the channel gain sensed at the UAV from the transmitting device of the i_{th} D2D pair and n_U denotes the additive white Gaussian noise (AWGN) at the UAV which has zero mean and variance N_o.

The received signal at the BS can be expressed as:

$$\begin{aligned} Y_{BS} = &\underbrace{\sqrt{P_U}h_{U,BS}X_U}_{\text{transmitting signal of UAV}} + \underbrace{\sum_{i=1}^{M}\sqrt{P_{d2d_i}}h_{d2d_i,BS}}_{\text{interference signal from D2D devices}} \\ &+ \underbrace{n_{BS}}_{\text{noise}}, \end{aligned} \tag{7}$$

where P_U is the transmitting power of the UAV, $h_{U,BS}$ is the channel gain from the UAV to the BS, X_U is the transmitting signal of the UAV and has unit energy, $h_{d2d_i,BS}$ is the channel gain sensed at the BS from the transmitting device of the i_{th} D2D pair and n_{BS} denotes the AWGN at the BS.

Assuming all D2D devices have the same transmitting power P_{d2d}, then from (6) and (7), the signal to-interference-noise-ratio (SINR) at the UAV and the SINR at the BS are given respectively as:

$$\gamma_U = \frac{P_M||h_{M,U}||^2}{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,U}||^2 + {\gamma_r}^2 P_{rr}||h_{rr}||^2 + N_o}, \tag{8}$$

$$\gamma_{BS} = \frac{P_U||h_{U,BS}||^2}{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,BS}||^2 + N_o}. \tag{9}$$

The received signal of the i_{th} D2D receiving device is given as

$$\begin{aligned} Y_{d2d_i} = &\underbrace{\sqrt{P_{d2d}}h_{d2d_{Tx_i},d2d_{Rx_i}}}_{\text{transmitting signal of D2D i}} + \underbrace{\sqrt{P_M}h_{M,d2d_i}}_{\text{interference signal from MD}} \\ &+ \underbrace{\sqrt{P_U}h_{U,d2d_i}}_{\text{interference signal from UAV}} + \underbrace{P_{d2d}\sum_{j=1,j\neq i}^{M}h_{d2d_{Tx_j},d2d_{Rx_j}}}_{\text{interference signal from other D2D transmitters}} \\ &+ \underbrace{n_{d2d_i}}_{\text{noise}}, \end{aligned} \tag{10}$$

where $h_{d2d_{Tx_i},d2d_{Rx_i}}$ is the channel gain from the i_{th} transmitting D2D device to the i_{th} receiving D2D device, $h_{M,d2d_i}$ is the channel gain from the MD to the i_{th} D2D receiving device, $h_{U,d2d_i}$ is the channel gain from the UAV to the i_{th} D2D receiving device and n_{d2d_i} denotes the noise at the i_{th} D2D receiving device which has Gaussian distribution (AWGN) with zero mean and variance N_o.

Therefore, the SINR of the i_{th} D2D receiving device is given by

$$\gamma_{d2d_i} = P_{d2d}||h_{d2d_{Tx_i},d2d_{Rx_i}}||^2 \times \Bigg[(P_M||h_{M,d2d_i}||^2 + P_U||h_{U,d2d_i}||^2 + P_{d2d}\sum_{j=1,j\neq i}^{M}||h_{d2d_{Tx_j},d2d_{Rx_j}}||^2 + N_o)\Bigg]^{-1}. \quad (11)$$

IV. Outage Probability Derivation

The outage probability of a communication link is defined as the probability that the received SINR falls below a predetermined threshold β_{th}. Consequently, the outage probability of the link from the MD to the UAV is defined as

$$P_{(M\rightarrow U)} = Pr(\gamma_U < \beta_{th}). \quad (12)$$

Similarly, the outage probability of the link from the UAV to the BS is defined as

$$P_{(U\rightarrow BS)} = Pr(\gamma_{BS} < \beta_{th}). \quad (13)$$

The communication link from the MD to the BS is successful if and only if both the transmission links from the MD to the UAV and that from the UAV to the BS succeed. Hence, the outage probability of the communication link from the MD to the BS can be expressed as:

$$\begin{aligned} P_{out} &= 1 - [1 - P_{(M\rightarrow U)}][1 - P_{(U\rightarrow BS)}], \\ &= 1 - [1 - Pr(\gamma_U < \beta_{th})][1 - Pr(\gamma_{BS} < \beta_{th})]. \end{aligned} \quad (14)$$

