# DUAL-ANTENNA SYSTEM COMPOSED OF PATCH ARRAY AND PLANAR YAGI ANTENNA FOR ELIMINATION OF BLINDNESS IN CELLULAR MOBILE COMMUNICATIONS

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**Abstract**—For a cellular mobile communication system in narrow streets of urban areas, blind spots caused by shadowing of high buildings are a significant problem. In this research, a new dual-antenna system (DAS) is proposed, including a power transmission network, a receiving and a reradiating antenna to realize a broad-angle beam control. An equivalent bi-static radar cross section (BRCS) is deduced to present a theoretical explanation to the operating principles of the DAS. The main advantage of this design over ordinary reflectarray antenna as a passive RF booster is its flexible beam control capabilities. The simulated BRCS of the proposed DAS, composed

of a microstrip patch array and a planar Yagi-Uda antenna, is given along with that of a metal plate of identical dimensions for comparison purposes.

## 1. INTRODUCTION

It is a serious problem that radio waves from base stations of cellular mobile communications are blocked by high and dense buildings in urban areas, especially in narrow streets, resulting in a very weak signal level and very poor communication qualities, and this kind of areas are typically called blind spots. Many efforts were made in order to eliminate the blind spots which dramatically degrade the efficiency of data transmission between mobile users and base stations by decreasing the receiving SNR. For a multi-input multi-output (MIMO) system, the channel capability may be greatly degraded due to the block of wave path. Generally, RF boosters are used to eliminate these blind spots but at very high cost, because receivers, transmitters, power supplies are required. Moreover, installation of the boosters is also a critical issue because quake-resistance regulations should be taken into account in areas with frequent earthquakes, especially in Japan, and it would be better to embed them into the top part of the vertical building walls or to integrate them into firmly settled advertisement boards on the top of buildings. Therefore, a passive device are generally desired from the economical and technological points of view. Furthermore, the incident angle of the EM waves is generally quite small, thus for simplicity of models and simulations it is assumed to be normal incidence but a large scattering angle is needed in practice as shown in Figure 1. Additionally, an enough bandwidth is also critical for a successful design, and for our applications, it is required to be over 10% for dual-band operation: one band for the uplink and the other for the downlink. In our previous works [1], a broadband reflectarray antenna was designed as a passive booster to remove the blind spots. However, the aperture efficiency of reflectarray is greatly degraded when a very large scattering angle is desired, which is a physical limitation instead of a technically solvable problem because it is known that the maximum aperture is a cosine function of the scattering angle. In this research, a dual-antenna system (DAS) is proposed, including a microstrip patch array for reception and a planar Yagi-Uda antenna for reradiation to realize a flexible and broad-angle beam control. The proposed DAS has a quasi-planar structure and can be massively fabricated with low cost by the mature PBC technology, meanwhile it also has a capability to orthogonally differ polarization of the reradiation from the incoming waves, which makes it more useful in some specific environment. An
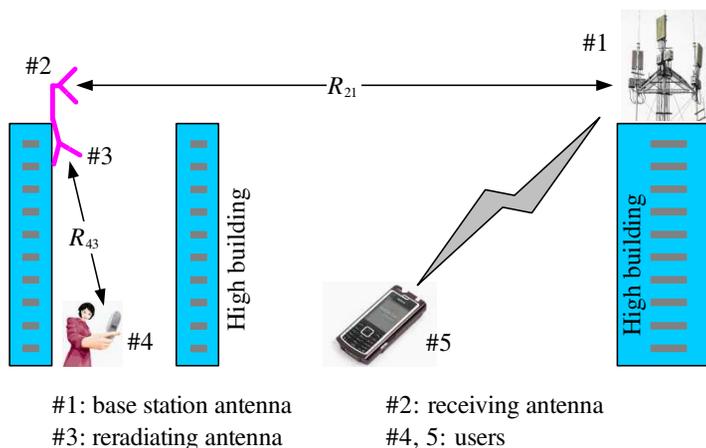
**Figure 1.** Wireless communications in narrow street of urban area.

equivalent bi-static radar cross section (BRCS) of the DAS is also deduced to show an effective way for BRCS improvement and to show an explanation to the operating principles of the DAS. Simulated results are also given compared with those of metal plates of identical sizes.

