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Multiple Access Techniques for VLC in Large Space Indoor Scenarios: A Comparative Study

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***Abstract*—The growing demand for high speed indoor wireless connectivity is among the driving forces for data transmission based on visible-light communications (VLC). For relatively large-space indoor scenarios, the development of appropriate spectrally-efficient multiple-access (MA) techniques enables efficient handling of multiple users, in particular, in dealing with the limited modulation bandwidth of the light-emitting diodes. In this paper, we present a comparative study between different MA techniques proposed in the recent literature for VLC networks. The most appropriate schemes for large-scale network deployments are further investigated in different scenarios to contrast their performance in terms of the achievable throughput.**

***Index Terms*—Visible light communications; multiple-access techniques; indoor VLC; OFDMA; NOMA.**

I. Introduction

Visible light communications (VLC) has been receiving increasing interest in the recent years, due to several promising features including: using an unregulated spectrum, immunity to radio-frequency (RF) interference, improved security at the physical layer compared to the RF wireless technologies, and exploiting the energy-efficient light-emitting diode (LED) lighting infrastructure [1]. Within this context, for large-space indoor scenarios such as lecture halls, libraries, convention centers, factories, airports, and shopping malls, the design and deployment of the VLC technology faces a number of challenges. In particular, handling a large number of users involving a heavy wireless traffic, and managing user mobility through multi-cell architectures with seamless handover, require efficient spectrum management and proactive coordination between the access points (APs), i.e., the LED luminaires, and the user terminals. There, an important consideration concerns the design of efficient multiple-access (MA) techniques of reasonable complexity, in order to optimize the network performance through the minimization of the inter-cell interference (ICI), as well as the inter-user interference (IUI) within a cell.

Multi-user (MU) VLC system design has been the subject of extensive research in the recent literature. Considering the general context of VLC applications, a general overview of the MU VLC techniques was presented in [2]. Also, a survey of different MA techniques for VLC applications was provided in [3] and [4]. Authors in [5] reviewed the non-orthogonal multiple access (NOMA) approach for VLC. The work in [6] studied suitable MA techniques for ultra-dense VLC networks with a focus on NOMA and orthogonal multiple-access techniques. However, these works did not specially study the large-space scenarios. Our aim in this paper is to focus on the large-space indoor scenarios and to investigate the performance of the most relevant MA techniques. In particular, we study the effect of increased number of users on the maximum achievable network data-rate.

The remainder of this paper is organized as follows. Focusing on downlink transmission, Section II presents different MA techniques that could be used in VLC applications and discusses the suitability of each technique for use in large-space VLC scenarios. Focusing on the most suitable techniques, which are orthogonal frequency-multiplexing modulation MA (OFDMA) and NOMA, as we will see, Section III presents the mathematical formulation of signal transmission. Afterwards, the performance of OFDMA and NOMA are contrasted in Section IV for typical scenarios through numerical results. Section V concludes the paper.

II. Multiple Access Techniques for VLC

We present here different MA techniques, namely, time-division MA (TDMA), space-division MA (SDMA), optical code-division MA (O-CDMA), OFDMA, and NOMA, while discussing their suitability for a multi-cell VLC network with the possibility of user mobility. Corresponding to each cell, an LED luminaire serves as AP, handling the signal transmission for users in its coverage area.

A. TDMA

By TDMA, the channel temporal resources are shared by allocating certain time slots for each user [7], [8]. Although in indoor applications, we are concerned with a relatively low mobility of users, the accurate synchronization required at the user terminals and at the AP could become a challenge due to very high data-rates, especially for increased number of users. Also, in a multi-cell network, TDMA suffers from increased ICI at overlapping areas between the cells [9]. Obviously, it can not benefit from the frequency reuse concept in such cases.

B. SDMA

SDMA basically consists in separating users in space domain, which could be realized using angle diversity transmitters (Txs) [9]. In RF systems, SDMA can be achieved using antenna arrays, which are used for generating narrow beams pointing at users locations [9]. However, in VLC systems, this requires employing either special LEDs or using special optics with the off-the-shelf LEDs. Therefore, from a practical point of view, SDMA is not well adapted to VLC networks in general. Nevertheless, it has been shown that combining TDMA and SDMA can result in a significant improvement in the network performance, compared with the simple TDMA approach [9].

