ABSTRACT The use of Unmanned Aerial Vehicles (UAVs) is expected to provide a prompt communication service area under disasters and emergencies. Using the multiple frequency bands called carrier aggregation increases the system throughput and can support situations where urgent traffic could explode. We previously developed a multiband sector antenna with multiple reflectors employing the metamaterial for a UAV-mounted mobile base station. The metamaterial reflector, which has electromagnetic band gap (EBG) characteristics, can reflect the electromagnetic waves of the desired band, i.e. EBG band, and transmit those of the specific bands. It has been a challenge to adjust the beamwidth under the constraint of the metamaterial reflector. This paper proposes the beamwidth adjustment algorithm considering the EBG band and evaluates the system throughput performance utilizing the designed multiband sector antenna. The proposed algorithm designed the dual-band sector antenna with 90 degrees beamwidth in the horizontal plane of each frequency band (800 MHz and 2 GHz), and the measurements match the electromagnetic field simulations well. Moreover, the system-level simulation evaluates the system throughput performance utilizing the designed dual-band sector antenna.

INDEX TERMS Unmanned aerial vehicle (UAV), sector antenna, woodpile metamaterial.
radiator and metal reflector, the beamwidth at the higher frequency is narrowed or split because the electric distance at the higher frequency is larger than that at the lower frequency [14], [15]. It is a critical issue that the distance between the radiator and the reflector is constant.

We previously developed the multiband sector antenna with the multiband radiator and the multiple reflectors which consist of a metamaterial structure [18], [19]. The metamaterial structure has Electromagnetic Band Gap (EBG) characteristics. It can reflect electromagnetic waves in a specified band and pass them through in other bands [20]–[22]. Reflectors with different characteristics are placed individually according to their wavelength ratios. Since each frequency band of electromagnetic waves is controlled by its own dedicated reflector, it is possible to design the same beamwidth.

However, controlling the beamwidth of multiple reflectors by the physical placement parameters may affect their positional constraints. Therefore, an optimized co-design is essential for taking the whole into account. In this paper, we clarify that the metamaterial structure design can control the beamwidth out of the EBG band, and then propose the novel beamwidth adjustment algorithm. Its beam pattern is numerically and experimentally verified by fabricating 800 MHz and 2.0 GHz antenna prototypes. Finally, unified system throughput performance is also presented through a link-level simulation.

Section II describes the system model and the challenge of the sector design. Section III exhibits the concept of the multiband sector antenna and its antenna design problem. Section IV shows the woodpile reflector design which has the EBG characteristics and presents the proposed beamwidth adjustment algorithm. In Section V, the fabricated prototype of the dual-band antenna and its performance are disclosed. Section VI concludes the paper.

II. SYSTEM MODEL AND SECTOR DESIGN
A. SYSTEM MODEL
Let us consider a system model shown in Fig. 1. The multiple UAVs create the network area over the damaged BS in a disaster area where wireless communication is interrupted by a disaster such as an earthquake or tsunami. The multiple UAVs organize a wireless relay network [3]–[5], and one of the UAVs is connected to the ground station (GS). The GS is connected to the remote control center via Internet access. At the remote control center, one can monitor the situation in the disaster area with the video transmitted from the camera mounted on the UAV. The UAVs autonomously control their attitude and stay above the damaged BS. The multicopter type UAV can maintain an attitude constantly by having a propulsion force in the vertical direction. Therefore, the vertical polarization antenna installed at the bottom of the UAV can be used to easily align the polarization plane.

The transmission distance in aerial communication is longer than that on terrestrial because the radio propagation environment is almost free space. However, overreach propagation could cause co-channel interference. Employing the directional antenna can suppress the undesired radiation while improving the transmission gain. A large-capacity wireless link should be established to accurately understand the disaster situation in more detail, e.g., high-definition video transmission. Therefore, the carrier aggregation technique, which uses multiple frequency bands, is applied to improve the system throughput.

