A Prototype Orthogonal Vertical Beamforming for Indoor Wireless Communications

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Abstract —The concept of Orthogonal Vertical Beamforming (OVB) is proposed in this paper to eliminate interference when users remain at the same angle in the horizontal plane but are positioned at different distances. This orthogonal property helps systems avoid interference in the vertical direction of the mainbeam. A fully constructed prototype tested in a real indoor environment validates the proposed concept, revealing that the proposed OVB provides higher Signal Interference plus Noise Ratio (SINR) and Packet Error Rate (PER) in the vertical plane than conventional vertical beamforming and Orthogonal Beamforming.

Index Terms—Beamforming, reduce interference, orthogonal, smart antenna, multiple antennas

I. Introduction

Indoor wireless communication is mainly accomplished through the use of a wireless local area network (WLANs). WLANs have become highly popular [1]-[3] because of the lots of benefits they provide. WLANs not only provide us with the ease and flexibility to utilize them, but they may also be used to link in-home or office computer networks, and wireless devices have evolved over the years. In the current generation, these technologies have become an essential part of our daily lives, and the significance of wireless communication cannot be overstated. As the number of personal wireless devices increases, so would the problem of interference, increased data traffic, and capacity as the RF spectrum gets more overcrowded. Developing interference mitigation technologies and appropriate radio resource allocation technology to improve communication reliability and enable high data rate applications is essential in such an environment. One technique is to use several antennas 2–4 to use the spatial domain of the communication channel. Multiple antenna systems are important in improving wireless system spectral efficiency [4]-[6]. To overcome the problem of interference, the combination of multiple antenna arrays with beamforming technologies assists in suppressing interfering signals and receiving signals from the desirable ones. The fundamental principle of beamforming is the cancellation of interfering signals by creating signals that produce constructive interference at appropriate angles and destructive interference at other angles.

According to the research reported in [7] the Orthogonal Beamforming (OBFM) primarily evaluated the gain provided by the horizontal plane while ignoring to include the gain provided by the vertical plane shown in Fig. 1. Figs. 1(a) and (b) depict the top and side views of a situation in which users are pointing in the same direction (angle in horizontal plane) but are separated by a distance. In this scenario, the proposed OBFM is inefficient since it can only produce one horizontal beam to a single user. The conventional vertical beamforming approach [8], [9] has a low Signal to Interference plus Noise Ratio (SINR) due to interference from other users, as seen in Fig. 2. As a result, this paper proposes Orthogonal Vertical Beamforming (OVB) to eliminate interference in an indoor vertical plane environment.

The following is the rest of this paper: Section II follows the brief introduction by describing a short system model of the OVB. Then, in Section III, experimental results in an orthogonal vertical beamforming prototype are carried out to demonstrate the performance of the suggested idea. The article is finally concluded in Section IV.

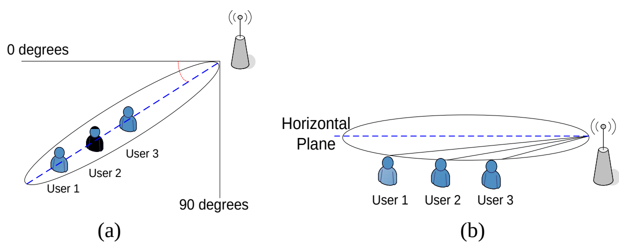

Fig. 1. Top view (a) and side view (b) in the horizontal beamforming.

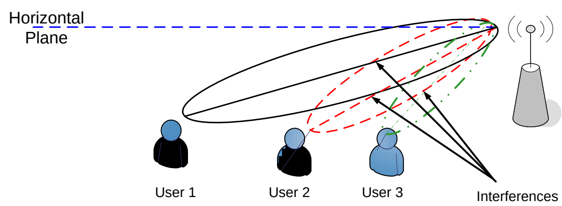

Fig. 2. Conventional vertical beamforming.

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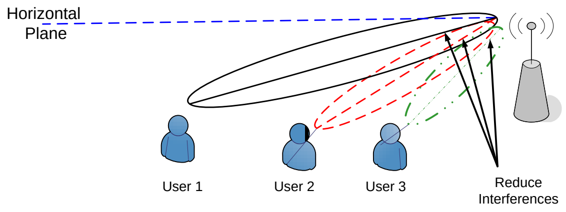

Fig. 3. Orthogonal vertical beamforming (OVB) concept

II. System Model

The concept of OVB in this paper is depicted in Fig. 3. As can be seen, the users maintain the same angle in the horizontal plane while being separated by varying distances. As a result, the beam must be able to tilt orthogonally in the vertical plane to each user. The system model shown in Fig. 4 is being used in the research to investigate a propagation scenario in multi-user communications in an indoor environment.