C. O-CDMA

By O-CDMA, a unique code, also called signature sequences (SS) is attributed to each user, which is typically an optical orthogonal code (OOC) [10]. Users then use full time and spectral resources of the VLC channel. At the receiver (Rx), each user correlates the received signal with its specific code in order to (ideally) suppress the IUI. For this, the SS should be distinguishable from its shifted version as well as the shifted versions of other users' SS [4]. Note that random optical codes (ROCs) are simpler to generate than OOCs [11], but they provide a sub-optimal performance. In general, to handle a larger number of users, longer OOCs are needed, which impacts the achievable data rates and also increases the system complexity [12]. This can be a serious disadvantage for a relatively dense VLC network in a typical large-space scenario.

D. OFDMA

Optical OFDM is a popular transmission technique to achieve high data-rates in VLC networks, overcoming the highly constrained modulation bandwidth (BW) of the LEDs [13].[1] When using intensity modulation with direct detection, which is the case for LED-based links, one drawback of optical OFDM is the necessity of transmitting a real and positive signal by, in particular, satisfying the Hermitian symmetry constraint. This causes a spectral efficiency loss of factor 2 and 4 for DC-biased optical OFDM (DCO-OFDM) and asymmetrically-clipped optical OFDM (ACO-OFDM) schemes, respectively [16], [17]. OFDMA relies basically on using an OFDM-based transmission scheme, where the MA feature is obtained via sharing the spectral resources (i.e., groups of sub-channels) between users.

For multi-cell scenarios, appropriate frequency reuse solutions can be used to decrease the network ICI [18]. For instance, fractional frequency reuse (FFR) has been proposed for DCO-OFDM-based systems in [18], which offers a good balance between the performance of cell-edge users (CEUs), the average spectral efficiency, and low system complexity. Therein, two approaches of *strict* and *soft* FFR were considered. Strict FFR is based on dividing the available BW to a common sub-band, used by cell-center users (CCUs), and a number of additional sub-bands, used by CEUs; these sub-bands are assigned so as to minimize the spatial reuse distance. For soft FFR, CCUs can use the sub-bands reserved to CEUs in the adjacent cells. In such a case, the performance of CEUs could degrade due to a higher interference level. To reduce this effect, more power is allocated to CEUs, compared with CCUs.

[1]Note that the LED BW limitation could be circumvented by appropriate pulse shaping at the Tx, see [14], [15].

E. NOMA

By power-domain NOMA (that we will simply refer to as NOMA), multiplexing of users' signals is carried out at the AP using superposition coding, which allows the users to simultaneously use the whole temporal and spectral resources [19]. NOMA is particularly interesting in VLC applications, compared for example to the context of 5G RF cellular networks. Indeed, VLC networks have likely a small number of users per cell, benefit from relatively high signal-to-noise-ratios (SNRs), and typically experience slow channel variations due to the limited user mobility in indoor environments.

At the Rx side, users apply successive interference cancellation (SIC) to its received signal, to partially or fully remove the IUI from the other users (except for the first user in the decoding order), requiring hence the corresponding channel state information (CSI). At the AP, users' signals are sorted based on their channel gains, so that users with lower channel gains are allocated a larger power. These latter decode their data first at the Rxs side.

F. Comparison of MA Techniques

Following the above mentioned discussions, we take OFDMA and NOMA schemes as the most relevant for a high-rate large-space VLC network. Table I shows a brief comparison between the MA schemes presented above, considering the three main features of large-space scenarios, i.e., the ICI, the potential large number of users, and the requirement to high data rate. We have shown which schemes can support each of these features.

TABLE I: Comparison between different MA techniques.