Since $h_{M,U} \sim CN(0, \sigma^2)$, then $||h_{M,U}||^2$ follows an exponential distribution with a zero mean and variance σ^2 given by

$$f(x) = \frac{1}{2\sigma^2}e^{-\frac{x}{2\sigma^2}}, \quad (15)$$

where σ^2 for THz channel is expressed as

$$\sigma^2 = G_{Tx}G_{Rx}(\frac{c}{4\pi fd})^2 e^{-k(f)d}. \quad (16)$$

Thus, the outage probability of the link from the MD to the UAV is derived as

$$\begin{aligned} P_{(M\rightarrow U)} &= Pr(\gamma_U < \beta_{th}), \\ &= Pr\Big\{\frac{P_M||h_{M,U}||^2}{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,U}||^2 + \gamma_r{}^2P_{rr}||h_{rr}||^2 + N_o} < \beta_{th}\Big\}, \\ &= Pr(||h_{M,U}||^2 < \\ &\Big\{\frac{\beta_{th}(\gamma_r{}^2P_{rr}||h_{rr}||^2 + P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,U}||^2 + N_o}{P_M}\Big\}. \end{aligned} \quad (17)$$

Let:

$$S = \frac{\beta_{th}(\gamma_r{}^2P_{rr}||h_{rr}||^2 + P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,U}||^2 + N_o}{P_M}. \quad (18)$$

Hence, the outage probability of the link from the MD to the UAV can be given as

$$P_{(M\rightarrow U)} = \int_0^S f(x)dx = \int_0^S \frac{1}{2\sigma_1{}^2}e^{-\frac{x}{2\sigma_1{}^2}}dx, \quad (19)$$

where $\sigma_1{}^2$ is the variance of the THz channel of the MD to the UAV link. From (16), $\sigma_1{}^2$ is given as:

$$\sigma_1{}^2 = G_MG_U(\frac{c}{4\pi fd_{M,U}})^2 e^{-k(f)d_{M,U}}. \quad (20)$$

By evaluating the integration in (17), the outage probability from the MD to the UAV can be expressed as

$$P_{(M\rightarrow U)} = 1 - \exp\Big\{ -B_{th}(\frac{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,U}||^2 + \gamma_r{}^2P_{rr}||h_{rr}||^2 + N_o}{2\sigma_1{}^2P_M})\Big\}. \quad (21)$$

Similarly, the outage probability from the UAV to the BS can be expressed as

$$P_{(U\rightarrow BS)} = 1 - \exp\Big\{-B_{th}(\frac{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,BS}||^2 + N_o}{2\sigma_2{}^2P_U})\Big\}, \quad (22)$$

where $\sigma_2{}^2$ is the variance of the THz channel from the UAV to the BS. From (16), $\sigma_2{}^2$ is given as:

$$\sigma_2{}^2 = G_UG_{BS}(\frac{c}{4\pi fd_{U,BS}})^2 e^{-k(f)d_{U,BS}}, \quad (23)$$

From (21) and (22), the total outage probability from the MD to the BS over THz channel can be obtained and expressed in (24) as:

$$\begin{aligned} P_{out} = 1 - \Big\{ &\exp\Big[-\beta_{th}(\frac{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,U}||^2 + \gamma_r{}^2P_{rr}||h_{rr}||^2 + N_o}{2\sigma_1{}^2P_M})\Big] \\ &\times \exp\Big[-\beta_{th}(\frac{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,BS}||^2 + N_o}{2\sigma_2{}^2P_U})\Big]\Big\}. \end{aligned} \quad (24)$$

