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A switched dual antenna array for mobile computing networks

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The 2.4 GHz licence-free ISM band is used extensively for hosting high performance mobile computing networks. The demand for wireless mobile computing networks with high aggregate throughput and channel quality is countered by the high levels of multipath noise in indoor environments. Although the use of directive antennas has shown good results in overcoming the multipath effect, antennas with large directivity cannot be used in a mobile computing network without affecting the functionality of the wireless protocol used. This paper presents a solution to this problem, introducing a dual antenna diversity scheme for the 2.4 GHz ISM band and its beam selector circuit for controlling the diversity scheme. The proposed antenna produces an omnidirectional pattern and two directional patterns with very large nulls in their azimuth pattern, while its low complexity and low cost allows easy integration into consumer products.

1. Introduction

Home networking, mobile computing and small-office/home-office (SOHO) multimedia are technological areas with a fast rising demand for extended wireless throughput. The wireless channel imposes several restrictions to this demand, due to its high level of multipath fading. Multipath fading is caused when multiple instances of the same signal, with different power level, phase and time delay characteristics, arrive at the receiver's antenna. These multipath components may cause severe degradation to the quality of the received signal. This effect increases the channel bit-error-rate and thus degrades the aggregate throughput of the communication link.

One of the most efficient ways to confront the effect of multipath is by using directive antennas (Driesen 1996). A directive antenna at the receiver side attenuates the multipath instances arriving from a number of different directions and thus improves the received signal quality. When the nulls of the directive antenna are large, the effect of multipath on the received signal quality decreases. On the other hand, mobile computing network protocols include several algorithms that deal with inherent wireless environment problems, such as hidden terminals, roaming and synchronization. All these algorithms were based on the assumption that omnidirectional antennas are used, and therefore the use of antennas with large directivity requires changes to the medium access control (MAC) protocol procedures.

In the majority of current mobile computing terminal implementations, a simple switched diversity scheme has been adopted in order to deal with the multipath effects without affecting the MAC layer of the protocols used. Two antennas with

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nearly omnidirectional patterns are placed in close proximity and the receiver switches between these antennas in order to achieve the best signal quality. Although this scheme is neither a spatial diversity scheme, since the correlation between the two signals is high, nor an angle diversity scheme, since the nulls of the produced patterns are quite shallow, it has shown good performance when used in an indoor environment. Nevertheless, the performance of the network would be much better if antennas with much higher directivity were used. Additionally, if these antennas had the ability to produce also an omni-directional pattern, high performance could be achieved without the need to alter the MAC layer of the mobile computing network.

In this paper we present a dual antenna switched diversity scheme that can produce three radiation patterns, two directional and one omnidirectional. The proposed antenna consists of two planar slot elements and is controlled by a low cost feeding network. Section 2 gives a brief introduction to the parameters that have to be considered in the design of such an antenna array, while § 3 describes the proposed antenna diversity scheme. Finally, § 4 highlights the feeding network that was designed to support the proposed diversity scheme.

2. Antenna array design considerations

Switched beam arrays that produce an omnidirectional and a number of directive beams have already been reported in the literature. Interesting work has been reported on patch (Iwasaki 1999) and slot (Kalis *et al.* 2000) antenna arrays that consist of active and parasitic elements and have the characteristics presented in the previous section. In general, the choice of the appropriate antenna element is a crucial factor in the design of such an array. In mobile communications, printed, planar, small-aperture elements are preferred due to their low fabrication costs and their ability to be integrated in a printed circuit board with the rest of the wireless communication system. Additionally, in these applications, an element that can produce an omnidirectional pattern similar to that of a wire monopole, in order to be suitable for ad-hoc as well as for base-station based mobile computing networks, would be preferred.

Element coupling and bandwidth are two characteristics that also play a critical role for producing both omnidirectional and directional patterns. These characteristics interact in a manner that is described in the following text. When two resonant elements are placed in close proximity and only one of these elements is fed, then some amount of energy is coupled to the other element. If this coupled energy is large enough, it changes the overall current distribution of the array and thus affects the S-parameters and the radiation pattern. In order to design a dual antenna array that can produce an omnidirectional pattern, coupling between the elements must be very small, so that when only one element of the array is fed, the other element will not affect the omnidirectionality of the pattern. This can be achieved either by placing the two elements a large distance apart, or by changing the input impedance of one of the elements, or by designing elements that have small mutual coupling, even for small inter-element spaces.

