Non-Orthogonal Multiple Access for Terahertz Communication Networks

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***Abstract*—Terahertz communications is one of the promising technologies for the future mobile communication networks. Due to the ever increasing need for high-speed data transfer, higher bandwidths are required. As a solution, higher frequencies in the spectrum may be considered for future networks. In this paper, Terahertz band is selected since the latest technological advances make it possible to deploy mobile networks in this high-frequency band. To support higher bandwidth with an advanced multiple access method, non-orthogonal multiple access (NOMA) is implemented in this paper. Different from orthogonal multiple access (OMA), NOMA makes it possible for users to share the same frequency and time resources simultaneously, therefore increases the spectral efficiency. To measure the efficiency of the implemented methods, computer simulations are used and results are obtained for different scenarios. In the simulation results, it is shown that NOMA provides higher average data rates for these scenarios where users are located on variety of distances far from the Terahertz access point. As a result, this work shows NOMA for Terahertz communication networks is a promising method for future communication networks.**

***Index Terms*—non-orthogonal multiple access, NOMA, power-domain NOMA, PD-NOMA, terahertz communication, high-speed data networks**

I. INTRODUCTION

The need for speed in wireless data networks is increasing every day. Contemporary applications require up to hundreds of megabits per second (Mbps) but it is not far from today that applications will require several gigabits per second (Gbps) data transfer speed. In the latest user-ready technology in mobile communications, 5G, it is possible to go up to 4.5 Gbps [1]. Researchers in information and communication technologies are working to improve the data transfer speed in multiple ways. One of the solutions offered is using the higher frequency bands in the spectrum. In the earlier mobile communication networks, 1G to 4G, and in the other commonly used wireless technologies such as Wi-Fi and Bluetooth, sub-6GHz is used. Recently, as a big step of high frequency usage after WiGig [2], 5G offers millimeter wave band communication [3]. Although millimeter wave is a decent step, future wireless communication networks are expected to go upper frequencies. Researchers offer to use Terahertz (THz) band in the next generations of wireless communication. THz band is usually referred to the band between 0.1 THz to 10 THz [4] (See Figure 1).

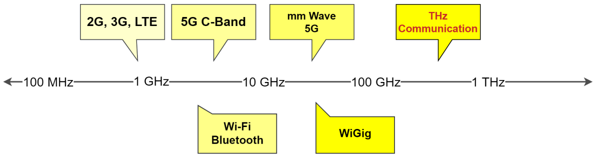

Fig. 1. Frequency bands for wireless communication networks

By going up to higher frequencies available bandwidth is increased. As a result, this increases data transfer speed of a single user. Although this approach presents required high data transfer speed for a single user, for multiple user scenarios alternative multiple access techniques should be considered. In traditional networks, orthogonal multiple access (OMA) methods are used but it divides the resources (time, frequency or code-domain) by the number of users. The increase in the number of users therefore creates a problem for each user to reach a limited speed of data transfer. To tackle this problem, new approaches such as implementing avant-garde methods like non-orthogonal multiple access (NOMA) or more specifically power-domain NOMA (PD-NOMA) instead of OMA methods such as orthogonal frequency division multiple access (OFDMA) may be considered.

In this paper, PD-NOMA in THz communication networks is considered. By using this multiple access method, it is expected to increase average data transfer speed for each user in a network compared to the data transfer speed for the users that use OFDMA in the same network scenario.

The paper is organized as follows. Section II explains NOMA and THz communication networks. In Section III, system model is presented with mathematical explanation of the channel model. In Section IV, proposed link adaptation algorithm for NOMA in THz communications is given. In Section V, comparison of NOMA and OFDMA for two users that use an adaptive link algorithm in THz band is given with the computer simulations in different scenarios. Finally in Section V, the paper is concluded.

