Research Article

Scalable Notch Antenna System for Multiport Applications

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A novel and compact scalable antenna system is designed for multiport applications. The basic design is built on a square patch with an electrical size of $0.82\lambda_0 \times 0.82\lambda_0$ (at 2.4 GHz) on a dielectric substrate. The design consists of four symmetrical and orthogonal triangular notches with circular feeding slots at the corners of the common patch. The 4-port antenna can be simply rearranged to 8-port and 12-port systems. The operating band of the system can be tuned by scaling (S) the size of the system while fixing the thickness of the substrate. The antenna system with S: 1/1 in size of $103.5 \times 103.5 \text{ mm}^2$ operates at the frequency band of 2.3–3.0 GHz. By scaling the antenna with S: 1/2.3, a system of $45 \times 45 \text{ mm}^2$ is achieved, and thus the operating band is tuned to 4.7–6.1 GHz with the same scattering characteristic. A parametric study is also conducted to investigate the effects of changing the notch dimensions. The performance of the antenna is verified in terms of the antenna characteristics as well as diversity and multiplexing parameters. The antenna system can be tuned by scaling so that it is applicable to the multiport WLAN, WIMAX, and LTE devices with port upgradability.

1. Introduction

The capacity can be excessively increased and the fading effects can be reduced by using multiple input multiple output (MIMO) concept thanks to providing spatially multiplexing and diversity [1]. Hence the MIMO innovation has been implemented to the latest wireless communications such as long term evolution (LTE), worldwide interoperability for microwave access (WIMAX), and wireless and local area network (WLAN) standards.

Designing the multiport antenna elements for MIMO devices has become more difficult since they are going to be smaller, and thus the multiple elements must be placed in restricted board with the other essential electronic components. In this case, the elements are inevitably exposed to high mutual coupling among them, because of operating closely. The mutual coupling must be minimized to isolate channels between reciprocal antenna elements [2]. Modifying techniques applied to the antenna models such as positioning the elements orthogonally [3], employing parasitic structures [4], using neutralization-line [5], utilizing shorting-pin [6], and loading slots [7] have been lately proposed to improve

the isolation. Note that designing these additional geometries together with the multiple elements needs extra considerable efforts. However computational electromagnetic (CEM) [8] software can facilitate designing such antennas.

Several antenna systems with multiple ports have been recently reported for the access points [9–15]. These designs are reviewed and compared to each other in Section 8. Nevertheless the prominent features are merely given here. In [9], an antenna was composed of four meandered loop elements for dual band operations. An antenna system with 6 elements was designed in [10] for single band of WLAN standard. In [11], four monopole elements on a common patch were formed for wide band operations. A quad-element dipole system having V-shaped ground branches for few bands of WLAN and WIMAX standards was proposed in [12]. A quad-port antenna system with enhanced isolation using double-layer mushroom wall was presented in [13] to operate at a single band of WLAN standard. In [14], a system integrating four inverted-F antennas and a slot on the ground was designed for WLAN bands. A quad-element antenna comprising several rings was studied in [15] for quad band operations. The multiport antennas suggested in

FIGURE 1: 3D geometry of the proposed notch antenna system: (a) overall view and (b) elaborate view of Notch 2.

the literature have varied geometries for different bands of wireless standards. Compact and scalable antenna systems of which ports can be upgraded are still necessary for modern small multiport wireless devices.

In this work, a simple and compact scalable notch antenna system is designed suitably for 4-port, 8-port, and 12-port applications. In order to show the scalability of the systems, two 4-port antennas denoted as Ant. 1 and Ant. 2 are basically designed by notching the corners of square patches triangularly. The 4-port antenna can be simply rearranged to obtain 8-port and 12-port systems. Ant. 1 design with size of $103.5 \times 103.5 \text{ mm}^2$ is obtained by scaling (S) the system with S: 1/1 operating at 2.4 GHz band, while Ant. 2 design in size of $45 \times 45 \text{ mm}^2$ is achieved by scaling Ant. 1 with S: 1/2.3 to operate at 5.4 GHz band. The impacts of dimension variations of the notch elements on the scattering performance are studied as well. The characteristics of Ant. 1 design are investigated and verified by the simulations and measurements in terms of envelope correlation coefficient (ECC), apparent diversity gain (ADG), mean effective gain (MEG), and multiplexing efficiency (ME) parameters. The ECC is achieved less than 0.035; the ADG and MEG are close to 10 and 0.5, respectively. The ME is greater than 0.6 for the interested band.