B. SECTOR DESIGN
The relationship between the antenna beam pattern and the system throughput is discussed. Fig. 2 shows the example of the antenna directivity of the GS in the horizontal plane. According to the required sector design, it is necessary to use the optimal beamwidth at each frequency band. The wider beamwidth can achieve a wide coverage area, however, the system throughput degrades because of interfering with neighbor cells. For example, when three sector cell is designed, the beamwidth should be set to 90°, which is narrower than 120°.

Fig. 3 shows the relationship between the beamwidth and aggregated system throughput of two frequency bands based on LTE with 20 MHz bandwidth. The parameters are listed on Table 1. The GS employs the directional multiband sector antenna, which radiates the electromagnetic waves at $f_1 = 2$ GHz and $f_2 = 800$ MHz. The half-power beamwidth at 800 MHz, $\theta_{BW}(f_2)$, is set to 90° and the following radiation pattern is used: the antenna gain, $G(\theta)$, of azimuth angle $\theta$ is given by

\[
G(\theta) = \begin{cases} 
C \cos^k(\theta), & \text{if } \cos^k(\theta) \geq G_{SL} \\
CG_{SL}, & \text{otherwise,}
\end{cases}
\]
where $C$ is a constant determined by the beamwidth and $G_{SL}$ denotes the sidelobe level [23]. Parameter $k$ is calculated by the half-power beamwidth, $\theta_{BW}(f_n)$, as

$$\cos^k \left( \frac{\theta_{BW}(f_n)}{2} \right) = \frac{1}{\sqrt{2}}. \quad (2)$$

The radio propagation is assumed to be the free space, and the distance between the GS and UAV is set to $d = 500, 1500$ m. The main direction is defined as $\theta = 0^\circ$. The system throughput with $\theta_{BW}(f_1) = 60^\circ$ at 2 GHz is the highest in the range of $|\theta| \leq 45^\circ$. On the other hand, in the region of $|\theta| > 45^\circ$, it shows the degraded system throughput. When $\theta_{BW}(f_1) = 120^\circ$ at 2 GHz, the average system throughput is high, but the throughput in the main direction is the lowest. As a result, designing the three sectors antenna, it is desirable to set the same beamwidth, $\theta_{BW}(f_n) = 90^\circ$, at each frequency band.

C. CHALLENGES FOR BEAMWIDTH DESIGN IN THE REFLECTOR ANTENNA

It is difficult to design the same beamwidth at each frequency band in the conventional reflector antenna. Its antenna configuration with a multiband radiator and single metal reflector is shown in Fig. 4. In this antenna, the distance between the multiband radiator and metal reflector should be a quarter of the wavelength when the beamwidth is set to $90^\circ$ [24]. As shown in Fig. 4, when the wavelength at 800 MHz is $\lambda_{800\text{MHz}}$, the distance $s$ between the radiator and the reflector is $s = 0.25\lambda_{800\text{MHz}}$. In the case of the radiator for 2 GHz band, let corresponding wavelength denote $\lambda_{2\text{GHz}}$, $s$ should be set to $0.625\lambda_{2\text{GHz}}$ to maintain $90^\circ$ beamwidth; it is a longer distance in electrical length. The radiation patterns in the horizontal plane at each band are plotted in Fig. 5. The radiation pattern at 800 MHz is unidirectional with $90^\circ$ beamwidth. On the other hand, the radiation pattern at 2 GHz is divided into three directions. If the distance $s$ is designed so that the beamwidth at 2 GHz is $90^\circ$, the required beamwidth at 800 MHz cannot be obtained. Therefore, there is a significant barrier to designing the same beamwidth in multiple frequency bands with a single reflector.