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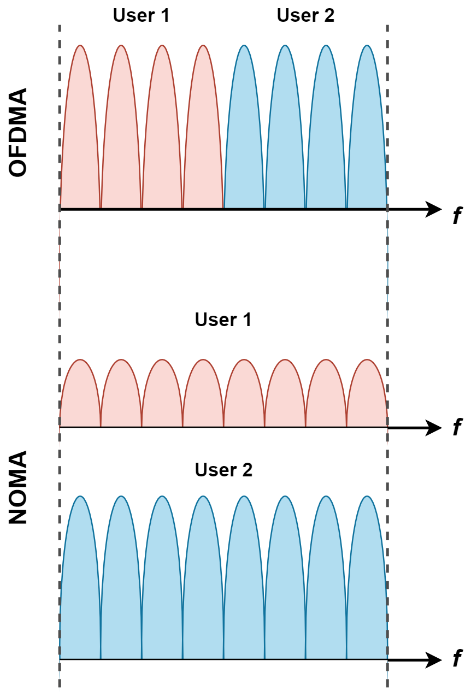


Fig. 2. Spectrum sharing of OFDMA and NOMA for two users

II. BACKGROUND

A. Non-Orthogonal Multiple Access

Non-orthogonal multiple access is a method that is proposed mainly to improve spectral efficiency, since with the earlier OMA methods spectrum is not shared with the users efficiently enough to realize desired high throughputs. As it is shown in Figure 2, in OFDMA, while two users use the same frequency band, the band should be orthogonally used by each user, which causes each users' throughput to be reduced. On the other hand, in the power-domain version of NOMA, both users are able to use the same frequency band without separation of frequencies but instead, transmission powers of the users are adjusted and effective interference cancellation methods are implemented to avoid interference between these two users.

For future generation of mobile communication networks, NOMA can be used by benefiting effective interference cancellation and signal detection methods. The main superiority of NOMA to other multiple access methods can be summarized as following [5], [6], [7]:

- Spectral Efficiency: High spectral efficiency (SE) is the main feature of NOMA. By allowing resource blocks of the same time, frequency or code domains to be used by multiple users, NOMA provides fairness to each user and improved spectral efficiency compared to earlier alternatives [8].
- Connectivity: Since NOMA makes it possible to serve multiple number of users in the same resource block, massive connectivity of massive number of users is possible. The recent trend of communication, Internet of Things (IoT) applications can implement NOMA to transmit small data packets while having high number of users using the same resource block without interference [9].
- Channel feedback: Since only the strength of the received signal is considered in the channel feedback, base stations in NOMA method do not need successive uplink channel state information (CSI) [10].
- Transmission latency: As compared to OMA, NOMA uplink channel does not need users to send schedule requests to the base stations. Therefore, by adopting a grant-free uplink transmission the latency of transmission is reduced significantly in NOMA [11].

There are mainly two types of NOMA methods in the literature, which are code-domain NOMA and power-domain NOMA. In the code-domain NOMA, different codes are designated to different users in the same resource block in order to support concurrently multiple transmissions [12]. On the other hand, in the power-domain NOMA, two users use the same frequency resource block with a limitation in total power. This power is allocated between two users with rate pairs. For the symmetric and asymmetric channels, where power rate pairs are differentiated between two users, it is shown and compared with OFDMA in Figure 3. With the help of interference cancellation, in power-domain NOMA, these two users do not interfere each other and continue their communication [13]. This cancellation and decoding process is shown in Figure 4. In this paper, when NOMA is mentioned, it refers to power-domain NOMA.

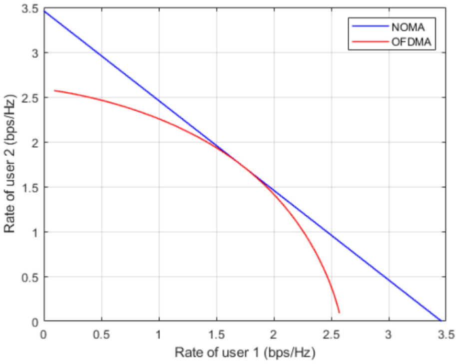
B. Terahertz Communication Networks

In the recent years in wireless communication, data traffic has been overly increased due to the change in technologies that people use daily. Especially, after social media and increased quality of video streaming, demand for data rates is enormous. In a decade or so, Terabit per second links are expected to be needed.