	TDMA	SDMA	CDMA	OFDMA	NOMA
ICI		√		√	
Large no. users				√	√
High data rate		√			√

III. SYSTEM MODEL AND MATHEMATICAL FORMULATION

To characterize the link between the AP_i and the Rx_j, we define the channel gain h_{ij}, which takes into account only the line-of-sight (LOS) path [20]. Assuming a Lambertian pattern for the LED luminaire of order m, we have:

$$h_{ij} = \mathcal{S}\,\frac{(m+1)\,\rho_j\,A_j}{2\pi\,\ell_{ij}^2}\cos^m(\phi_{ij})\cos(\theta_{ij}), \qquad (1)$$

where $\mathcal{S}$ denotes the LED conversion efficiency, ϕ_{ij} the angle of transmission with respect to AP_i, θ_{ij} the angle of incidence with respect to Rx_j, m the Lambertian order of the LED, ρ_j the photo-detector (PD) responsivity, and ℓ_{ij} is the path length between AP_i and Rx_j. Also, A_j denotes the collection area of the j^{th} Rx, which is given by:

$$A_j = \frac{q_j^2}{\sin^2(\theta_{cj})} A_{\mathrm{PD}_j}, \tag{2}$$

where A_{PD_j}, θ_{cj}, and q_j represent the PD active area, the field-of-view (FOV) of Rx_j, and the refractive index of the optical concentrator, respectively.

For both OFDMA and NOMA approaches, we will consider signal transmission based on DCO-OFDM.

A. OFDMA-based Signal Transmission

We consider OFDMA with strict FFR approach for ICI mitigation. We consider determining the BW allocation to CCUs and CEUs based on the ratio of the number of CCUs to the total number of users, with respect to the cell which has the largest number of CEUs, that we denote by ζ, i.e.,

$$\zeta = \frac{\text{No. of CCUs}}{\text{No. of CCUs + No. of CEUs}}. \tag{3}$$

This parameter is equal to the fraction of the BW which is attributed to CCUs:

$$\mathrm{BW}_{\mathrm{CCU}} = \zeta \; B, \tag{4}$$

where B denotes the total system BW. Note that a different approach was proposed in [18], where a certain non-overlapped area of the total cell coverage area is considered to include CEUs (instead of considering CEUs in the intersecting areas between cells, that we consider in this paper).

Using the approach in (4), the signal-to-interference-plus-noise ratio (SINR) For Rx_j is then given by:

$$\mathrm{SINR}_{\mathrm{OFDMA}_j} = \frac{(h_{ij}\sqrt{P_e\, K_j})^2}{\sigma_j^2}, \tag{5}$$

where P_e is the electrical signal power at the AP, K_j denotes the percentage of power allocated to Rx_j, and σ_j^2 stands for the noise variance. Denoting the allocated BW to Rx_j by B_j, the maximum achievable rate for Rx_j is then:

$$R_{\mathrm{OFDMA}_j} = \frac{B_j}{2}\log_2(1 + \mathrm{SINR}_{\mathrm{OFDMA}_j}). \tag{6}$$

B. NOMA-based Signal Transmission

As explained in the previous section, with NOMA, users' signals are multiplexed in the power domain, while assigning to each user a power allocation weight, which is smaller for users with a higher channel gain. At the Rx, to reduce IUI, SIC is performed, where the decoding order is based on the channel gain of the users. For instance, the user with the highest channel gain is the last to decode its signal. Obviously, for this, the corresponding users' CSI is required at the Rx.

The received signal at Rx_j can be written as [21]:

$$r_j = \sqrt{P_e} h_{ij}\Big(\sum_{k=1}^{j-1} a_{ik} d_k + a_{ij} d_j + \sum_{k=j+1}^{N_r} a_{ik} d_k\Big) + z_j, \tag{7}$$

where P_e denotes the transmitted electrical power, d_j refers to Rx_j message, and a_{ij}^2 represents the power allocation weight of the link from AP_i to Rx_j. In (7), the first term ($k < j$) in the parentheses represents the interfering signals that will be canceled using SIC, the second term contains the desired signal, and the third term ($k > j$) represents the residual interference, which will not be canceled using SIC. Also, z_j represents the additive white Gaussian noise, comprising the ambient, shot, and thermal noises.

A number of previous works have considered the power allocation techniques for NOMA signaling such as [22]–[24]. For the sake of simplicity, we consider here the so-called static power allocation [21], where

$$a_{ij}^2 = \alpha \; a_{ij-1}^2. \tag{8}$$

Here, α is the power allocation factor, which represents the ratio between the allocated powers to successive users in the decoding order, such that $\sum_{j=1}^{N_r} a_{ij}^2 = 1$.