III. DUAL-BAND SECTOR ANTENNA EMPLOYING WOODPILE REFLECTOR

A. CONCEPT OF MULTIBAND SECTOR ANTENNA

Fig. 6 shows the concept of the multiband sector antenna for the GS. It employs multiple metamaterial reflectors and a multiband radiator. Desired center frequencies are defined as $f_n (f_1 > f_2 > \ldots > f_N)$. The entire sector antenna is constructed by placing each squared reflector in order of the center frequency, i.e. reflectors #1, #2, \ldots, #N, are designed for frequencies $f_1, f_2, \ldots, f_N$, respectively. The side length of the $n$-th metamaterial reflector is $L_n$. The metamaterial reflectors have EBG characteristics, and hence they can reflect/transmit electromagnetic waves according to their specific frequency band; behave as band-stop or band-pass filters. The $n$-th metamaterial surface reflects the electromagnetic waves at $f_n$ but transmits them at the other frequency bands $(f_1, f_2, \ldots, f_N$ except $f_n$) and radiate into the air. It can be applied to the woodpile structure [20] or the frequency selective surface (FSS) [25]. The $N$-th metamaterial reflector, located farthest
from the multiband radiator, can be implemented as a metal reflector to suppress the undesired radiation in the back lobe direction.

**B. ANTENNA GEOMETRY OF DUAL-BAND SECTOR ANTENNA EMPLOYING WOODPILE REFLECTOR**

Fig. 7 shows the configuration of the dual-band antenna with 800 MHz and 2 GHz frequencies. It comprises a multiband radiator, a woodpile reflector, and a metal reflector. The woodpile reflector consists of metamaterial and it transmits the electromagnetic waves except for the 2 GHz band. The woodpile/metal reflectors and the multiband radiator are aligned on the X-axis and parallel to the Y-Z plane. The multiband radiator is located at a distance $s_n$ away from the reflectors. It is a quarter of the wavelength of 800 MHz and 2 GHz, respectively.

The multiband radiator consists of a biconical antenna and sleeve dipole antenna, each of which resonates at 800 MHz and 2 GHz, respectively. Its detailed parameters are described in Fig. 7(b). The multiband radiator is fed from the backside of the metal reflector using a semi-rigid cable pierced through the center of the woodpile/metal reflectors.

The woodpile metamaterial has a periodic structure of three-dimensionally stacked dielectric rods as shown in Fig. 8. The woodpile metamaterial produces a wider EBG band [22]. As shown in the figure, the thickness of each rod is $w$ meters square. The woodpile metamaterial consists of four layers of rods; layers B and D are spatially perpendicular to layers A and C. Each layer is configured with the spacing of $a$. Layers A and C, B and D are placed at the offset of $a/2$, respectively.

**C. CONSTRAINTS ON BEAMWIDTH ADJUSTMENT FOR MULTIBAND SECTOR ANTENNA**

The proposed antenna with multiple reflectors can achieve the same beamwidth characteristics by keeping each electrical distance from the reflectors to the radiator constant at all resonant frequencies. However, the woodpile reflector, which has wider EBG characteristics than other types of metamaterial, has a non-negligible thickness which limits the installation flexibility. In [19], the thickness of the woodpile reflector is determined by the distance between each reflector according to the resonant frequencies. The thickness design that can achieve reflection characteristics is insufficient because the rod width at the X-axis direction is smaller than that at Y and Z-axis directions. In addition, EBG band becomes smaller at higher frequency band. A key challenge is to control beamwidth by adjusting rod width under the constraints of target center frequency as well as EBG band requirements. In order to address the above issue, this paper proposes the design framework of the woodpile reflector.
IV. PROPOSED WOODPILE REFLECTOR DESIGN

A. DESIGN METHODOLOGY OVERVIEW

The beamwidth requirements for each frequency band are determined from the system requirements, such as frequency and number of sectors. A key feature of our proposed approach is to align beamwidths for multiple frequency bands by optimizing woodpile parameters, even though the radiator-reflector distances are different. First, we design a Woodpile reflector to reflect high-frequency electromagnetic waves (Section IV-B). Since the Woodpile reflector has a three-dimensional structure, it is necessary to design the thickness of the Woodpile reflector so that it does not interfere with other reflectors (Section IV-C). Since the thickness of the Woodpile reflector depends on the relative permittivity of the material, the relative permittivity should be chosen so that the reflector can be installed. Next, the side length of the Woodpile reflector is determined in consideration of the effect on other than the EBG band (Section IV-D). Finally, the beamwidth is designed by changing the thickness of the rods of the Woodpile reflector (Section IV-E).