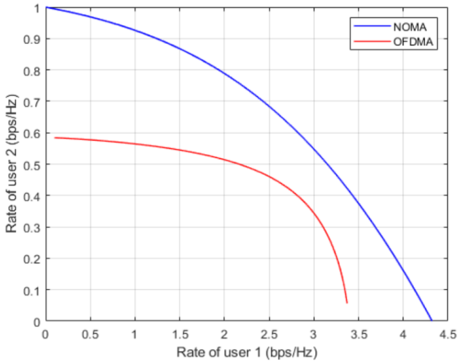
The first alternative for this problem is millimeter wave (mmWave) communication networks. In 5G, there are 28 GHz and 60 GHz bands commercially available for mmWave communication [14]. Although, this is a good alternative, the data rates of mmWave communication is still not enough to answer the possible need.

The second alternative is free space optical (FSO) communication networks, which operates in infrared (IR) frequencies and above [15]. The impact of the atmospheric effect on signal propagation in these frequencies is quite harsh such as the effect of rain, dust, pollution etc. Also, the achievable data rates are limited due to the insufficiency of the technology to design the required transceivers.

Considering these two options, there may be an alternative approach where enough high bandwidth can be provided but



(a) Symmetric channel



(b) Asymmetric channel

Fig. 3. Symmetric and asymmetric channel rate pairs for downlink NOMA

signal propagation is still not vulnerable as much as in the FSO communication networks. This alternative is THz communications. There are still many challenges in this band. To solve these challenges, the IEEE 802.15 Wireless Personal Area Networks (WPAN) study group 100 Gb/s wireless (SG100G) has been established [16]. Since this paper is mainly focused on physical layer characteristics of THz communications, the main physical layer challenges in THz communications are listed below:

- Since the path loss is highly frequency-selective, after a few meters it can easily go up to 100 dB.

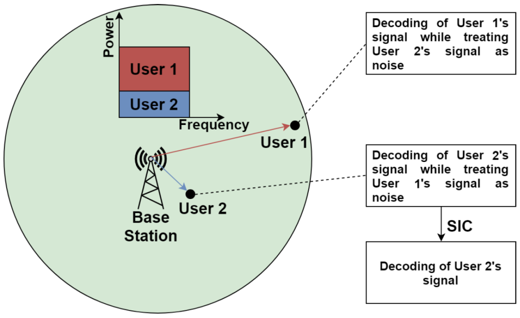


Fig. 4. Downlink transmission of power-domain NOMA

- Non-line of sight communication and multi-path channel gains are almost non-existent.
- Due to operating a higher frequency bands than conventional systems, achieving synchronization among user devices is hard with traditional methods.
- Traditional massive multiple-input multiple-output systems are not easily deployed. Razor-sharp beams between transmitter and receiver are needed.

III. SYSTEM MODEL

In this section, the system model is explained. Simplified channel model for THz communications is given and described in detail. Then, the network topology for the given model is presented and finally link adaptation algorithm is given. For transmission, time division duplex (TDD) mode downlink transmission scenario is considered and uplink transmission is avoided. To compare NOMA results with OMA results, OMA results are obtained as explained in [17].

A. Channel Model

As in [17], the channel coefficient, $h(k)$, is assumed to follow zero-mean complex Gaussian distribution with variance that models the path loss. In THz communications, different than the traditional mobile communication networks such as LTE or 5G that use fairly low frequencies, in addition to free space path loss, atmospheric absorption is considered.