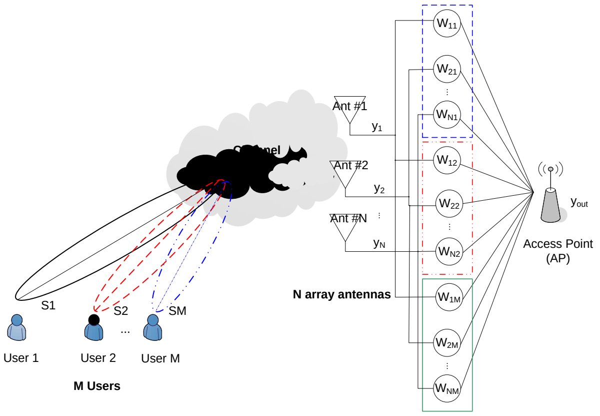

Fig. 4. System model of multi-user indoor communications

In this figure, desired signals from M users arrive at the array antennas at the same time. Those M users are still using the same frequency. The M users each have a single antenna element, and the Access Point (AP) has N linearly aligned antenna elements. When all users send their signal to AP, the received signal vector (before weighting) can be written as

$$\boldsymbol{y} = \sqrt{P}\boldsymbol{H}\boldsymbol{x} + \boldsymbol{n} \tag{1}$$

where s is the $M\times 1$ signal vector containing user data x_1, x_2, …, x_m , and s_m is the m^{th} user's user data. In addition, y is the obtained signal vector at each antenna element, which includes y_1, y_2, …, y_n and $\boldsymbol{w}$ is the weighting coefficients of each antenna element at AP. Let $\boldsymbol{y_{out}}$ denote the obtained signal vector at AP after beam formation, and P denote the transmitted power of each user. The vector of channel coefficients between all M users and the AP using N array antennas is given by

$$\boldsymbol{H} = \boldsymbol{S}^{LOS}\boldsymbol{A}^{LOS} + \sum_{l=1}^{L}\boldsymbol{S}_l^{NLOS}\boldsymbol{A}_l^{NLOS} \tag{2}$$

where $\boldsymbol{A}^{LOS}$ is Line-Of-Sight (LOS) signal vector, $\boldsymbol{A}^{NLOS}$ is Non-Line-Of-Sight (NLOS) signal vector, $\boldsymbol{S}^{LOS}$ is the steering vector of LOS signal and $\boldsymbol{S}^{NLOS}$ is the steering vector of NLOS signal.

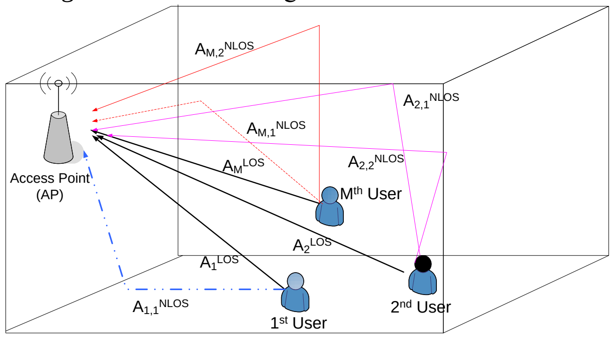

Fig. 5. Propagation channel model of multi-user indoor communications

Fig. 5 depicts a multipath environment with M users in the case where users are surrounded by local scattering structures. This figure describes how each user transmits signals to the AP, including LOS and multipath or NLOS signals. Since the antenna used at mobile terminals is omni-directional, these NLOS signals can occur in several directions.

The LOS signal from the m^{th} user (A_m^{LOS}) can be modeled using a simplified path loss as expressed in (3).

$$A_m^{LOS} = PK\left(\frac{d_0}{d_m}\right)^{\gamma} \tag{3}$$

where P is the transmitted power of users, K is a unitless constant that depends on antenna characteristics and free-space path loss up to distance d_0, which is the reference distance between the user and the BS [10], d_m is the distance between the m^{th} user and the AP, and γ is a path-loss exponent with typical values ranging from 1.6 to 1.8. [11]. It should be noted that these principles were selected because we are only concerned with the indoor environment.