B. EBG CHARACTERISTICS OF WOODPILE REFLECTOR

The EBG characteristics of the woodpile metamaterial for incident plane waves are designed using ANSYS HFSS [26]. The electromagnetic field is simulated assuming an infinite array of woodpile reflectors. Fig. 9a shows a dispersion diagram [27] of the woodpile metamaterial in the X-axis when the relative permittivity of rods is set to $\varepsilon_r = 38$. The frequency response of the woodpile reflector to the transmission phase is shown. To reflect the electromagnetic waves at 2 GHz band, the rod width and rod spacing are set to $w = 10.8$ mm and $a = 43.0$ mm, respectively. It can be seen that there is an EBG between 1.6 GHz and 2.5 GHz, and this gap tends to expand as the phase increases. The woodpile reflector cannot transmit but reflects the electromagnetic waves in these bands. In practice, the woodpiles should be stacked in a limited period. Fig. 9b evaluates the S21 transmission characteristics in the X-axis direction with the woodpile structure of one period, as shown in Fig. 7. The electromagnetic field analysis sets the periodic boundary condition in the Y-axis and Z-axis directions, respectively. It can be seen that EBG frequency is from approximately 1.5 to 2.5 GHz with respect to the band edges where the S21 transmission is lower than $-10$ dB. The EBG frequency of the S21 characteristics matches that of the dispersion diagram of Fig. 9a. Therefore, the woodpile metamaterial antenna can be designed by controlling S21 characteristics so as to have reflectance properties at 2.0 GHz.

C. RELATIONSHIP BETWEEN MATERIAL AND SIZE OF WOODPILE REFLECTOR

The woodpile reflector has a non-negligible thickness because of a layered structure with dielectric rods. In order to keep the distance between the multiband radiator and each reflector constant for all commonly-utilized frequencies, there exists an inevitable physical constraint. The EBG band and the size of the woodpile reflector should be designed so that each reflector does not overlap with the other. This section discusses the material of the woodpile reflector to prevent the reflector overlap.

The maximum thickness of the woodpile reflector is determined by the distance between each reflector. The thickness of the woodpile reflector is defined as $D$. Its maximum can be expressed as $D_{\text{max}} = s_2 - s_1$. When $s_2$ is set to the quarter of the wavelength ($s_1 = 37.5$ mm, $s_2 = 93.8$ mm), the maximum thickness is $D_{\text{max}} = 56.3$ mm. To meet such limitations, EBG characteristics should be designed by controlling the thickness of the woodpile reflector in lower than 56.3 mm.

The resonant frequency varies in relation to the relative permittivity of the dielectric rods. Fig. 10 shows the thickness of the woodpile reflector, $D$, as a function of the relative permittivity of the dielectric rods, $\varepsilon_r$, when the resonant center frequency is 2.0 GHz. The relationship between $w$ and $a$ is set to be constant as $w/a = 0.25$. Setting the relative permittivity larger, the thickness of the woodpile reflector becomes small. When $\varepsilon_r > 24.5$, the woodpile reflector cannot overlap with...
the other since the thickness becomes $D < 56.3$ mm. The material with $\varepsilon_r = 38$ is used for the woodpile reflector where the overall thickness satisfies lower than $D_{\text{max}}$.

**D. IMPACT ON RADIATION PATTERNS OF WOODPILE REFLECTOR**

The woodpile structure may affect the radiation patterns because of its uniqueness. This subsection clarifies its impact at the out of EBG band.

Fig. 11 shows the radiation pattern in the horizontal plane when the multiband sector antenna has the multiband radiator, the metal reflector, and the woodpile reflector. It compares the metal and woodpile reflectors. The transmission frequency is set to 800 MHz. The structural parameters of the woodpile reflector are the same as Section IV-B, and the lattice period is set to six. It can be seen that the woodpile reflector narrows the beamwidth; antenna gain for diagonal directions, i.e. in the range of 15 to 75 degrees, is reduced. Such degradation should be compensated, and the beamwidth of the woodpile reflector should be controllable according to the requirement.