## 2. EQUIVALENT BRCS OF DUAL-ANTENNA SYSTEM

Figure 1 shows the schematic of propagation channel in urban areas, where Antennas #1, #2, #3, #4, and #5 represent the base station, the receiving and reradiating antennas of the DAS, and two users, respectively. The user #4 is located in a blind spot caused by the high building in front of the DAS. The distance between Antennas #1 and #2, #3 and #4 are denoted by $R_{21}$ and $R_{43}$, respectively. In this design, the electromagnetic (EM) waves can be flexibly controlled as follows, taking downlink transmission as an example. Firstly, Antenna #2 receives the EM waves from the base station; then, the received waves are guided by a low-loss transmission network and reradiated by Antenna #3, and finally received by the user #4. Here the DAS can be evaluated in terms of an equivalent BRCS, similar to ordinary scatterers. The channel gain can be calculated by Friis transmission equation in Equation (1):

$$\frac{P_{r4}}{P_{t1}} = \left(\frac{\lambda}{4\pi}\right)^4 \left(\frac{1}{R_{21}R_{43}}\right)^2 G_1 G_2 G_3 G_4. \tag{1}$$

where $G_1$, $G_2$, $G_3$, $G_4$, $P_{r4}$ and $P_{t1}$ are gains of Antennas #1, #2, #3, and #4, the received power by the user #4, and the transmitting power by Antenna #1, respectively. On the other hand, we introduce a parameter $\sigma_{eq}$ as the equivalent BRCS of the proposed DAS, and the radar range equation can be expressed as

$$\frac{P_{r4}}{P_{t1}} = \left(\frac{G_{t1}}{4\pi R_{21}^2}\right)\left(\frac{\sigma_{eq}}{4\pi R_{43}^2}\right)\left(\frac{G_4 \lambda^2}{4\pi}\right). \tag{2}$$

and $\sigma_{eq}$ can be calculated from Equations (1) and (2):

$$\sigma_{eq} = \frac{\lambda^2}{4\pi} G_2 G_3. \tag{3}$$

It is obvious that $\sigma_{eq}$ is proportional to the gains of Antennas #2 and #3. Therefore, if a large $\sigma_{eq}$ is expected, we should increase the gains of Antennas #2 and #3 as high as possible. It should be noted that the complicated scattering process of the DAS in practice will deteriorate the accuracy of this equation from an ideal model, but the equivalent BRCS can still give us a qualitative evaluation of the performance.

## 3. DUAL-ANTENNA SYSTEM DESIGN

Actually it is flexible to make the proposed DAS concept come true, for example a compact high-gain folded-patch antenna (FPA) [4] and a planar directive antenna, e.g., famous Yagi-Uda antenna [2], can be chosen as Antennas #2 and #3, respectively, and other combinations are also good solutions but here only the DAS composed of the FPA and Yagi antenna is carefully addressed. For the above mentioned DAS, the FPA is compact enough to fabricate and to mount on the wall or on the top of high buildings in urban area, and Yagi antenna is able to present a high gain which is of benefit to a larger BRCS according to Equation (3). Moreover, the quasi-planar structure of combination between the FPA and Yagi antenna permits ease of massive fabrication and mounting.

The employed Yagi antenna is located in $xy$ plane as shown in Figure 2, and it has a driven element, two directors and a large corrugated ground plane as a reflector, and it is fed by a parallel stripline through a transition from a microstrip line. The ground plane is corrugated periodically to suppress the side lobes in $H$ plane and consequently to improve antenna gain [3]. Its double-layered structure is designed on a substrate with a relative permittivity of 3.3 and thickness of 0.8 mm. Its geometrical parameters are shown in the figure in millimeter (mm), and the total size is $150 \times 170 \, \text{mm}^2$. The element in the FPA is identical to Set 1 in [4] due to its compact size. It should
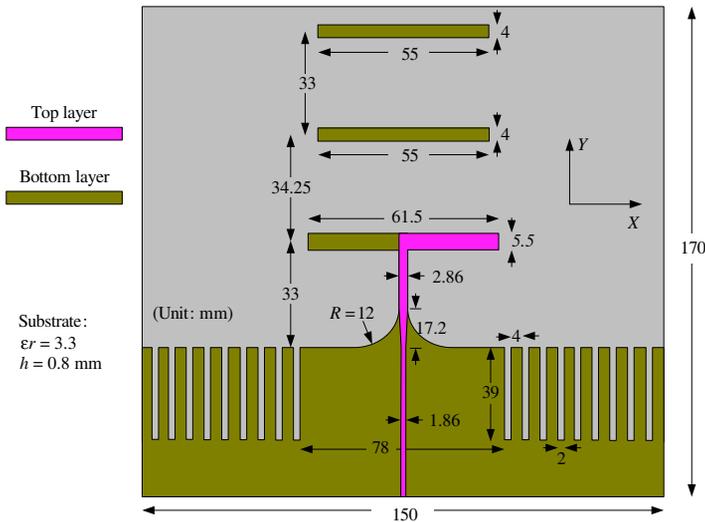
**Figure 2.** Geometry of the planar Yagi-Uda antenna with corrugated ground plane.