The first approach is not suitable for mobile terminals, since the available space for the antennas is usually very limited. The second approach is used when elements having large mutual coupling characteristics are placed in close proximity. This method has been widely reported in switched monopole arrays using parasitic elements (Preston *et al.* 1991, Sibille *et al.* 1997, Scott *et al.* 1999). These monopole arrays produce a number of directional beams that aim at diverse azimuth angles depending on the state of the parasitic elements. In order to design a switched beam array that can produce an omnidirectional pattern using parasitic elements with large mutual coupling, the bandwidth of these elements must be adequately large. For example, when an element of a dual switched antenna array is driven in and out of resonance, then the overall current distribution of the array changes, resulting in a shift of the array resonant frequency. When the bandwidth is adequately large, then a small change in the resonant frequency may not affect radiation in the desired frequency range. In other words, the return loss coefficient may rise, but when the elements have adequate bandwidth the overall structure will still radiate with acceptable mismatch losses.

In this work the last approach was used. We designed the array with the use of elements that have very small mutual coupling characteristics. This approach has the following advantage: once the antenna element is selected or designed, the array design is a straightforward task, since the elements of the array are virtually 'invisible' to one another.

3. Dual switched antenna design

Slot antennas in general show very small mutual coupling when placed in close proximity (Rengarajan and Nardi 1991, Porter and Gearhart 1998). Kalis *et al.* (2000) have proposed an antenna for the 5.2 GHz band that is printed and capable of producing the desired pattern, but has a bandwidth of only 2%, which is inadequate for the 2.4 GHz ISM band. Motivated by this work, we designed an antenna with much larger bandwidth in order to support mobile computing communications in the 2.4 GHz ISM band.

The antenna element is a slot antenna on an infinite ground plane, with a microstrip coupled line feed. Figure 1 shows the element's geometry, while table 1 gives precise dimensional information. Figure 2 shows the element's return loss coefficient. The two external arms of the antenna are of resonant length, producing a standing wave in the resonant frequency of the antenna. The bent shape of the external arms allows a considerable amount of current to circulate in both the x and y directions of the antenna. The overall current distribution, shown in figure 3, is similar to that of the TM_{21} mode of a microstrip patch. In this mode, peak gain is obtained near elevation angles of 90°, enabling ad-hoc network communications, and is preserved nearly constant up to polar angles of 40°. The small dimensions of the slot element enabled us to form arrays with an inter-element space equal to or less than $\lambda/2$. Evaluation of the design was made with the use of a commercial electromagnetic simulation tool based on the method of moments (MOM), which is very accurate in predicting the exact antenna characteristics (Agilent Technologies 2000). The proposed element radiates with more than 90% efficiency in the desired band and has a bandwidth of 4%, which corresponds to 100 MHz at 2.4 GHz. Figure 4 shows the radiation pattern of the element, while figure 5 shows the element's polarization, which is linear but not pure. A compromise on the polarization purity of the element was inevitable in order to produce the desired bandwidth. However, since the indoor channel significantly depolarizes transmitted signals (Cotton *et al.* 1999), purity of the antenna polarization is not as crucial as in a multipath free environment.

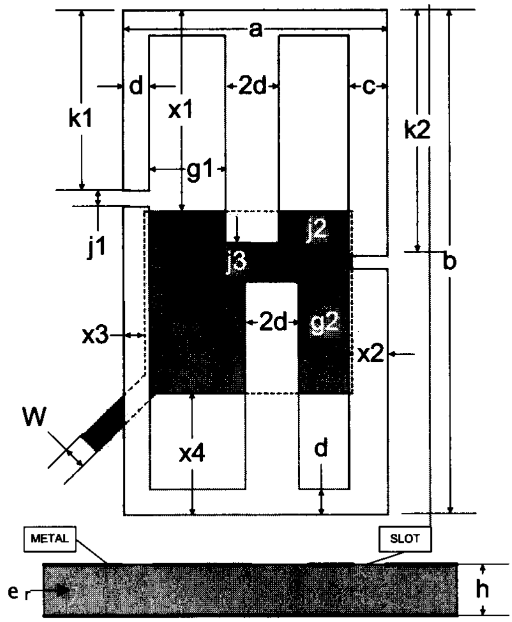

Figure 1. Geometry of the single element.