Total path loss is calculated as follows [17]:

$$PL(f,d,\mu) = exp(-d(\sum_{i=1}^{4} y_i(f,\mu) + g(f))) \tag{1}$$

where f is the operating frequency, d is the distance between transmitter and receiver and μ is described as

$$\mu = \frac{\phi}{100}\frac{p_w(T,p)}{p} \tag{2}$$

where ϕ consists of the relative humidity and p is the pressure. p_w is a function of T temperature in a given pressure, which as a result gives the water vapor partial pressure.

The other parameters to determine the atmospheric absorption lines between 250 GHz to 450 GHz, y_1, y_2, y_3, y_4, are given as

$$y_1(f,\mu) = \frac{A(\mu)}{B(\mu) + (\frac{f}{100c} - p1)^2} \tag{3}$$

$$y_2(f,\mu) = \frac{C(\mu)}{D(\mu) + (\frac{f}{100c} - p2)^2} \tag{4}$$

$$y_3(f,\mu) = \frac{E(\mu)}{F(\mu) + (\frac{f}{100c} - p3)^2} \tag{5}$$

$$y_4(f,\mu) = \frac{G(\mu)}{H(\mu) + (\frac{f}{100c} - p4)^2} \tag{6}$$

$$g(f,\mu) = \frac{\mu}{0.0157}(q_1 f^4 + q_2 f^3 + q_3 f^2 + q_4 f + q_5) \tag{7}$$

where f is the frequency in Hertz,

$$\begin{aligned}A(\mu) &= 0.2251\mu(0.1314\mu + 0.0297)\\ B(\mu) &= (0.4127\mu + 0.0932)^2\\ C(\mu) &= 2.053\mu(0.1717\mu + 0.0306)\\ D(\mu) &= (0.5394\mu + 0.0961)^2\\ E(\mu) &= 0.177\mu(0.0832\mu + 0.0213)\\ F(\mu) &= (0.2615\mu + 0.0668)^2\\ G(\mu) &= 2.146\mu(0.1206\mu + 0.0277)\\ H(\mu) &= (0.3789\mu + 0.0871)^2\end{aligned}$$

and $p_1 = 10.84cm^{-1}$, $p_2 = 12.68cm^{-1}$, $p_3 = 14.65cm^{-1}$, $p_4 = 14.94cm^{-1}$, $q_1 = 8.495 \times 10^{-48}$, $q_2 = -9.932 \times 10^{-36}$, $q_3 = 4.336 \times 10^{-24}$, $q_4 = -8.33 \times 10^{-13}$ and $q_5 = 5.953 \times 10^{-2}$. These absorption lines are the lines at 325 GHz, 380 GHz, 439 GHz and 448 GHz.

With the given parameters, path gain between 200 GHz to 500 GHz is given in Figure 5 with different transmission and receiver distances.

B. Network Topology and Scenarios

It is assumed in this work that there are two user equipment (UEs) connected to the access point (AP) via THz link and the operating frequency is 350 GHz. Multipath fading is not considered and it is assumed that UEs communicate with AP through line-of-sight. As seen in Figure 6, one of the users' distance from the AP is d_1 and the other one's is d_2.

There are two scenarios considered in this paper. For the scenario 1, it is assumed that both users have the same distance (d_1 = d_2). In scenario 2, it is assumed that users have different distances. For each scenario capabilities of NOMA and OMA are compared in average data rates per user and the results are given in section IV.