The organization of the paper will be as follows: In Section 2, the structure of the proposed scalable notch antenna system will be described. Section 3 will outline the working mechanism of the system scalability. In Section 4, a parametric study will be carried out. The prototype and the measurements of the antenna system will be presented in Section 5 and the antenna arrangements with 8 ports and 12 ports will be studied in Section 6. In Section 7 the performance of antenna system will be carried out. A comparison with the literature will be reviewed in Section 8. Eventually, interpretation and conclusion will be expressed in Section 9.

2. Design of the Scalable Notch Antenna System

The antenna system is modelled, simulated, and optimized using CEM software of HyperLynx® 3D EM [16] with the method of moment (MoM) [17] solver. The antenna system is empirically modelled and then fine-tuned thanks to genetic algorithm which is built-in optimization module of HyperLynx 3D EM. The optimization is performed with an objective function of $|S\text{-parameter}| < -12 \text{ dB}$ for desired operating band in order to achieve optimal dimension of the notch element. Therefore the notch antenna system of which 3D geometry is depicted in Figure 1 is achieved in this study. As shown, the antenna structure is built on a single layer common patch over a substrate. Each antenna element is triangularly formed by notching the four corners of the patch. Circular feeding slot is formed to energize each notch. In simulations, each notch is fed with 1 Volt wave source. The antenna model meshed with lines per wavelength ratio 30 at maximum frequency 7 GHz is simulated in a frequency range of 1–7 GHz at 121 discrete frequency points. The geometry of the antenna system can be scaled to tune the operating band. This is examined through two system designs named Ant. 1 and Ant. 2 of which geometric parameters are given in Table 1. S-parameters of the simulated Ant. 1 and Ant. 2 designs are illustrated in Figure 2. Ant. 1 design of $103.5 \times 103.5 \text{ mm}^2$ whose scale is S: 1/1 operates at 2.4 GHz band (2.3–3.0 GHz). On the other hand, Ant. 2 design with size of $45 \times 45 \text{ mm}^2$ is obtained by scaling Ant. 1 design with S: 1/2.3 to operate at 5.4 GHz band (4.7–6.1 GHz) fixing thickness h of the substrate. Therefore the operating band of the system can be tuned by scaling the antenna geometry. It should be noticed, from Figure 2, the isolation is higher than 13.3 dB between Notch 1 and Notch 2 (or Notch 4); it is also more than 17.5 dB between Notch 1 and Notch 3 for both

TABLE 1: Dimensions of the proposed scalable antenna system (unit: mm).

Ant.	Band (GHz)	Center f_r	Scale (S:)	L/λ_0	L	l	p	t	r	h
1	2.4	2.4	1/1	0.82	103.5	6.9	21.97	5.15	2.3	1.6
2	5.0	5.4	1/2.3	0.81	45.0	3.0	9.55	2.23	1.0	1.6

FIGURE 2: Simulated S-parameters of scalable 4-port antenna system for Ant. 1 (S: 1/1) and Ant. 2 (S: 1/2.3) designs.

antenna designs. This means that the antenna systems have high isolation for efficient multipoint operations without using any additional structure thanks to the orthogonal design of notches.

3. The Working Mechanism of the Antenna System

The surface current distributions of Ant. 1 and Ant. 2 designs when Notch 1 is activated are presented in Figure 3 so as to investigate the working principles and similarities between the two antenna designs. From the figure, most current concentrates at the two edges of the notch elements for both designs. At the same time, less current couples to the other notches even though they share common surface current. This low mutual coupling between the notches is thanks to orthogonal positioned notches. Note that current distributions of the two antenna designs show similar behavior. It means that changing the scale of the antenna system does not alter the electrical characteristics. It can be also seen from Table 1 that the electrical sizes (L/λ_0) of the two designs remain almost the same while changing the geometric dimensions. Since the 4-element system consists of four electromagnetic symmetrical elements, the electrical size of Ant. 1 is $0.82\lambda_0 \times 0.82\lambda_0$ at center frequency of 2.4 GHz while that of Ant. 2 is $0.81\lambda_0 \times 0.81\lambda_0$ at 5.4 GHz. Hence the operating frequency band can be decreased or increased by, respectively, increasing or decreasing the effective length

of the antenna according to (1) while keeping the electrical characteristics [18].

$$f_r = \frac{c}{2L_{\text{eff}} \sqrt{\epsilon_r}}, \quad (1)$$

where c is the speed of the light, ϵ_r is the relative dielectric constant, and L_{eff} is the effective length of the antenna geometry that includes the effects of notches and the length extension due to travelling waves in both the substrate and air.