be noted that there is a tradeoff between compact size and high gain, and if large antenna gain is in priority, other antennas with planar patches will be competent, i.e., patch antenna in [5].

Figure 3 shows the geometry of one unit of the proposed DAS in detail, including 3D view, side view and top view. One unit of the DAS is composed of a 4-element FPA (including the power divider/combiner) and a planar Yagi antenna. The FPA is built on the top side of the substrate, and its microstrip-line-based feeding network is etched on the bottom side, connected to the input port of the Yagi antenna, and the EM waves incident from $+z$ direction will be received by the FPA and then be delivered to the Yagi antenna through a microstrip line for reradiation. Feeding probes $A$, $B$, $C$, and $D$ of four patch elements are connected to four output ports of the power divider through four via holes on the ground plane. The total dimensions of one unit are $110 \times 440 \times 20.8\,\text{mm}^3$, in width, length and thickness, respectively. Practically, one can place this kind of unit as many as required along $x$ direction or increase the number of patch elements on one unit in order to improve the equivalent BRCS. It should be noted that one of the critical techniques to improve the equivalent BRCS is the polarization transition in $yz$ plane here, i.e., from the $\theta$-polarized incident waves to the $\varphi$-polarized re-radiated waves. The polarization transition is necessary because the required large aperture of re-radiating antenna cannot be obtained if the re-radiated waves
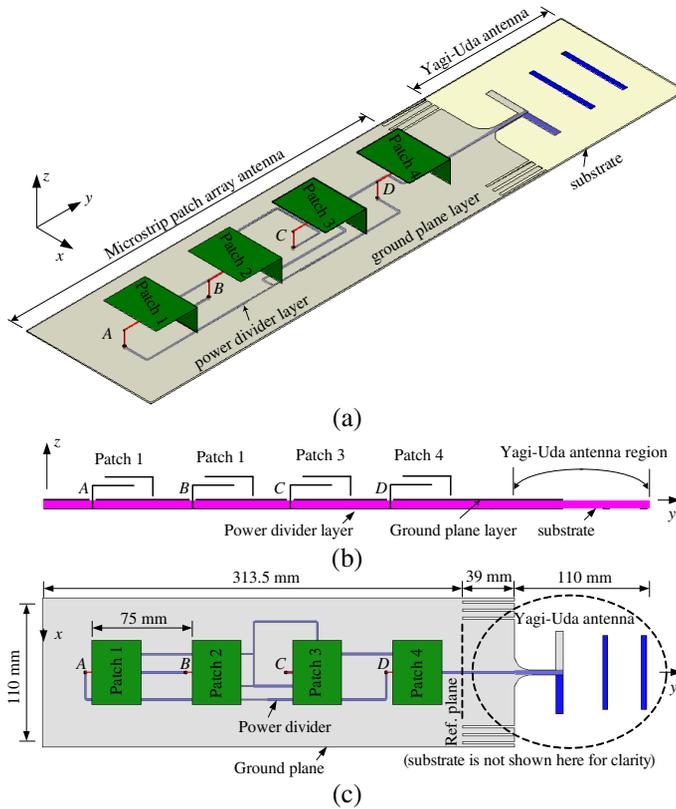
**Figure 3.** Geometries of the proposed DAS composed of an FPA and a planar Yagi-Uda antenna. (a) 3D view. (b) Side view. (c) Top view.

are still $\theta$-polarized due to quite small thickness. In contrast, if a unchanged polarization is expected, we need a certain thickness functioning as an effective aperture for a $\theta$-polarized radiation.