The NLOS signals from the m^{th} user and the l^{th} path ($A_{m,l}{}^{NLOS}$) can be modelled using a Rayleigh fading channel consideration as seen below.

$$A_{m,l}{}^{NLOS} = \alpha_{m,l}e^{j(\emptyset_{m,l}+2\pi f_D t\cos\theta_{m,l})} \tag{4}$$

where $\alpha_{m,l}$ is the real number representing the difference in amplitude of the l^{th} path component from the m^{th} user, $\emptyset_{m,l}$ is the random phase of each l^{th} path uniformly distributed over $[0,2\pi]$, $\theta_{m,l}$ is the l^{th} path's direction of arrival (DOA), and f_D is a Doppler frequency.

Furthermore, the channel model considers the DOA of each direction, so let $\boldsymbol{S}^{LOS}$ and $\boldsymbol{S}_l{}^{NLOS}$ be the LOS and NLOS steering vectors, respectively. Since this thesis only considers linear array antennas, the steering vector is given by

$$\boldsymbol{S}^{LOS} = [\boldsymbol{a}(\theta_1) \quad \boldsymbol{a}(\theta_2) \quad \cdots \quad \boldsymbol{a}(\theta_M)]_{N\times M} \tag{5}$$

$$\boldsymbol{S}_l{}^{NLOS} = [\boldsymbol{a}(\theta_{1,l}) \quad \boldsymbol{a}(\theta_{2,l}) \quad \cdots \quad \boldsymbol{a}(\theta_{M,l})]_{N\times M} \tag{6}$$

where,

$$\boldsymbol{a}(\theta_m) = (1 \quad e^{jkd_x sin\theta_m cos\emptyset+\beta_x} \quad \dots \quad e^{jkd_x(N-1)sin\theta_m cos\emptyset+\beta_x})^T \tag{7}$$

and

$$\boldsymbol{a}(\theta_{m,l}) = (1 \quad e^{jkd_x sin\theta_{m,l} cos\emptyset+\beta_x} \quad \dots \quad e^{jkd_x(N-1)sin\theta_{m,l} cos\emptyset+\beta_x})^T \tag{8}$$

where N is the number of antenna elements in the x-direction. The antenna elements along the x-axis spaced by dx. βx is phase delays in antenna elements. θ_m is DOA in vertical plane from LOS signal of the m^{th} user, $\theta_{m,l}$ is DOA in vertical plane from NLOS of the m^{th} user and the l^{th} path, k is wave number which equals 2π/λ and ∅ is DOA in horizontal plane.

Therefore, the channel coefficient vector shown in (2) includes both LOS and NLOS signals. The BS is equipped with linear array antennas for beam formation in this work. The beamforming approach, also known as array signal processing, is an operation that produces a beam with maximum gain in one direction while giving significant attenuation in the other, which is often the direction of interfering signals. Array antennas and signal processing units are common components of beamforming systems. The processing units are generally employed to determine the direction of arrival (DOA) of incoming signals and to steer the main beam to the desired signal.

In the DOA of each user, the incident signal at each antenna element will be multiplied by the vector of each antenna element at BS. As a result, the received signals at the BS after beam formation or the output signal is

$$\boldsymbol{y_{out}} = \boldsymbol{wy} \tag{9}$$

Substituting (1) back into (9) returns the $\boldsymbol{y}_{out}$ as

$$\boldsymbol{y_{out}} = \boldsymbol{w}(\sqrt{P}\boldsymbol{Hx} + \boldsymbol{n}) \tag{10}$$

Then,

$$\boldsymbol{y_{out}} = \sqrt{P}\boldsymbol{wHx} + \boldsymbol{n_s} \tag{11}$$

where $\boldsymbol{n_s} = \boldsymbol{wn}$. The $\boldsymbol{y}_{out}$ is then obtained by reversing (2) to (11).

$$\boldsymbol{y_{out}} = \sqrt{P}\boldsymbol{w}(\boldsymbol{S}^{LOS}\boldsymbol{A}^{LOS} + \sum_{l=1}^{L} \boldsymbol{S}_l^{NLOS}\boldsymbol{A}_l^{NLOS})\,\boldsymbol{x} + \boldsymbol{n_s} \tag{12}$$