$a = 20.00$	$x1 = 15.30$	$j1 = 1.25$	$g1 = 5.75$	$W = 1.600$
$b = 38.60$	$x2 = 2.75$	$j2 = 1.00$	$g2 = 3.75$	$h = 0.813$
$c = 3.00$	$x3 = 1.50$	$j3 = 3.00$	$k1 = 11.75$	
$d = 2.00$	$x4 = 9.30$		$k2 = 16.75$	

Table 1. Single element dimensions (mm; central frequency = 2.44 GHz, $e_r = 3.65$).

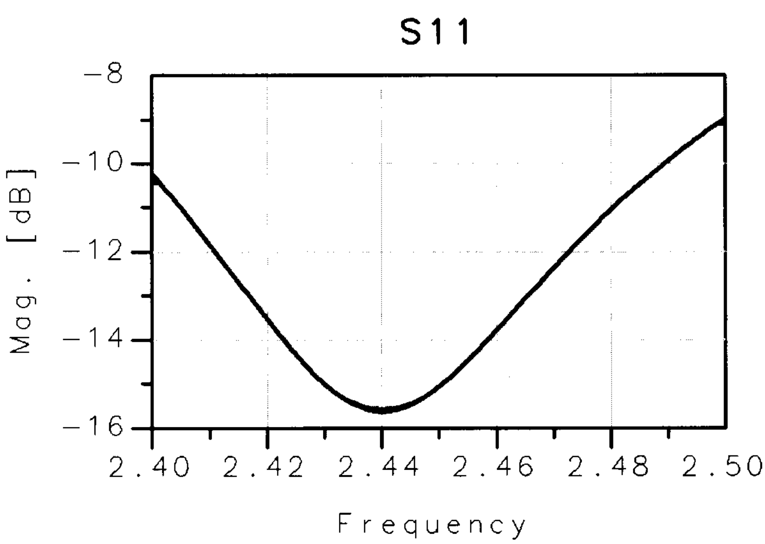

Figure 2. Single element return loss coefficient.

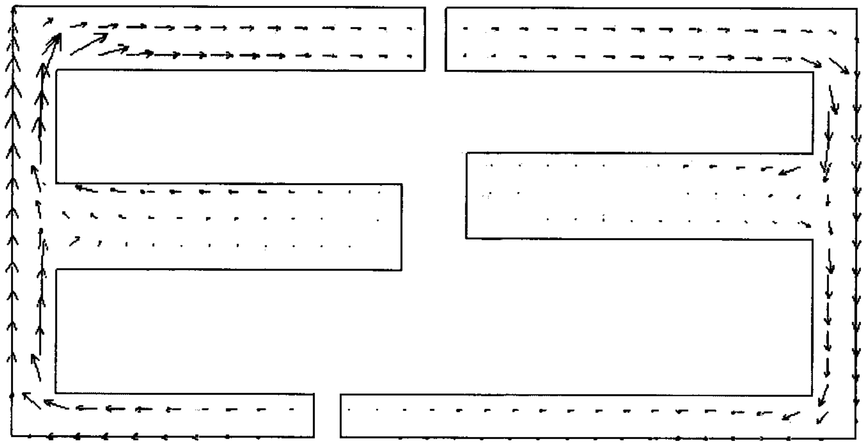

Figure 3. Single element current distribution at 2.44 GHz.