Let:

$$X = N_o + \gamma_r{}^2P_{rr}||h_r||^2, \quad (25)$$

$$Y = \frac{D_{m,u}{}^2e^{k(f)D_{m,u}}}{G_M}, \quad (26)$$

$$Z = \frac{D_{u,bs}{}^2e^{k(f)D_{u,bs}}}{G_U}. \quad (27)$$

Substituting with $\sigma_1{}^2$ and $\sigma_2{}^2$ in (24), the outage probability is now given by:

$$\begin{aligned} P_{out} = \; &1 - \Big\{\exp\Big[-\frac{\beta_{th}(4\pi f)^2}{2C^2G_U}(Y\frac{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,U}||^2 + X}{P_M})\Big] \\ &\times \exp\Big[-\frac{\beta_{th}(4\pi f)^2}{2C^2G_U}(Z\frac{P_{d2d}\sum_{i=1}^{M}||h_{d2d_i,BS}||^2 + N_o}{P_U})\Big]\Big\}. \end{aligned} \quad (28)$$

In the following, we derive the optimum power P_M^* and P_U^* that minimize the outage probability expressed in (28).

$$P_{out} = 1 - \exp\Bigg\{\frac{AY\sum_{i=1}^{M}||h_{d2d_i,U}||^2(\mu_1 P_M + \mu_2(P_{max} - P_M) + \mu_3 N_o) + AXY}{P_M} + \frac{AZ\sum_{i=1}^{M}||h_{d2d_i,BS}||^2(\mu_1 P_M + \mu_2(P_{max} - P + M) + \mu_3 N_o) + AZN_o}{P_{max} - P_M}\Bigg\}, \tag{29}$$

$$I = \Bigg\{\frac{AY\sum_{i=1}^{M}||h_{d2d_i,U}||^2(\mu_1 P_M + \mu_2(P_{max} - P_M) + \mu_3 N_o) + AXY}{P_M} + \frac{AZ\sum_{i=1}^{M}||h_{d2d_i,BS}||^2(\mu_1 P_M + \mu_2(P_{max} - P_M) + \mu_3 N_o) + AZN_o}{P_{max} - P_M}\Bigg\}. \tag{30}$$

V. Power Optimization

The objective is to minimize the outage probability expression given in (28) by optimizing the transmit powers P_M and P_U. Let P_{max} be the system budget power dedicated for the communication link between the MD and the BS. Thus, the problem can be formulated as:

$$\min_{P} P_{out}, \tag{31a}$$

$$s.t. P_M + P_U \leq P_{max}, \tag{31b}$$

$$P_M > 0, P_U > 0, P_{d2d} > 0 \tag{31c}$$

$$\gamma_{d2d_i} \geq T, \tag{31d}$$

where T is the minimum SINR required for any D2D receiving device. The constrain (31d) is provided to guarantee good quality of service (QoS) at the D2D devices. The minimum QoS is obtained when $\gamma = T$. Hence, from (11), the power of the i_{th} D2D device that guarantee the QoS at the i_{th} D2D is given as:

$$P_{d2d} = \Bigg\{\frac{T\Big[P_M||h_{M,d2d_i}||^2 + P_U||h_{U,d2d_i}||^2 + N_o\Big]}{||h_{d2d_{Tx_i},d2d_{Rx_i}}||^2 - T\sum_{j=1,j\neq i}^{M}||h_{d2d_{Tx_j},d2d_{Rx_j}}||^2}\Bigg\}. \tag{32}$$

Then by substituting by (32) in (28) and by letting $P_U = P_{max} - P_M$ from (31b), the outage probability of the link from the MD to the BS is given by (29) at the top of this page.

Let I be given by (30) at the top of this page, where

$$A = \frac{-B_{th}(4\pi f)^2}{2C^2 G_U}, \tag{33}$$

$$\mu_1 = \frac{T||h_{M,d2d_i}||^2}{||h_{d2d_{Tx_i},d2d_{Rx_i}}||^2 - T\sum_{j=1,j\neq i}^{M}||h_{d2d_{Tx_j},d2d_{Rx_j}}||^2}, \tag{34}$$

$$\mu_2 = \frac{T||h_{U,d2d_i}||^2}{||h_{d2d_{Tx_i},d2d_{Rx_i}}||^2 - T\sum_{j=1,j\neq i}^{M}||h_{d2d_{Tx_j},d2d_{Rx_j}}||^2}, \tag{35}$$

$$\mu_3 = \frac{T}{||h_{d2d_{Tx_i},d2d_{Rx_i}}||^2 - T\sum_{j=1,j\neq i}^{M}||h_{d2d_{Tx_j},d2d_{Rx_j}}||^2}. \tag{36}$$

To minimize the outage probability given in (29), the exponential term must be maximized. The maximization of the second exponential term is performed by minimizing the power of the exponential, that is minimizing I with respect to P_M.