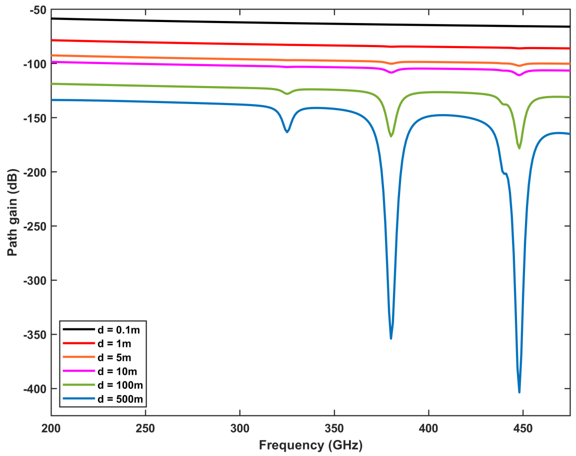


Fig. 5. Simulation results for path gain between 200 GHz and 500 GHz

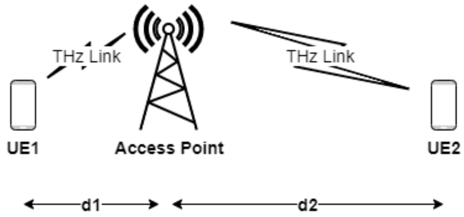


Fig. 6. Network Topology

IV. LINK ADAPTATION ALGORITHM

In order to distinguish the differences between OMA and NOMA similar algorithms are implemented. The adaptive modulation order selection is the method chosen for the link adaptation for OMA [17], therefore available transmission bandwidth, number of subcarriers for the given bandwidth, instantenous path loss for the given subcarriers to determine virtual subcarriers, the power allocation of the non-virtual subcarriers and achievable SNR with the given power of the subcarriers must be determined step by step in order to select the appropriate modulation order in the proposed algorithm.

For the first step available transmission bandwidth is given as:

$$B(d) = f_c^h - \Delta f_h - (f_c^l + \Delta f_l) \tag{8}$$

where B is the available bandwidth for the distance d, f_c^h is the high absorption line center frequency and f_c^l is the low absorption line center frequency. Δf_h and Δf_l are obtained as in [17] and [18].

Number of subcarriers are selected as $N = 128$ for both OMA and NOMA. For each subcarrier instantaneous pathloss is calculated and checked if the pathloss is greater than the determined threshold, L_{th}, which is calculated as:

$$L_{th} = \frac{P_t}{N} + G_b + G_u - (\gamma_b + P_n) \tag{9}$$

where P_t is fixed total transmission power, P_n is the noise power, N is the number of subcarriers, G_b and G_u are antenna gains for transmitter and receiver and γ_b is the average signal-to-noise (SNR) ratio as calculated in [15, eq. (22)].

The subcarriers whom instantaneous pathlosses are higher than the threshold, are selected as virtual subcarriers and they are excluded from the further steps. In NOMA, since $P_t = \sum_{i=1}^{U} p_i$, where P_t is the total transmission power that is shared between users, and p_i is the power allocated for the user i, power of one user depends on other users' powers. Since there are two users in this scenario, the power pairs are given as [19]:

$$p_1 = \frac{p_1'}{p_1' + p_2'} \tag{10}$$

where

$$p_i' = \frac{U_i(d)}{r_{max}} \tag{11}$$

where $U_i(d)$ is the user i's distance from the access point, and r_{max} is the maximum communication distance from access point with the selected Bit Error Rate (BER) requirement. Therefore the second user's power is p_2 = P_{total} - p_1. With the calculated rates, power is allocated to the subcarriers. In this scenario, perfect successive interference cancellation (SIC) is assumed.

After the SNR calculation of each power allocated to non-virtual subcarriers, the modulation order is selected as shown in [20]. Modulation order M_k is selected to satisfy to following BER requirement R_{BER},

$$M_k \leq \frac{2\gamma_k}{3}\left(\frac{1}{(1-\frac{2R_{BER}}{a})^2}-1\right)+1 \tag{12}$$

where

$$a = \begin{cases} 1 & \text{for} M_k = 4 \\ \frac{4}{log_2(M_k)} & \text{for} M_k > 4 \end{cases} \tag{13}$$

Above mentioned algorithm, NOMA Link Adaptation Algorithm, is given below as Algorithm 1.