Each user's information is included in the output signal ($\boldsymbol{y}_{out}$) at BS, as shown in (12). This work proposes an alternate beamforming technique able to perform multi-beam formation when all beams operate at the same frequency and time. The beamforming must determine the weighting coefficients for turning the main beam to the users. The weighting coefficients are taken into account in the vertical plane. Assume the users are at the same and different thetas. Then, w must be the inverse of the $\boldsymbol{S}^{LOS}$ signal.

$$\boldsymbol{w} = (\boldsymbol{S}^{LOS})^{-\mathbf{1}} \tag{13}$$

According to the equation (13), the steering matrix $\boldsymbol{S}^{LOS}$ must be a non-singular matrix in order to be invertible. However, if the system employs a larger number of antennas than users, the matrix $\boldsymbol{S}^{LOS}$ cannot be directly inversed. The Moore-Penrose preudoinverse can be useful in this scenario [12]. The weighting coefficients ($\boldsymbol{w}$) are then provided by

$$\boldsymbol{w} = (\boldsymbol{S}^{LOS})^{\dagger} = (\boldsymbol{S}^{LOS})^{*}(\boldsymbol{S}^{LOS}(\boldsymbol{S}^{LOS})^{*})^{-\mathbf{1}} \tag{14}$$

where $(\boldsymbol{S}^{LOS})^{\dagger}$ denotes the Moore–Penrose pseudoinverse of $\boldsymbol{S}^{LOS}$. This equation also demonstrates the orthogonal property, which is an independent relationship between weighting coefficients and steering vectors. Because all beams are orthogonal to one another, users experience no interference.

The proposed concept is to determine an acceptable weighting coefficient w to avoid interference in the main beam direction because all beams are launched at the same time and frequency in the vertical plane. When the system employs weighting coefficients, the received signal will have an independent relationship between the weighting coefficients and the steering vectors, a property known as orthogonality. Because all beams in the vertical plane are orthogonal to one another, users in the vertical plane no more interfere with one another. However, all of the previous simulation results [13] have verified the beamforming capability of the proposed OVB. The following section verifies the proposed concept by evaluating a produced prototype of the proposed orthogonal beamformer under actual situation.

III. Experimental Results in Orthogonal Vertical Beamforming Prototype

The proposed concept consists of a set of Array antennas, weighting networks, and a processing unit. Since all beams are fired at the same time and with the same frequency, the device model was created to find suitable weighting coefficients to prevent interference in the main beam vertical direction. Fixed beamforming networks were used to construct an orthogonal vertical beamformer prototype. The three cases below are depicted in Fig. 6-8, which depicts our experiments.

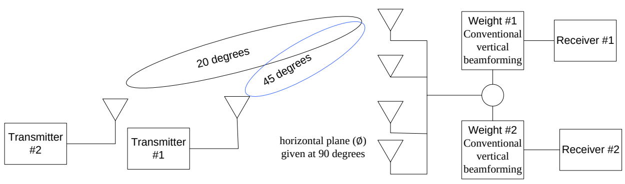

Fig. 6. Experiment case I: Conventional vertical beamforming is used in multi-user communications.

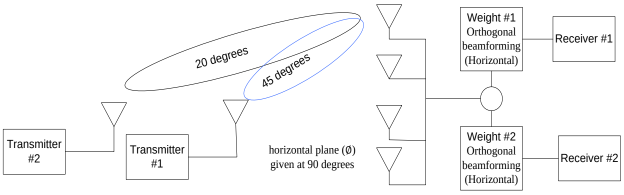

Fig. 7. Experiment case II: Orthogonal beamforming is used in multi-user communications.

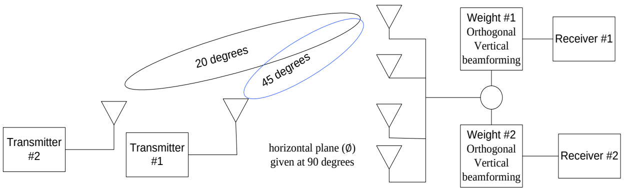

Fig. 8. Experiment case III: Orthogonal vertical beamforming (proposed) is used in multi-user communications.

The weights were different for each of the three cases in the experiment: conventional vertical beamforming, orthogonal beamforming, and orthogonal vertical beamforming (proposed). When two users are in an equally horizontal plane (Ø) given at 90 degrees, the directions of the incoming signal are placed in a vertical angle (θ) at 20° and 45°. The 4 x 1 dipole antennas are used in the receiver, uniformly spaced by a half-wave range. The operation frequency is 2.4 GHz. On the transmitting side, a single-dipole antenna is used to convey the signal to the receiver shown in Fig. 9. Under realistic circumstances, the measurement was focused on signal interference plus noise ratio (SINR) and packet error rate (PER). To perform full two-way communications, the beamformer was connected to a universal software radio peripheral (USRP) as shown in Fig. 10.