In general, the edge of the reflector contributes to the antenna radiation pattern. Here we clarify the effect of the radiation patterns in the horizontal plane at 800 MHz by the lattice period of the woodpile reflector at the Y-axis and Z-axis directions. Fig. 12 shows the beamwidth for 800 MHz as a function of the lattice period of the woodpile reflector. That with the metal reflector is plotted as the solid line. When the period of the woodpile structure is four or less, there are few changes in the beamwidth. On the other hand, the beamwidth is narrowed as the lattice period increases to four. The beamwidth of the 8-period woodpile reflector is more than 60° narrower than that of the metal reflector.

The physical side length of the woodpile reflector with five periods is $L_1 = 182.8$ mm, which is almost equal to the half-wavelength at 800 MHz. The woodpile reflector affects the beamwidth at the other bands when the side length of the woodpile is more than half of the wavelength at the other band. Decreasing the period of the woodpile lattice structure also degrades EBG characteristics. Considering these constraints, the lattice period of the woodpile reflector is set to four which is the maximum size not to affect the radiation pattern at the out of EBG bands.

**E. BEAMWIDTH ADJUSTMENT ALGORITHM**

Fig. 13 shows a flowchart for the proposed beamwidth adjustment algorithm. The detail is exemplified below to design the dual-band sector antenna with the same 90° horizontal beamwidth for 800 MHz and 2.0 GHz. The beamwidth is sequentially adjusted for each band. Basically, the beamwidth for the woodpile reflector can be adjusted by changing the rod width in the Y-Z plane. The EBG band of the woodpile reflector is varied by designing its thickness. Therefore, the proposed algorithm should be conducted under the constraints of a controllable rod width range where the woodpile reflector can satisfy the target EBG band characteristics.

**Step 1** The EBG characteristics of the woodpile reflector in the X-axis direction (antenna boresight) are designed. The rod width, rod spacing, and relative permittivity are parameters to design EBG
at 2.0 GHz. It follows the woodpile reflector design as presented in Section IV-B.

Step 2 The beamwidth adjustment for 2.0 GHz is achieved by changing the rod width in the Y-Z plane, however, the resultant rod width changes the EBG characteristics; the designed EBG band may deviate from the target band. To keep the EBG band in the required band, this step firstly finds a range of \( w \) where the EBG band falls into the target frequency. Fig. 14 shows the band gap range where the S21 transmission of the woodpile reflector is lower than \(-10 \text{ dB}\), as a function of \( w \) when \( a \) is fixed. It can be confirmed that the S21 transmission can be achieved whenever the controllable range is \( 7.5 < w < 13.5 \text{ mm} \).

Step 3 The size of the woodpile reflector, i.e., lattice period, is determined so as not to affect the radiation pattern at the out of EBG band. As shown in Fig. 12, the radiation pattern is affected according to the period of the woodpile lattice structure. The lattice period is determined less than half wavelength of the out of EBG band as discussed in Section IV-D. It is set to four to mitigate the impact of the radiation pattern at 800 MHz.

V. MEASUREMENT RESULTS

Based on the proposed beamwidth adjustment algorithm, the dual-band sector antenna having 90° beamwidth at 800 MHz and 2.0 GHz is fabricated. Fig. 16 shows an exterior of the prototype. Detailed parameters can be found in Section IV. Note that the relative permittivity is set to \( \varepsilon_r = 38 \) and the rod width is set to \( w = 12.1 \text{ mm} \), respectively.