For DCO-OFDM based NOMA signal, the upper bound on the achievable rate for Rx_j using NOMA is given by:

$$R_{\mathrm{NOMA}_j} = \frac{B}{2}\log_2(1 + \mathrm{SINR}_{\mathrm{NOMA}_j}) \tag{9}$$

where B represents the signal BW and $\mathrm{SINR}_{\mathrm{NOMA}_j}$ is the SINR for Rx_j:

$$\mathrm{SINR}_{\mathrm{NOMA}_j} = \frac{(h_{ij}\sqrt{P_e}\, a_{ij})^2}{I_{\mathrm{NOMA}} + \sum_{k=j+1}^{N_r} (h_{ij}\sqrt{P_e}\, a_{kj})^2 + \sigma_j^2} \tag{10}$$

where I_{NOMA} denotes the ICI from other cells.

IV. Performance Comparison

We present here numerical results for three different 4-cell scenarios to compare the performances of NOMA and OFDMA. Note that a comparison between these approaches was presented in [19], [25] but for a single cell architecture.

In the considered scenarios, an LED luminaire serving as AP handles the Rxs in its cell. A central control unit connects the APs, and is responsible for exchanging the channel information of all users between APs, classifying users into CEUs or CCUs according to the channel information, and determining the BW allocated to each user. For both OFDMA and NOMA schemes, CEUs are associated with the AP from which the receive the strongest signal; this way, the signals of other APs are considered as interference. This results in penalizing CEUs in the NOMA approach due to SINR degradation. By OFDMA, however, CEUs do not suffer from ICI, because the interfering signals are received on different frequency bands and, furthermore, every CEU is associated with the AP corresponding to the highest channel gain. Table II summarizes the simulation parameters that we consider.[2]

[2]Notice that we have assumed the maximum FOV of 90° as we consider a large room dimension with only 4 APs, so that Rxs can have a LOS link with the AP at any location inside a cell. For a larger number of APs, i.e., reduced cell size, a smaller FOV can be used.

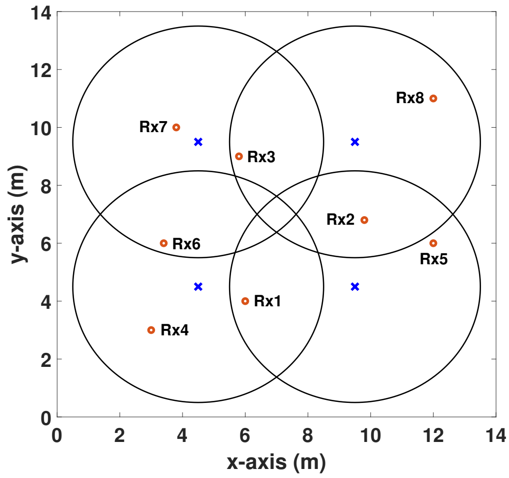
TABLE II: Simulation parameters.

Indoor environment dimension	(14 m $\times$ 14 m $\times$ 3 m)
AP1 location	(4.5, 4.5, 2.5)
AP2 location	(4.5, 9.5, 2.5)
AP3 location	(9.5, 4.5, 2.5)
AP4 location	(9.5, 9.5, 2.5)
Lamertian order of LED m	1
PD responsivity	0.4 A/W [19]
PD area	1 cm^2 [19]
FOV of Rx	90 deg.
Refractive index of optical concentrator	1.5
System BW B	10 MHz
Noise power spectral density	10^{-21} A^2/Hz [19]
Current per LED luminaire	7.2 A
LED conversion efficiency $\mathcal{S}$	0.44 [26]
Power allocation factor α	0.3

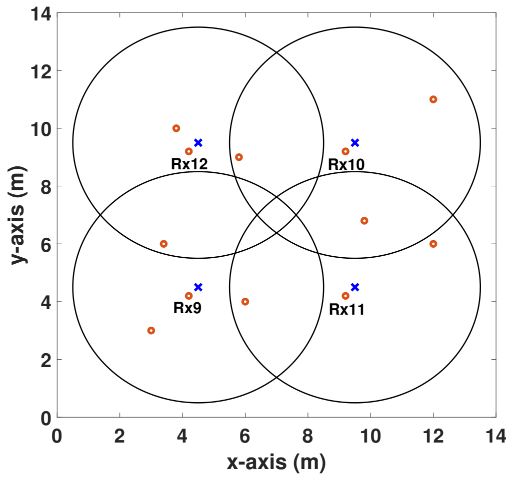
Figure 1 shows the three considered scenarios with increased complexity from Scenario 1 to 3. Scenario 1 is composed of 4 CCUs and 4 CEUs such that each AP has 1 CCU and 2 CEUs in its coverage area. For Scenario 2, with a total of 12 users, we consider 8 CCUs and 4 CEUs, where each AP has 2 CCUs and 2 CEUs in its coverage area. For Scenario 3 with a total of 16 users, we consider 12 CCUs and 4 CEUs, while 3 CCUs and 2 CEUs are served by each AP. All Rxs are considered to be placed at $0.85\,$m above the floor level.