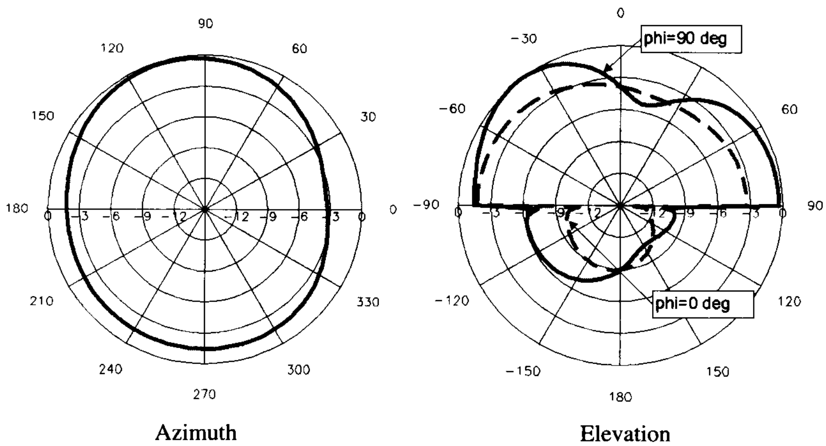

Figure 4. Single element radiation patterns.

Figure 6 shows the array geometry where two elements where placed in close proximity. The S-parameters of this structure are shown in figure 7 for an inter-element distance equal to 20 mm. The transmission coefficient S_{12} is very small, which means that the coupling between the elements is minimal. Therefore, if we feed only one of these two elements, a very small amount of current will be coupled to the other element, without even changing its input impedance. In this case, the omnidirectional pattern of figure 8 is produced, which is similar to that of a single element.

When both elements are fed with signals of the same power level and 90° phase difference, two possible directive radiation patterns are produced, as shown in figure 9. Pattern 'Dir1' is produced when the phase difference between the left and the right element is equal to +90°. Pattern 'Dir2' is produced when the phase difference between the left and the right element is equal to −90°. Both patterns have three maxima and three large nulls. Moreover, the maxima of the one pattern lie on the

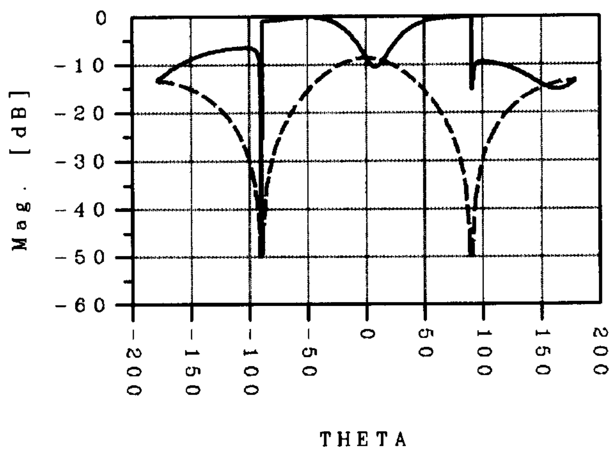

Figure 5. Magnitude of E-vertical (solid line) and E-horizontal (dashed line) of single element at 2.44 GHz.

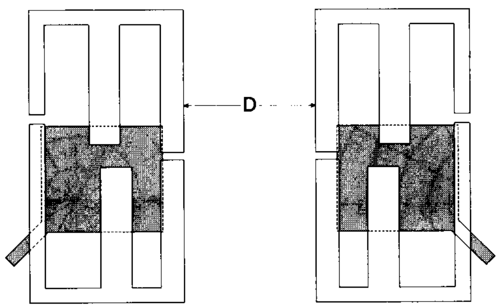

Figure 6. The two-element array geometry.