To obtain the power P_M that minimizes I, $\frac{\partial I}{\partial P_M}$ is obtained and equated to zero. After mathematical manipulation, P_M is the solution of the following quadratic equation:

$$\Delta {P_M}^2 + \Gamma P_M + \Phi = 0 \tag{37}$$

where

$$\Delta = A\Bigg[P_{max}\big[\mu_1 Z\sum_{i=1}^{M}||h_{d2d_i,BS}||^2 - \mu_2 Y\sum_{i=1}^{M}||h_{d2d_i,U}||^2\big] + N_o \big[\mu_3 Z\sum_{i=1}^{M}||h_{d2d_i,BS}||^2 + Z - \mu_3 Y\sum_{i=1}^{M}||h_{d2d_i,U}||^2\big] - XY\Bigg], \tag{38}$$

$$\Gamma = 2P_{max}AY\Big[\sum_{i=1}^{M}||h_{d2d_i,U}||^2\big]\big[\mu_2 P_{max} + \mu_3 N_o\big] + X\Big], \tag{39}$$

$$\Phi = -{P_{max}}^2 AY\Big[\sum_{i=1}^{M}||h_{d2d_i,U}||^2\big[\mu_2 P_{max} + \mu_3 N_o\big] + X\Big]. \tag{40}$$

TABLE I
SIMULATION PARAMETERS.

Parameter	Description	Value
f	Operating Frequency	1 THz
$k(f)$	Absorption Coefficient	0.1
P_{max}	Power Budget	$0\ dB$
N_o	Noise Variance	$-50\ dBm$
B_{th}	Threshold of γ_U and γ_{BS}	$-80\ dB$
T	Threshold ofγ_{d2d_i}	$-20\ dB$
D	Distance between MD and UAV	$90\ m$
H	Height of BS	$15\ m$
G_{d2d}	Height of the BS	$20\ dB$

The solution of this quadratic equation is expressed as:

$$P_M^* = \frac{-\Gamma \pm \sqrt{\Gamma^2 - 4\Delta\Phi}}{2\Delta}. \tag{41}$$

From (31b), P_U^* is given as:

$$P_U^* = P_{max} - P_M^*, \tag{42}$$

where only positive power values are considered as constrained in (31c).

VI. Performance Evaluation and Numerical Results

In this section, the outage probability expressed in (28) is evaluated using the optimum obtained powers ${P_M}^*$ and ${P_U}^*$ expressed in (41) and (42), respectively. The outage probability is compared with fixed power scheme which divides the power budget P_{max} equally between MD and UAV. The values of the simulation parameters are summarized in Table I. The simulations are performed at $1\ THz$, which is one of the transmission windows at THz frequency range presented in [21].

Fig. 2 shows the achieved outage probability versus the available power budget P_{max} for the proposed optimum power allocation scheme and fixed power scheme. As expected, the figure depicts a decrease in the total outage probability when increasing the system dedicated power P_{max}. This is because the increase of P_{max} allows higher transmit power for the MD and the UAV which is found to decrease the outage probability by 20% at $P_{max} = 2$ Watt. Moreover, the proposed power optimization scheme achieves a better outage probability as compared to a fixed power dedication. This is because the proposed power allocation is derived based on minimizing the outage probability rather than giving fixed power to MD and UAV as the fixed power scheme.

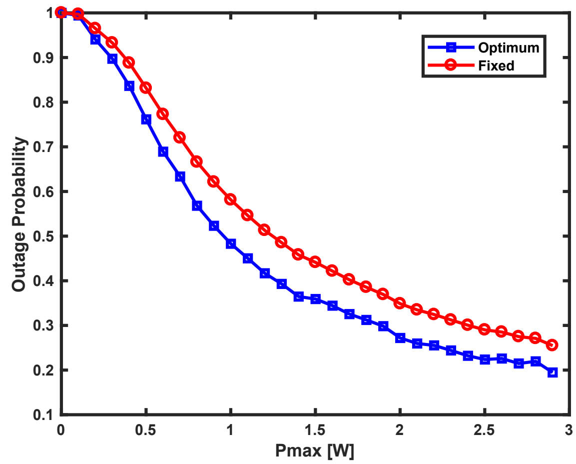

Fig. 2. Outage Probability achieved through the optimum and fixed power allocation schemes vs. P_{max}.