Figure 4 shows the geometry of the 4-way power divider as the feeding network of the FPA, and only microstrip line layer is shown for clarity. It is very classical and reference [6] provides minute explanations and design procedure, including how to calculate the width of microstrip lines with different characteristic impedance, how to design the 90° microstrip bending section, and so on. The characteristic impedance of the microstrip line at the output ports of the power divider is set to be 57 Ω in order to make the impedance matching better between the power divider and each patch elements. Simulation shows that its insertion loss is about 1 dB in the interesting frequency band.
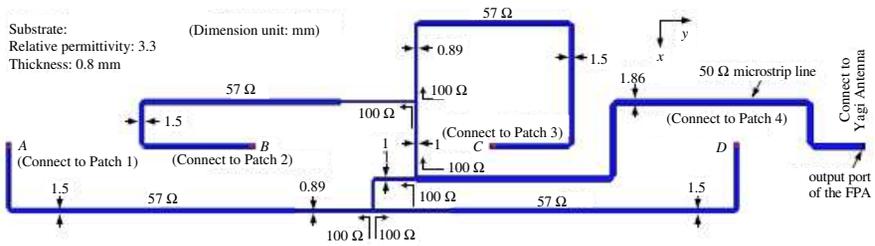
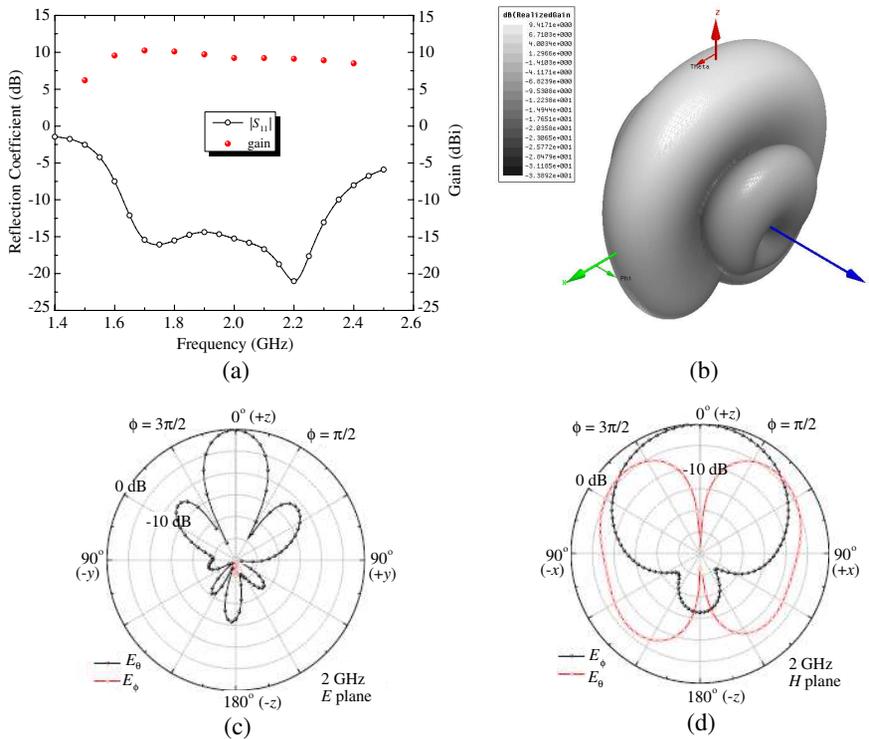**Figure 4.** Geometry of the power combiner/divider as feeding network of the FPA.



**Figure 5.** Simulated gain and reflection coefficient. (a) 3D pattern, (b) $E$- and (c) $H$-plane patterns at 2 GHz (d) of the FPA.