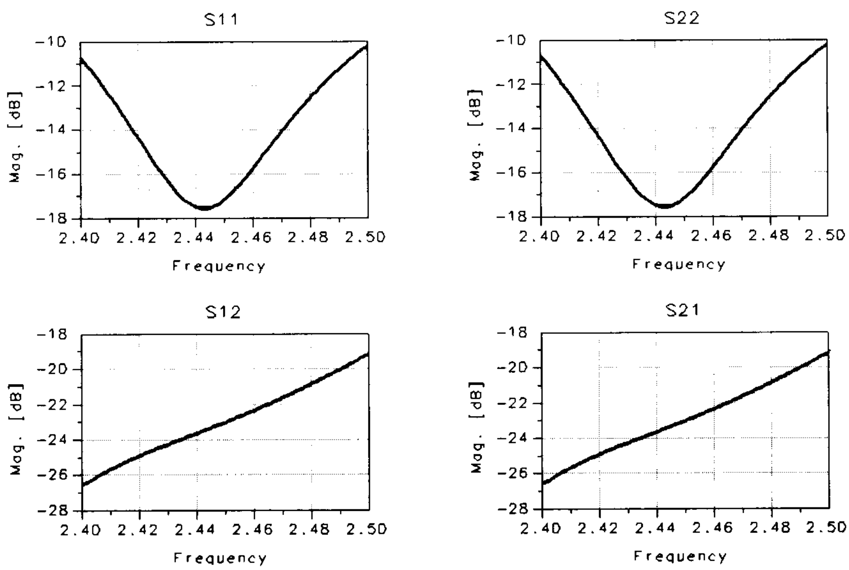

Figure 7. Antenna array S-parameters for $D = 20\,\text{mm}$.

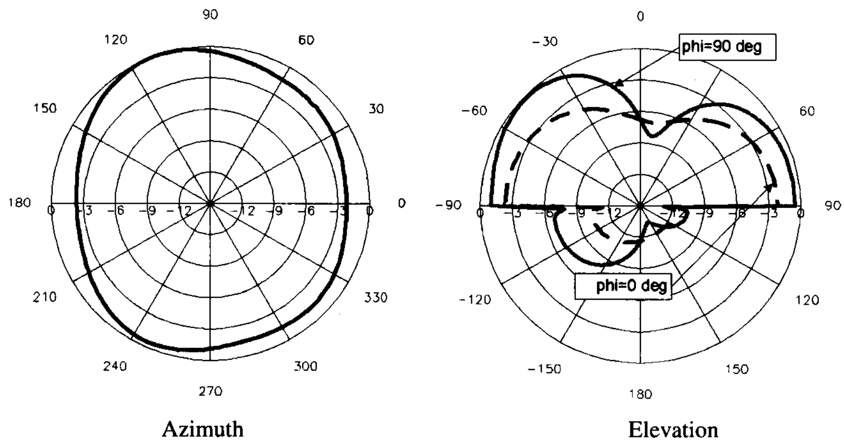

Figure 8. Radiation patterns of the proposed array when only one element is driven.

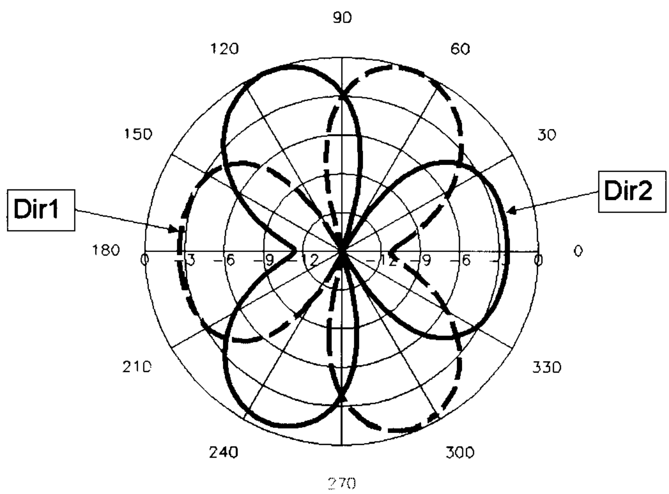

Figure 9. Azimuth radiation patterns of the proposed array when both elements are fed with signals of the same power level and a phase difference of 90°.

same angles as the nulls of the other pattern, and vice-versa. These two patterns cover 100% of the azimuth plane angles. The desired directional pattern is selected by using a 3 dB quadrature hybrid in the feeding network, as described in the next section. Therefore, the above scheme is suitable for mobile computing networks, since the large nulls of the directional patterns of the array counter the effect of multipath more efficiently than existing implementations, while the omnidirectional pattern guarantees that the antenna is compatible with current MAC layer protocols.