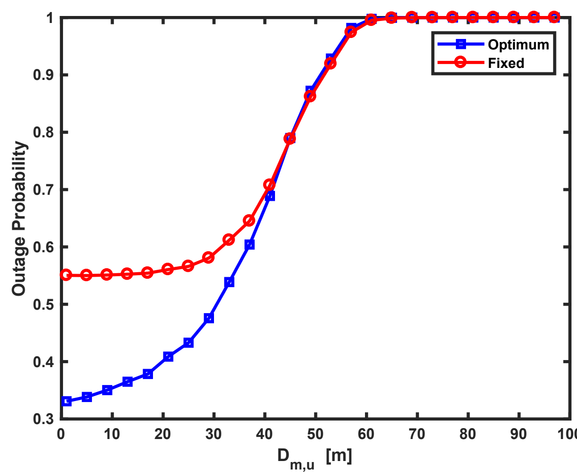

Fig. 3. Outage Probability achieved through the optimum and fixed power allocation schemes vs. $D_{m,u}$ at $D_{u,bs} = 50$ m.

Fig. 3 shows the achieved outage probability at different values of $D_{m,u}$, whereas $D_{u,bs}$ is fixed and is equal to 50 m. The figure depicts a dramatic increase in the outage probability when increasing $D_{m,u}$ due to the higher pathloss that the propagating signal encounters at a longer travelling distance which is one of the challenges of THz communications. This problem can be solved using MIMO system which increases the transmit power significantly. Furthermore, it is clear from the figure that the proposed power optimization scheme achieves a much lower outage probability up to a certain limit, then both the fixed and optimized power allocation schemes achieve the same outage probability.

Similarly, Fig. 4 shows the achieved outage probability at various values of $D_{u,bs}$ given a fixed distance $D_{m,u}$ of 20 m. The figure shows an increase in the outage probability whenever $D_{u,bs}$ increases. This is because of the attenuation

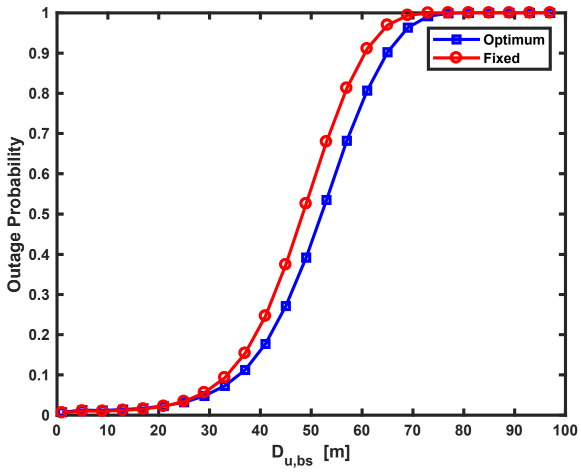

Fig. 4. Outage Probability achieved through the optimum and fixed power allocation schemes vs. $D_{u,bs}$ at $D_{m,u} = 20$ m.

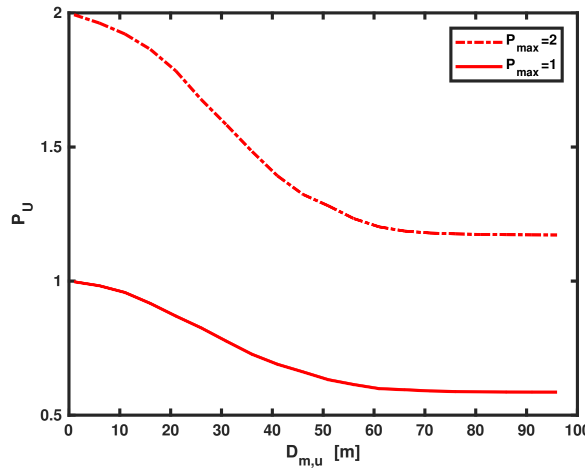

Fig. 6. Transmitted power of the UAV P_U vs $D_{m,u}$ for P_{max}= 1 Watt and P_{max} = 2 Watt.