4. Parametric Study for the Notch Element

The effects of varied notch's dimensions on scattering parameters are studied. Hence S-parameter plots of Ant. 1 design for different dimensions of l and p are comparatively given in Figure 4. $|S_{11}|$ and $|S_{21}|$ are only considered here for the sake of simplicity. The varied dimensions are 5 mm, 7 mm, and 9 mm for l and 17 mm, 22 mm, and 27 mm for p . Notice that the proposed Ant. 1 design operating at 2.3–3.0 GHz band has dimensions of $l = 7$ mm and $p = 22$ mm. S-parameters of $|S_{21}|$ regarding the isolation levels are almost the same with the proposed one. Whereas the band of Ant. 1 design is tuned to 2.2–2.7 GHz for $l = 5$ mm and 2.5–3.2 GHz for $l = 9$ mm (see Figure 4(a)), it is tuned to 3.1–3.7 GHz for $p = 17$ mm and 1.95–2.3 GHz for $p = 27$ mm (see Figure 4(b)). These results demonstrate that the operating band can be tuned by readjusting the dimensions of the notches without altering the main scattering characteristics. Therefore smaller or larger antenna designs can be achieved by adjusting the dimensions of notches.

5. Prototyping the Antenna System

In order to experimentally validate the antenna system, Ant. 1 design operating at 2.4 GHz band illustrated in Figure 5 is realized on single layer FR4 PCB board with relative dielectric permittivity of 4.4, tangent loss of 0.02, and thickness of 1.6 mm. The feeding slots are energized via a 50-Ohm pigtail cable ending with a 50-Ohm SMA. Therefore a distance between the slots and the SMA is provided to prevent the antenna system from the spurious radiation. The experiments are performed by the agency of Keysight Technologies N5224A PNA network analyzer. The measured S-parameters are shown in Figure 6 in comparison with the simulated ones. There is a satisfactory agreement between those of plots. According to the measured results, Ant. 1 design operates between 2.30 GHz and 2.95 GHz with minimum isolation of 16 dB among multiple elements.

FIGURE 3: Surface current distributions of the scalable 4-port antenna system as Port 1 is activated at (a) 2.4 GHz for Ant. 1 design and (b) 5 GHz for Ant. 2 design.

FIGURE 4: S-parameters of Ant. 1 design for different notch dimensions: (a) $l = 5$ mm, $l = 7$ mm*, and $l = 9$ mm and (b) $p = 17$ mm, $p = 22$ mm*, and $p = 27$ mm (*it is of the proposed model).

6. Multiport Antenna Arrangements

In order to design antenna systems with more than 4 ports, various concepts are essayed by rearranging the scalable 4-port antenna system. Thus new antenna concepts with 8 ports and 12 ports are achieved by arranging orthogonally Ant. 1 design as presented in Figure 7. The simulated S-parameters for 12-port system are accordingly given in Figure 8. In spite of increasing the port numbers, the 12-port system shows similar scattering characteristics and isolation performance with Ant. 1 design. Therefore the proposed antenna system is capable of not only tuning the frequency band but also increasing the ports.

7. Performance Study

In this section, the performance of Ant. 1 design is analyzed in terms of radiation pattern, peak gain, efficiency, multiport parameters of diversity, and multiplexing gain since the two designs show similar characteristic behavior.

2D radiation gain patterns of Ant. 1 design on x - z and y - z planes at the frequency of 2.4 GHz are displayed in Figure 9. The patterns are very similar to each other as is expected due to electromagnetic symmetrical notches. The radiations show quasi-omnidirectional pattern. The maximum gains are 0.73 dBi and 0.72 dBi, respectively, on x - z and y - z both in direction of 90° .

FIGURE 5: Prototype of Ant. 1 design.