Fig. 17 shows the measured EBG characteristics of the fabricated woodpile reflector. The S21 transmission characteristics are measured using a vector network analyzer and two microwave horn antennas base on the experiment configuration shown in [19]. From the simulation result, it can be seen that the EBG band is approximately from 1.3 GHz to 2.3 GHz concerning the band edges where the S21 characteristics cross the amplitude of transmission at \(-10 \text{ dB}\).
The EBG band in the measurements and electromagnetic field simulations are in good agreement. Since a finite lattice structure, i.e. four periods, is employed in the prototype, the amplitude degrades in comparison to that in the electromagnetic field simulations wherein the periodic boundary condition is set. On the other hand, the woodpile reflector transmits the electromagnetic waves through the air because the amplitude at 800 MHz is approximate $-2$ dB. The woodpile reflector has little effect on 800 MHz electromagnetic waves.
Fig. 18 shows a voltage standing wave ratios (VSWRs) for the dual-band sector antenna. The simulation and measurement results are in good agreement. The dual-band sector antenna achieves a VSWR lower than 2.0 in 800 MHz and 2.0 GHz, and the relative bandwidths are almost 8%. Since the LTE generally uses 20 MHz bandwidth, 8% relative bandwidth at 800 MHz, i.e. 64 MHz width, of the proposed antenna is sufficient. Fig. 19 shows S11 characteristics in the measurement results. For comparison, the figure also shows S11 of the antenna that does not employ a woodpile reflector. It can be seen that employing the Woodpile reflector reduces the bandwidth at 800 MHz and S11 is shifted to a lower frequency band at around 2 GHz. The Woodpile reflector affects the frequency characteristics. Although the proposed antenna employed the dual-band radiator, a broadband radiator can reduce the impact of the woodpile reflector.

Fig. 20 shows the radiation patterns in the horizontal plane for each frequency band. The measurement results are in good agreement with the simulation results. The proposed dual-band sector antenna achieves approximately 90° beamwidth at 800 MHz without being affected by the woodpile reflector. Moreover, the front-to-back ratio of this antenna is less than 20 dB for each frequency and sufficient for the base station antenna. Fig. 21 shows the radiation patterns in the vertical plane at 800 MHz and 2.0 GHz. These measurement results also well match the simulation results. Therefore, it is possible to design the dual-band sector antenna without being affected by the woodpile reflector.

Finally, the link-level simulation verifies the effectiveness of the fabricated antenna in terms of throughput performance. Fig. 22 shows the aggregated system throughput as a function of the azimuth angle, $\theta$. The parameters of the link-level simulation were the same as those in Section II-B. The radiation pattern of the proposed antenna is based on the measurement results in Fig. 20, and the ideal pattern is from (1). When the GS–UAV distance, $d$, is 500 m, the system throughput provided by the proposed antenna is degraded in the range of $|\theta| > 30^\circ$ compared with those of the ideal and simulation. This is because the radiation pattern at 2.0 GHz, as shown in Fig. 17b, can achieve 90\(^\circ\), but the gain decreases sharply in the range exceeding 30\(^\circ\). At $d = 1500$ m, although the tendency is the same between ideal and proposal, the system throughput with the prototype is slightly lower than that with the ideal condition. This is because that the antenna gain of the prototype is lower than that of the ideal and simulation patterns. Its impact cannot be negligible as the transmission distance gets longer. Nevertheless, it has been confirmed that the proposed antenna structure can reduce the angular and frequency dependence of the system throughput, as firstly presented in Fig. 3. As a result, the effectiveness of the proposed antenna was validated in terms of throughput performance.

VI. CONCLUSION

This paper discussed the UAV network in the disaster scenario to expand the service area. We proposed the beamwidth adjustment algorithm considering the EBG band of the woodpile reflector for the multiband sector antenna and fabricated the prototype. First, the relationship between the size of the woodpile reflector and the relative permittivity of the dielectric rod is revealed. It is because the thickness of the woodpile reflector consisting of a layer of dielectric rods cannot be negligible. Then the effect of the radiation
pattern by the woodpile reflector in the transmission band (out of the EBG band) was clarified. Considering these points, the proposed beamwidth adjustment algorithm designed the dual-band sector antenna, which has the same 90° beamwidth at 800 MHz and 2.0 GHz with minimizing mutual impact to 800 MHz. Its prototype was fabricated, and approximately 90° beamwidth is achieved for each band in the horizontal plane. Link level simulation verified its effectiveness, suppressing the angular dependency in carrier aggregated system throughput performance.

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