Algorithm 1: NOMA Link Adaptation Algorithm

```
Result: Selected Modulation Order
initialization;
// Calculate the available bandwidth
$B \leftarrow$ Eq. (8);
// Number of subcarriers selected as
   128
$N \leftarrow$ 128;
for each subcarrier do
    // Calculate instantaneous path
       loss $PL_i$
    // Determine the treshold
    $L_{th} \leftarrow$ Eq. (9);
    if $PL_i > L_{th}$ then
        Set the subcarrier as virtual;
    else
        // Power allocation according to
           the power rates
        Power rate $\leftarrow$ Eq. (10);
        Power is allocated for the given rate;
        // For the given BER
           requirement, Modulation order
           is selected
        $M_k \leftarrow$ Eq. (12);
end
```

V. SIMULATION RESULTS

For the given channel model, network topology and link adaptation algorithm, computer simulation results are obtained. For the atmospheric conditions, it is assumed as 101325 Pa (1 atmosphere) for pressure with 50% humidity and 23 degrees Celsius as the temperature. Maximum transmission power of AP is 10 dBm, and antenna gains are 45 dB for both transmission and receiving. Absorption loss tolerance is assumed as 1 dB and BER requirement for successful communication is set to 10^{-5}. Finally as mentioned earlier, operating frequency is 350 GHz for the downlink transmission.

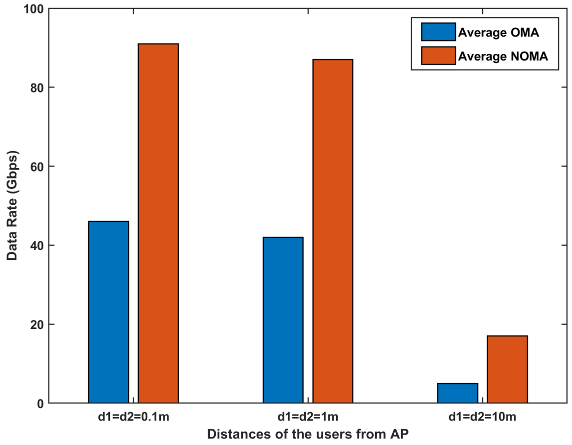


Fig. 7. Average data rates per user for the Scenario 1

In Figure 7, average data rates are given for the Scenario 1 where two users are at the same distance to the AP. It is observed that by using NOMA when the distances are 0.1 and 1 meters, average data rates are doubled. When the distance grows NOMA results are getting even more favorable when compared to OMA. It is shown that for the distances 10 meters, NOMA is three times superior than OMA in average data rate.

For the Scenario 2, different distances are considered and results are presented in Figure 8. For the first case, distances are 0.1 meters and 1 meters and in the second case, distances are 1 meters and 10 meters. In the simulations, 1000 instances are considered and the minimum and maximum data rates are also given in the figure. It is shown that in Scenario 2, NOMA has doubled the results of OMA again and shown it is superior to OMA.

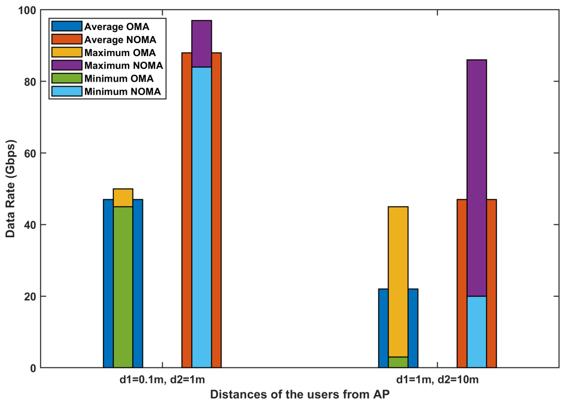


Fig. 8. Average data rates per user for the Scenario 2

VI. Conclusion

In this paper, NOMA method has been proposed and compared with OMA in THz communication networks. Two different scenarios have been considered and in both scenarios it is shown that NOMA is superior to OMA in average data rates. For further work, it is aimed to consider increased number of users and implementation of smart resource allocation methods for NOMA in THz communication networks.

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