Figure 2 presents the maximum achievable throughput for the users in the three considered scenarios. For OFDMA, we observe less dissimilarity (or in other words, more homogeneity) in the users' performance, compared to NOMA. This results from employing FFR in the OFDMA approach for ICI mitigation, making CEUs' performance close to that of CCUs. Indeed, for OFDMA, users' performance mostly depends on their channel gain, the size of the sub-bands allocated to them, and the power allocated to these sub-bands. On the other hand, for the NOMA approach, users' performances largely depend on their channel gain, their decoding order (which determines the amount of interference canceled by SIC), and the power allocation technique used. In fact, although this power allocation corresponds to the channel gains of the users, they experience different levels of interference. In addition, for NOMA, CEUs suffer from ICI because of receiving signals from more than one AP.

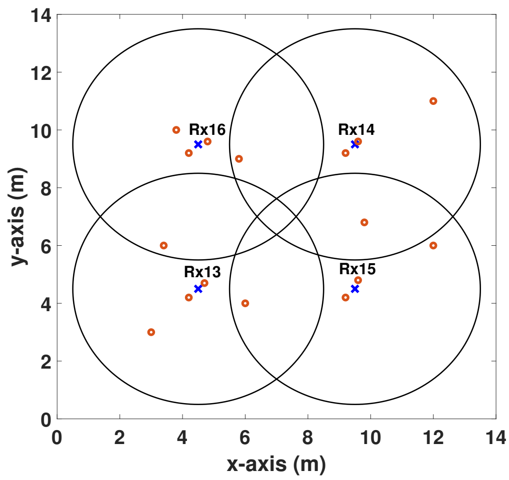
We have further contrasted in Fig. 3 the sum-rate (i.e., the sum of maximum achievable throughputs) of CEUs and the ensemble of users for the two cases of NOMA and OFDMA signaling and the three considered scenarios of Fig. 1. Considering the sum-rate of CEUs, we notice that OFDMA outperforms NOMA in all scenarios, elucidating the efficacy of FFR in mitigating ICI. Meanwhile, the difference between the CEUs' sum-rates with OFDMA and NOMA is less significant in Scenarios 2 and 3, which shows that increasing the cell density improves CEUs performance in NOMA, compared to OFDMA. On the other hand, when considering the total network sum-rate, we notice that for all scenarios, NOMA outperforms OFDMA, which shows the merit of the former in