# 4. RESULTS OF PATCH ARRAY AND YAGI ANTENNA

All simulations were performed by Ansoft High Frequency Structure Simulator (HFSS) [7]. Simulated results of the 4-element FPA

are presented in Figure 5, including reflection coefficient, gain and radiation patterns at 2 GHz. The impedance bandwidth for $|S_{11}| < -10\,\text{dB}$ ($-14\,\text{dB}$) is 1.63–2.35 GHz (1.68–2.28 GHz), i.e., a fractional bandwidth of 36.1% (30.3%) as Figure 5(a) shows, which is wide enough to cover the required 10% bandwidth. (Noted that the reference plane for reflection coefficient calculation is shown in Figure 3(c) and Figure 4.) The realized gains are 8.9–10.24 dBi in the whole operating band, and the value is 9.2 dBi at 2 GHz. The antenna also shows good-looking 3D pattern ($\theta$ and $\varphi$ components of electric fields are included), e.g., that at 2 GHz in Figure 5(b), and the main beam is along $+z$ direction. The antenna also shows narrow main beam and $-12\,\text{dB}$ side lobe level in $E$ plane, but worse polarizations in $H$
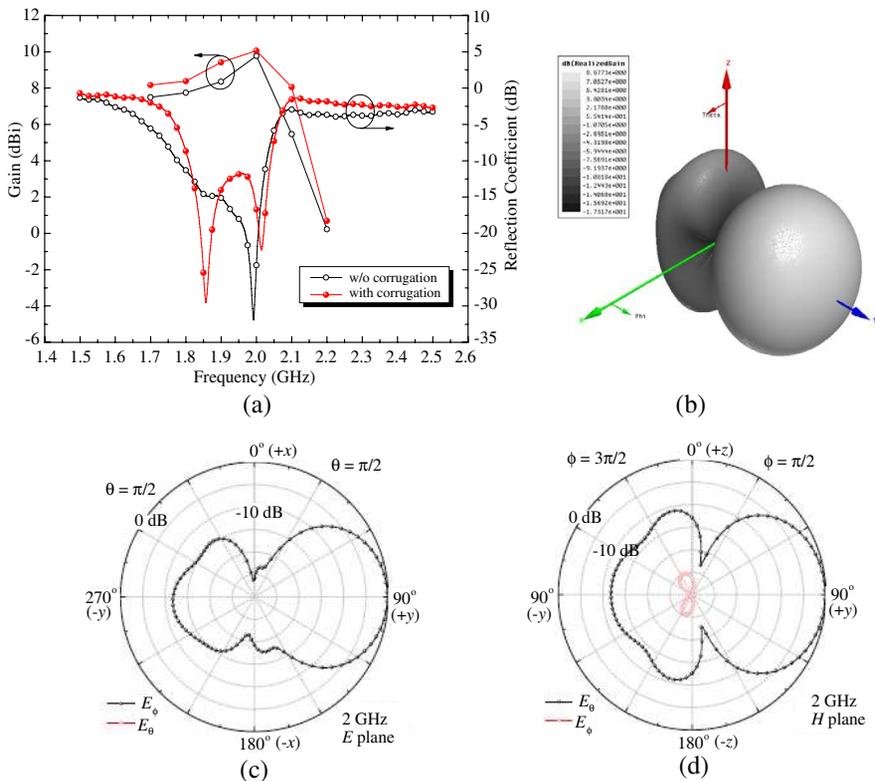


**Figure 6.** Simulated results of the planar Yagi-Uda antenna. (a) Gain and reflection coefficient of the Yagi antenna with and without corrugated ground plane. (b) 3D pattern at 2 GHz. (c) $E$-plane pattern at 2 GHz. (d) $H$-plane pattern at 2 GHz.

plane (cross polarization is $-4$ dB), as given in Figures 5(c) and (d).

Figure 6 shows the simulated reflection coefficient, gain and radiation patterns of the planar Yagi antenna ($\theta$ and $\varphi$ components of electric fields are included for 3D pattern in Figure 6(b)). It presents an impedance bandwidth for $|S_{11}| < -10$ dB is 1.81–2.04 GHz, corresponding to a fractional bandwidth of 12%, and a gain of 8.4–10 dBi. Compared to the one without corrugated ground, the operating bandwidth is slightly decreased from 13.7% but the gain is obviously enhanced by $1 \sim 2$ dBi. It also shows directive radiating performances and small side lobes in both $E$ and $H$ planes. Noted that the side lobe level is reduced from $-7$ dB of the Yagi antenna without corrugated ground plane to $-10.6$ dB of the present design.