FIGURE 6: Simulated and measured S-parameters of Ant. 1 design.

Figure 10 shows the peak gain together with the total efficiency. It is known that the total efficiency of an antenna is the product of the efficiencies regarding radiation, mismatch, conduction, and dielectric. It is observed that the peak gain and the total efficiency maintain, respectively, higher than 3.4 dBi and 60%, and they regularly vary across the interested band of 2.3–3.0 GHz.

The ECC (ρ_e) is the square of the correlation coefficient (ρ) appreciating the isolation level of the antenna elements [19]. As the elements isolate from each other, the ECC closes to zero. In the isotropic environment, the ECC is calculated from the patterns of two elements by using [20].

$$\rho_e = |\rho|^2 = \frac{\left| \iint_{4\pi} [\vec{F}_1(\theta, \phi) \cdot \vec{F}_2(\theta, \phi) d\Omega] \right|^2}{\iint_{4\pi} |\vec{F}_1(\theta, \phi)|^2 d\Omega \iint_{4\pi} |\vec{F}_2(\theta, \phi)|^2 d\Omega}, \quad (2)$$

TABLE 2: Diversity and multiplexing parameters.

Frequency (GHz)	ECC ₁₂	ADG ₁₂	MEG ₁	ME ₁₂
1.50	0.026	9.872	0.5011	0.072
1.75	0.252	8.648	0.5014	0.134
2.00	0.232	8.766	0.5013	0.262
2.25	0.035	9.826	0.5013	0.586
2.50	0.000	9.998	0.5013	0.791
2.75	0.013	9.937	0.5033	0.679
3.00	0.051	9.744	0.5012	0.587
3.25	0.049	9.753	0.5012	0.392
3.50	0.000	10.000	0.5012	0.233

where $F_i(\theta, \phi)$ is the radiation pattern of the multiple elements, $\bullet$ indicates the Hermitian product, and Ω is the solid angle. The ADG [21] based on the correlation coefficient is also important metric evaluating the diversity performance. It can be calculated by [22]

$$\text{ADG} = 10 \sqrt{(1 - |\rho|^2)}, \quad (3)$$

where 10 is the maximum value that ADG will be. The MEG is another diversity metric that evaluates incident power imbalance between the antenna elements. The MEG of the i th antenna element is described as the ratio of the mean received (P_{rec}) to the mean incident power (P_{inc}) at the element. The MEG can be calculated by the following expression [23]:

$$\text{MEG}_i = \oint \left[\frac{\text{XPR} \cdot G_{\theta i}(\Omega) \cdot P_{\theta}(\Omega) + G_{\phi i}(\Omega) \cdot P_{\phi}(\Omega)}{1 + \text{XPR}} \right] d\Omega, \quad (4)$$

where XPR is the ratio of cross-polarization power of the incident fields. P is angular density functions of the incident field and G is active power gain pattern at polarized components of θ or ϕ angles.

The ECC, ADG, and MEG distributions for the isotropic environment are calculated in Table 2 using the 3D radiation gain patterns obtained by HyperLynx 3D EM. The ECC maintains less than 0.035 which eminently satisfies the criteria of uncorrelated elements 0.5 [18]. The ADG is close to 10 for fully isolated elements. For the isotropic environment, the MEG_i can be simplified into $\text{MEG}_i = \eta_i/2$, where η_i is the total efficiency for i th element. Hence the MEG is 0.5 in totally lossless conditions [23, 24].

Spatial multiplexing is a fundamental parameter to increase the multiport spectral efficiency. The following intuitive metric calculates the ME (η_{MUX}) estimating the spatial multiplexing performance of a dual-element antenna system [25]:

$$\eta_{\text{MUX}} = \sqrt{(1 - |\rho|^2) \eta_1 \eta_2}, \quad (5)$$

where η_i is the total efficiency of the element. From (5), the ME takes account of the total efficiency and the correlation. The calculated results of ME are added in Table 2 as well. The ME varies higher than 0.6 over the interested band.

FIGURE 7: The antenna system arrangements with (a) 8 elements and (b) 12 elements.

FIGURE 8: Simulated S-parameters of 12-port antenna arrangement.