(a) Top view for Scenario 1

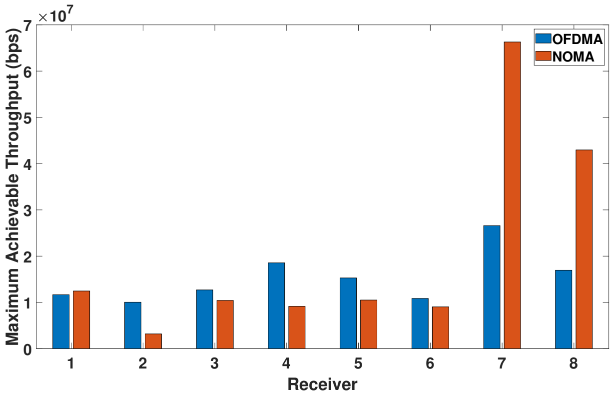


(b) Top view for Scenario 2

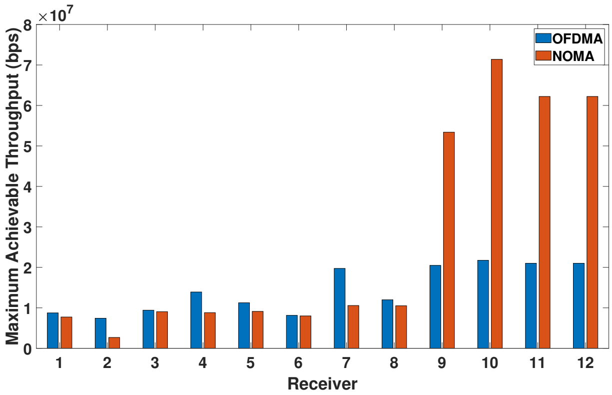


(c) Top view for Scenario 3

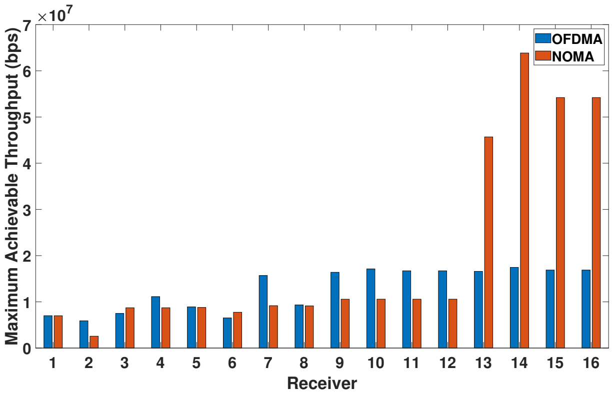
Fig. 1: Illustration of the considered scenarios, where $\times$ and $\circ$ refers to APs and users locations, respectively. Scenario 2 has four additional users with respect to Scenario 1, and Scenario 3 has four additional users with respect to Scenario 2, whose locations are indicated on Figs. 1(b) and 1(c), respectively.



(a) Scenario 1



(b) Scenario 2



(c) Scenario 3

Fig. 2: Contrasting users' maximum achievable throughput using NOMA and OFDMA approaches for the scenarios presented in Fig. 1.

dealing with multi-cell VLC networks. This clear advantage can be attributed to partitioning BW resources among users in OFDMA, whereas in NOMA, users have access to the whole BW all the time.

V. Conclusions

We investigated appropriate MA techniques for large-space multi-cell VLC networks. Focusing on the most relevant techniques, i.e., OFDMA and NOMA, we contrasted their

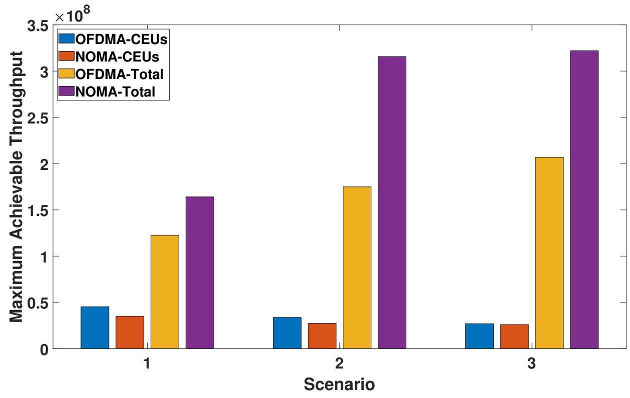


Fig. 3: Comparison between the sum-rates of the CEUs and the total network using NOMA and OFDMA approaches for the three considered scenarios.

performance for three scenarios of different complexities. We showed that, for all considered scenarios, NOMA outperforms OFDMA in terms of the total network sum-rate, which is similar to the conclusions of the recent literature on single-cell networks. However, we specifically showed that OFDMA outperforms NOMA in terms of the total achievable throughput of CEUs in a multi-cell network.

Note that, the improvement in network sum-rate using NOMA comes at the expense of decreased homogeneity of users' performance. This results from the difference in the allocated power and in the interference level experienced by each user (depending on its decoding order and ICI). Although OFDMA shows a better performance for CEUs due to interference mitigation using FFR, increasing user density in the cells reduces the performance gain with respect to NOMA.

Lastly, regarding the complexity of the MA approach, by NOMA, the CSI of the other users is required at the Rx side in order to perform SIC. The quantity of the required CSI depends on the number of users in a cell and their decoding order. That is, for increased number of users handled by an AP, more CSI needs to be transmitted to the users. In contrast, by OFDMA, ideally the users do not need the CSI for interference reduction. In this regard, OFDMA can be considered as less complex to implement.

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