## 5. RESULTS OF DUAL-ANTENNA SYSTEM

The simulated equivalent BRCS of one unit of the proposed DAS in $yz$ plane are illustrated by Figure 7, compared to the BRCS of a metal plate with the same size, when plane waves are incident from $+z$ direction. The metal plate presents a symmetrical BRCS pattern and the value in $\theta = 90°$ is tending to zero, determined by how thin the metal plate is. For the proposed DAS, the forward scattering is over 10 dB smaller than the metal plate, indicating that the aperture efficiency of the FPA is quite good, but the scattering along $+y$ direction are over 10 dB larger as $75° < \theta < 105°$ ($\varphi = \pi/2$) with a maximum value of $-8.1$ dBsm, benefiting from the reradiation of
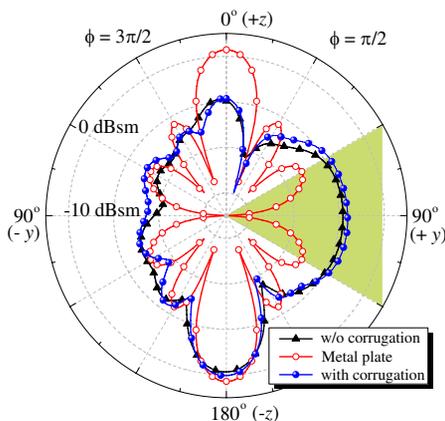


**Figure 7.** Simulated BRCS of the one-unit DAS with and without corrugated ground plane and that of a metal plate with the same dimensions, when the EM waves are incident from $+z$ axis.
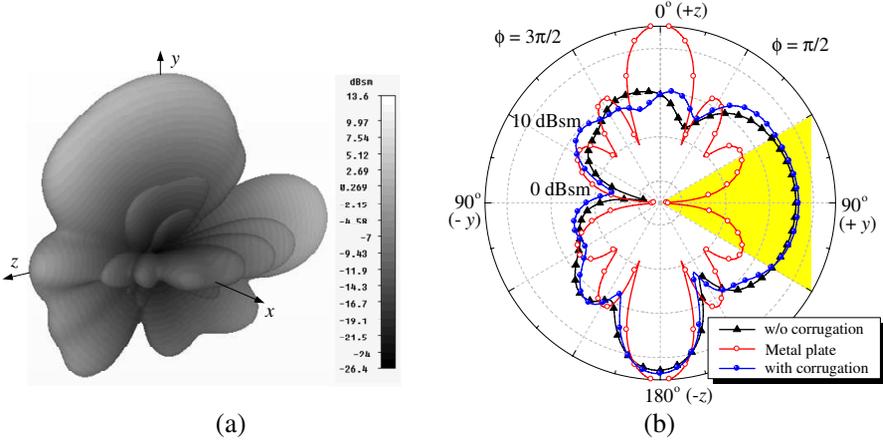
(a)                                          (b)

**Figure 8.** Simulated BRCS of the 5-unit DAS with and without corrugated ground plane and that of a metal plate with the same dimensions, when the EM waves are incident from $+z$ axis. (a) 3D pattern. (b) 2D pattern.

the planar Yagi-Uda antenna. Moreover, the scattering in the lower-right half plane is similar to that of the metal plate. Thus, our method realizes large orthogonal scattering with a normal incidence that cannot achieve naturally by traditional reflectarray or other planar structures. Compared to the one without corrugated ground plane, the maximum BRCS can be improved by 1 dB along $+y$ direction. In order to increase the equivalent BRCS, 5 units of the DAS are placed side by side along $x$ axis. The simulated result is given in Figure 8, and there is 14.5 dB improvement than that of the one unit, slightly larger than the ideal increment of 14 dB from Equation (3). It is probably because the patterns of the FPA elements will be thinner due to a large ground plane in an array environment, and the numerical errors during simulations. The application of the proposed DAS for elimination of blind spots in MIMO environment has been checked experimentally [8].

## 6. CONCLUSION

An idea of the DAS for broad beam angle application to eliminate blindness of wireless communications was investigated and realized. A practical DAS is proposed to implement this idea, i.e., a combination between an FPA and a planar Yagi-Uda antenna, with a capability to swerve the normal-incident EM waves to the direction in the plane of the system itself. Actually, beyond that, they can be designed to

scatter the EM waves to any desired directions, which is difficult to be realized by reflectarray antennas. Simulated results given in this paper can effectively prove the validity of the proposed DAS.

## ACKNOWLEDGMENT

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