As can be seen, the USRPs at both receivers are connected to a laptop computer for real-time recording of SINR and PER. In addition, Table I contains the USRP parameters for the experiments.

Fig. 9. Photograph of experiment setup at transmitting side

All of the experiments were carried out in an 8x4 m^2 room in the 62 building at Department of Electronics Engineering Technology, College of Industrial Technology, King Mongkut's University of Technology North Bangkok. This indoor environment was chosen because it contains a lot of multipaths from partitions and walls. At the same time, both transmitters transmit data through the same array of antennas. Both receivers' USRPs are connected to a laptop computer, which records SINR and PER in real time.

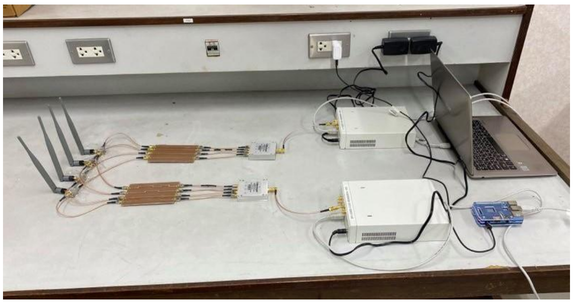

Fig. 10. Photograph of full prototype of Orthogonal Vertical Beamforming (OVB)

TABLE I: PAPERS USRP SET UP PARAMETERS.

MODULATION TYPE	BPSK
DATA RATE	2 Mbps
FREQUENCY	2.4 GHz
NUMBER OF PACKET	20000 Bytes
NUMBER OF DATA SUBCARRIERS	48
NUMBER OF CYCLIC PREFIX	4
TOTAL SUBCARRIER	52

Fig. 11 show the efficiency of the proposed Orthogonal Vertical Beamforming (OVB) in indoor communications as compared to conventional vertical beamforming and Orthogonal Beamforming (OBFM) in terms of PER. When the Orthogonal Beamforming (case II) operates at the same time and frequency, the PER value increases dramatically, implying that the precision of the obtained data is compromised because one interferes with the other. As seen in cases I and III, the impairment can be eliminated by using beamforming networks (Conventional vertical beamforming and Orthogonal Vertical Beamforming). The proposed OVB, on the other hand, outperforms the conventional one because of its orthogonal property, which results in null rates in interference vertical directions.

The SINR obtained from experiments versus distance between transmitter and receiver when users are located at vertical angles (θ) of 20° and 45° is shown in Fig.12. In comparison to conventional vertical beamforming and orthogonal beamforming, the proposed orthogonal vertical beamforming provides a higher average SINR. Since all users are in the same horizontal plane (Ø), the OBFM has the lowest SINR. As a result, the interference cannot be effectively rejected because all users remain within the main beam's range. The results show that the proposed orthogonal vertical beamforming will improve indoor communications efficiency when users are in the same horizontal but different vertical angles.

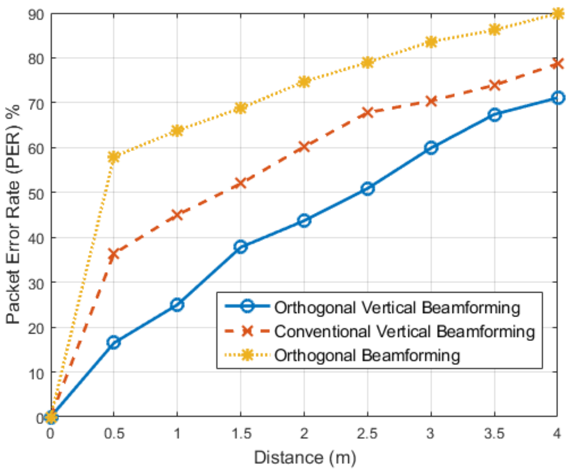

Fig. 11. The measured PER versus the distance between the transmitter and receiver when users are located at vertical angle (θ) at 20 °and 45 °.