8. Review and Comparison

Antenna designs with multiports reported elsewhere [9–15] have been reviewed. Their elements are symmetrically positioned for WLAN, WIMAX, and/or LTE bands, in common. In [9], an antenna with size of $150 \times 150 \text{ mm}^2$ consists of four meandered loop elements, two of them cover the bands of 699–798 MHz and 2.3–2.5 GHz, and the remainder operate on 1.7–2.0 GHz, 3.5–4.0 GHz, and 5.3–6.0 GHz. An antenna system with 6 elements each with size of $30 \times 30 \times 12.9 \text{ mm}^3$ was proposed in [10] for 5 GHz applications. In [11], four monopole elements on a $120 \times 140 \text{ mm}^2$ common patch were designed for operating over frequency range of 1.85–2.95 GHz. A quad-element dipole system with an overall size of $40 \times 40 \text{ mm}^2$ having V-shaped ground branches operating at the band of 2.3–4.4 GHz was constructed in [12]. A quad-port antenna system in a size of $113 \times 113 \times 20.8 \text{ mm}^3$ with isolation enhanced using double-layer mushroom wall was suggested in [13] to operate between 2.396 GHz and 2.450 GHz. In [14], a system integrating four inverted-F antennas and a slot on the ground size of $50 \times 50 \text{ mm}^2$ was presented for 2.4 GHz and 5 GHz bands. A quad-element antenna size of $152 \times 152 \times 12 \text{ mm}^3$ comprising several

rings was designed in [15] for triple-band of 2.4–2.5 GHz, 3.4–3.7 GHz, and 5.1–5.9 GHz. It is evident that the reviewed antenna designs differ in geometric simplicity, size, and operating bands. Several of them [9, 11, 13, 15] look relatively large in size, while few [10, 15] seem to have complex geometry. The height of some systems [10, 13, 15] was relatively high for small devices. Nonetheless they should be evaluated according to their own benefits and limitations and adopted properly to real implementations. On the other side, antenna system proposed in this study is only $45 \times 45 \text{ mm}^2$ with a simple geometry and it has satisfactory isolation without using additional structure. Moreover, the operating frequency band can be successfully tuned by scaling the dimension of the antenna system; the port number can be upgraded to 8 or 12 by rearranging the basic 4-port notch antenna system. Therefore the proposed antenna system comes to prominence over the literature in terms of scalability, compactness, and simplicity.

9. Conclusion

A compact and scalable notch antenna system is proposed for multiport applications. The antenna is basically designed as 4-port system and it can be easily rearranged to obtain 8-port and 12-port systems. The basic antenna structure is constructed with a single layer square patch on a substrate. The antenna elements are formed by notching the corners of the common patch, and the notches are energized via circular feeding slots. The scalability of the system is demonstrated through two antenna designs of Ant. 1 for 2.4 GHz band (2.3–3.0 GHz) and Ant. 2 for 5.4 GHz band (4.7–6.1 GHz). As Ant. 1 design is $103.5 \times 103.5 \text{ mm}^2$ with S: 1/1, Ant. 2 design with size of $45 \times 45 \text{ mm}^2$ is obtained by scaling Ant. 1 with S: 1/2.3. Even though the 4-notch elements operate over a common patch, the isolation levels among the multiple elements are more than 16 dB due to the orthogonal design of notches. The performance of Ant. 1 design is investigated for isotropic environment in terms of parameters of the ECC, ADG, MEG, and ME. The ECC is achieved less than 0.035; the ADG and

FIGURE 9: 2D radiation gain patterns of Notch 1 on (a) x - z plane and (b) y - z plane (the solid-line is the measured plots and the dot-line is the simulated plots).

FIGURE 10: The measured peak gain and the total efficiency variations of Notch 1.

MEG are close to 10 and 0.5, respectively. The ME is greater than 0.6 for the interested band. These results show that the systems have better antenna characteristics such as stable gain in near omnidirectional radiation as well as diversity and multiplexing performance. The operating band of the antenna system can be tuned by scaling the dimension and the 4-port system is capable of upgrading the ports to 8 or 12. Moreover, the notch antenna stands out among the designs reported elsewhere with regard to simplicity in geometry and smallness in size. From this point of view, the proposed notch antenna system has novel design concept. This makes the proposed notch antenna likely candidate for modern access point applications.

Competing Interests

The author declares that there is no conflict of interests about the publication of this paper.

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