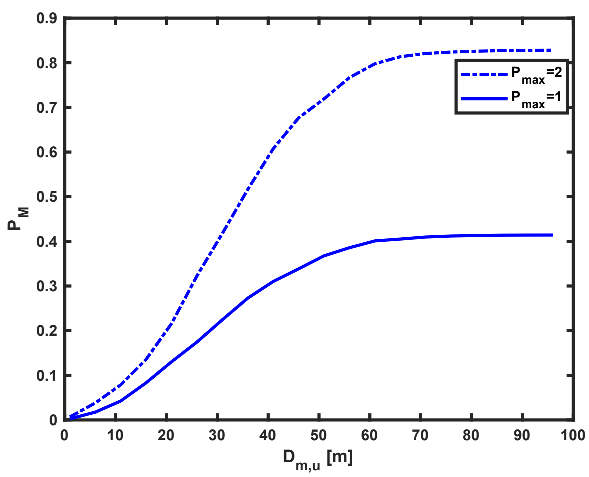

Fig. 5. Transmitted power of the MD P_M vs. $D_{m,u}$ for P_{max}= 1 Watt and P_{max} = 2 Watt.

of the signal due to high pathloss. Besides, it is obvious from the figure that the achieved outage probability of the proposed scheme is a bit better than that achieved at the fixed power allocation approach.

Figs. 5 and 6 show the transmitted power of the MD P_M and that of the UAV P_U, respectively. Both P_M and P_U are plotted versus $D_{m,u}$, for a power budget P_{max} equals to 1 Watt as well as 2 Watt. As Fig. 5 depicts, increasing $D_{m,u}$ leads to an increase of P_M up to a certain limit. Then, after this limit, P_M becomes constant. The reason behind that is increasing P_M causes decreasing of P_U because the sum is equal to P_{max}. Therefore, P_M remains constant even with the increasing of the distances to keep P_U within the minimum range required to attain good QoS of UAV to BS link. Furthermore, any increase in the dedicated system power P_{max} is reflected in increasing P_M and P_U. Meaning that the powers P_M and P_U are higher at $P_{max} = 2$ Watt than at $P_{max} = 1$ Watt.

VII. Conclusions and Future Work

In this paper, the optimum powers of the MD and the UAV that minimize the outage probability of the link between the MD and the BS in THz channel have been derived. The UAV is employed as a DF-FD relay to extend the coverage of the BS. Numerical results show that the total outage probability decreases when increasing the system dedicated power P_{max}. This is because any increase of P_{max} allows higher transmit power for MD and UAV which in turn decreases the outage probability. The proposed power allocation scheme has been compared with fixed power allocation scheme that allocates equal powers for the MD and the UAV. The results show that the outage probability using the obtained optimum powers is decreased by about 20% from that one that uses fixed power allocation scheme. It is noted that, the obtained optimum powers of the proposed scheme are adaptive and change according to the distance between the nodes. Furthermore, the outage probability increases drastically when increasing the distance between the MD and the BS. In fact, this is due to the severe pathloss that the propagating signal suffers during travelling. Consequently, MIMO system could be suggested for future work to increase the transmit powers effectively. Moreover, the dynamic positioning for the UAV and analyzing the outage probability in the context of re-positioning the UAV relay is to be investigated.

References

[1] H. Shin, J. Jung, and Y. Koo, "Forecasting the video data traffic of 5 g services in south korea," *Technological Forecasting and Social Change*, vol. 153, p. 119948, 2020.

[2] H. Elayan, O. Amin, R. M. Shubair, and M.-S. Alouini, "Terahertz communication: The opportunities of wireless technology beyond 5g," in *International Conference on Advanced Communication Technologies and Networking (CommNet 2018)*. IEEE, 2018, pp. 1–5.

[3] J. F. O'Hara, S. Ekin, W. Choi, and I. Song, "A perspective on terahertz next-generation wireless communications," *Technologies*, vol. 7, no. 2, p. 43, 2019.

[4] N. Elburki, S. Ben Amor, and S. Affes, "Evaluation of path-loss models for thz propagation in indoor environments," in *2020 IEEE Canadian Conference on Electrical and Computer Engineering (CCECE)*, 2020, pp. 1–5.