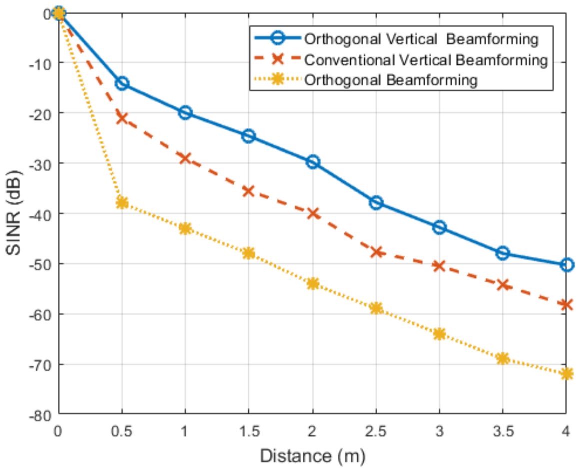

Fig. 12. The measured SINR versus the distance between the transmitter and receiver when users are located at vertical angle (θ) at 20 °and 45 °.

All of the previous experimental results have verified that orthogonal vertical beamforming (proposed) provides high SINR and PER as compared to the use of conventional vertical beamforming and orthogonal beamforming (Horizontal). A low packet error rate is also provided by the proposed systems.

IV. Conclusion

This article introduced the concept of Orthogonal Vertical Beamforming (OVB) and the development of a full prototype to reduce interference in an indoor environment for users who are at the same horizontal angle. To validate the proposed design, an orthogonal vertical beamformer prototype was built and tested in a real environment. Rich shadowing, multipaths, and mutual coupling between antenna elements were all occur in the experiments, which were performed in an indoor environment. The measured results show that the proposed orthogonal vertical beamforming scheme outperforms conventional vertical beamforming and Orthogonal Beamforming (OBFM) in the vertical plane in terms of SINR and PER since both beams are orthogonal in vertical direction to each other and do not interfere with one another when launched at the same time.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

Author conducted the research; analyzed the data; wrote the paper; and had approved the final version.

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References

[1] K. K. K. Fong and S. K. S. Wong, "Wi-Fi adoption and security in Hong Kong," *Asian Social Science*, vol. 12, no. 6, pp. 1–22, 2016.

[2] Pace Technical: Is Fast Wi-Fi the Most Basic of Human Needs? [Online]. Available: https://www.pacetechnical.com/fast-wifi-basic-human-needs/

[3] Berk-Tek, A NEXANS Company. Basic Human Needs: Food, shelter, and…Wireless? [Online]. Available: https://eipblog.net/2017/08/15/basic-human-needs-food-shelter-andwireless/

[4] T. Varum, A. Ramos, and J. N. Matos. "Planar microstrip series-fed array for 5G applications with beamforming capabilities," in *Proc. IEEE MTT-S International Microwave Workshop Series on 5G Hardware and System Technologies (IMWS-5G)*, Aug. 2018, pp. 30-31.

[5] T. Sai Saranya, "Hybrid digital beamforming design for massive planar antenna array for 5G communication," in *Proc. International Conference on Vision Towards Emerging Trends in Communication and Networking (ViTECoN)*, March 2019, pp. 30-31.

[6] Y. J. Song, S. J. Lim, S. K. Lee. and J. S. Jang, "Adaptive digital beamforming for uplink coverage enhancement in 5G NR system," in *Proc. 27th Telecommunications Forum (TELFOR)*, Nov. 2019, pp. 26-27.

[7] P. Wongchampa and M. Uthansakul, "Orthogonal beamforming for multiuser wireless communications," *IEEE Antennas & Propagation magazine*, pp. 38-49, August 2017.

[8] W. Lee, *et al*, "Downlink vertical beamforming designs for Multi-User MISO systems," in *Proc. IEEE Vehicular Technology Conference*, May 2015.

[9] J. Fan, *et al.*, "Vertical beamforming with downtilt optimization in downlink cellular networks," in *Proc. IEEE Global Communications Conference*, Dec 2015.

[10] H. Liu, Y. Zhang, and J. Luo, *Distributed Antenna Systems: Open Architecture for Future Wireless Communications*, Auerbach Publication, 2007.

[11] D. Tse and P. Viswanath, *Fundamentals of Wireless Communication*, Cambridge University Press, 2005.

[12] J. C. A. Barata and M. S. Hussein, "The moore-penrose pseudoinverse," *A Tutorial Review of the Theory*, pp. 1-23, 2011.

[13] P. Wongchampa, "Reduction of interference using orthogonal vertical beamforming in an indoor communication," in *Proc. MATEC Web of Conference*, 2019.

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