[5] C. Lin and G. Y. Li, "Indoor terahertz communications: How many antenna arrays are needed?" *IEEE Transactions on Wireless Communications*, vol. 14, no. 6, pp. 3097–3107, 2015.

[6] X. Gao, L. Dai, S. Han, I. Chih-Lin, and R. W. Heath, "Energy-efficient hybrid analog and digital precoding for mmwave mimo systems with large antenna arrays," *IEEE Journal on Selected Areas in Communications*, vol. 34, no. 4, pp. 998–1009, 2016.

[7] H. Elayan, R. M. Shubair, J. M. Jornet, and P. Johari, "Terahertz channel model and link budget analysis for intrabody nanoscale communication," *IEEE transactions on nanobioscience*, vol. 16, no. 6, pp. 491–503, 2017.

[8] O. Elkharbotly, E. Maher, A. El-Mahdy, and F. Dressler, "Optimal power allocation in cooperative mimo-noma with fd/hd relaying in thz communications," in *2020 9th IFIP International Conference on Performance Evaluation and Modeling in Wireless Networks (PEMWN)*. IEEE, 2020, pp. 1–6.

[9] A. Saeed, O. Gurbuz, and M. A. Akkas, "Terahertz communications at various atmospheric altitudes," *Physical Communication*, p. 101113, 2020.

[10] O. D. Oyeleke, S. Thomas, O. Idowu-Bismark, P. Nzerem, and I. Muhammad, "Absorption, diffraction and free space path losses modeling for the terahertz band," *Int. J. Eng. Manuf*, vol. 10, p. 54, 2020.

[11] E. Turgut and M. C. Gursoy, "Outage probability analysis in d2d-enabled mmwave cellular networks with clustered users," in *2018 IEEE 88th Vehicular Technology Conference (VTC-Fall)*. IEEE, 2018, pp. 1–5.

[12] S. Zeng, H. Zhang, K. Bian, and L. Song, "Uav relaying: Power allocation and trajectory optimization using decode-and-forward protocol," in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2018, pp. 1–6.

[13] H. Wang, J. Wang, G. Ding, J. Chen, Y. Li, and Z. Han, "Spectrum sharing planning for full-duplex uav relaying systems with underlaid d2d communications," *IEEE Journal on Selected Areas in Communications*, vol. 36, no. 9, pp. 1986–1999, 2018.

[14] S. K. Khan, A. Al-Hourani, and K. G. Chavez, "Performance evaluation of amplify-and-forward uav relay in millimeter-wave," in *2020 27th International Conference on Telecommunications (ICT)*. IEEE, 2020, pp. 1–5.

[15] H. Sarieddeen, M.-S. Alouini, and T. Y. Al-Naffouri, "An overview of signal processing techniques for terahertz communications," arXiv, eess.SP 2005.13176, May 2020.

[16] Z. Guan and T. Kulkarni, "On the effects of mobility uncertainties on wireless communications between flying drones in the mmwave/thz bands," in *IEEE INFOCOM 2019 - IEEE Conference on Computer Communications Workshops (INFOCOM WKSHPS)*, 2019, pp. 768–773.

[17] R. Mendrzik, D. Cabric, and G. Bauch, "Error bounds for terahertz mimo positioning of swarm uavs for distributed sensing," in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*, 2018, pp. 1–6.

[18] R. Mendrzik, D. Cabric, and G. Bauch, "Error bounds for terahertz mimo positioning of swarm uavs for distributed sensing," in *2018 IEEE International Conference on Communications Workshops (ICC Workshops)*. IEEE, 2018, pp. 1–6.

[19] H. Zhang, H. Zhang, K. Long, J. Dong, V. Leung *et al.*, "Energy efficient user clustering, hybrid precoding and power optimization in terahertz mimo-noma systems," *arXiv preprint arXiv:2005.01053*, 2020.

[20] J. M. Jornet and I. F. Akyildiz, "Channel modeling and capacity analysis for electromagnetic wireless nanonetworks in the terahertz band," *IEEE Transactions on Wireless Communications*, vol. 10, no. 10, pp. 3211–3221, 2011.

[21] C. Han and I. F. Akyildiz, "Distance-aware multi-carrier (damc) modulation in terahertz band communication," in *2014 IEEE International Conference on Communications (ICC)*. IEEE, 2014, pp. 5461–5467.