4. Beam selector

Low hardware complexity is a key factor to consider for a design targeting commercial applications. Regarding the proposed array, three different feeding patterns must be produced by the feeding network, corresponding to the different radiation patterns. Table 2 summarizes the different analogue inputs of the antennas

First antenna input		Second antenna input		
Magnitude	Phase	Magnitude	Phase	Azimuth pattern
V	0°	0	0°	Omnidirectional
$V/\sqrt{2}$	90°	$V/\sqrt{2}$	0°	Directional 1
$V/\sqrt{2}$	0°	$V/\sqrt{2}$	90°	Directional 2

Table 2. Array excitation.

that produce the corresponding radiation patterns of figure 10. The overall signal power level feeding the antenna elements remains the same for all cases. The omni-directional pattern is produced when all the energy is routed to one of the elements. In this case

$$V_{\mathrm{in}_1} = V\ \mathrm{V} \qquad V_{\mathrm{in}_2} = 0\ \mathrm{V} \qquad P_{\mathrm{omni}} = \frac{V^2}{Z_{\mathrm{in}}}$$

where V_{in_1} and V_{in_2} are the input voltages to the antenna elements, and $Z_{\mathrm{in}} = 50\,\Omega$ is the input impedance of the antenna elements.

In order to produce any of the directional patterns, both array elements should be fed with analogue signals having the same power level and 90° phase difference. In this case, the output power is divided into two equal levels and

$$V_{\mathrm{in}_1} = \frac{V}{\sqrt{2}}\,\mathrm{e}^{\pm(j\pi/2)}\ \mathrm{V} \qquad V_{\mathrm{in}_2} = \frac{V}{\sqrt{2}}\ \mathrm{V} \qquad P_{\mathrm{omni}} = \frac{V^2}{Z_{\mathrm{in}}}$$

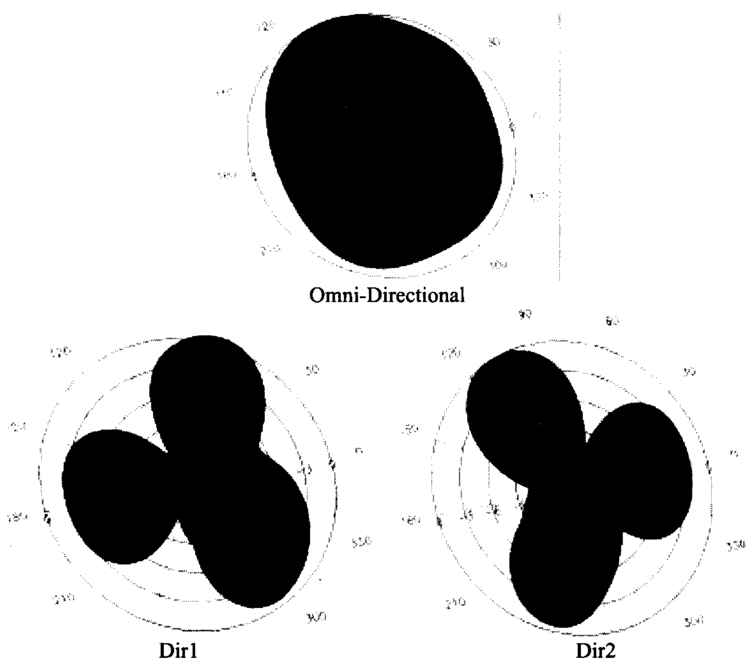

Figure 10. Radiation patterns of the proposed array.

A passive device that produces these outputs from a single input signal is the 3 dB quadrature hybrid. In order to produce all the desired radiation patterns, a feeding network is needed that could either route the RF signal to only one of the radiating elements in order to produce the omnidirectional pattern, or route the RF signal to both elements through a 3 dB quadrature hybrid in order to produce the two directional patterns. Figure 11 shows the block diagram of this feeding circuit. The circuit consists of a single-pole-triple-throw (SP3T) switch, a single-pole-double-throw (SPDT) switch and a 3 dB quadrature hybrid. The functionality of the feeding network is controlled by two digital lines that control the states of the two switches, and their logic is shown in table 3. When the SP3T switch is driven to state 3, the SPDT is driven to state 2 and all the energy of the RF signal is routed to the first element, thus producing an omnidirectional pattern. When the SP3T switch is driven to either of the other two states, the SPDT is driven to state 1 and all energy is routed through the quadrature hybrid. Therefore, the signals arriving at the antenna elements have the same power level and a phase difference of 90°, thus producing one of the two directional patterns described earlier, depending on the state of the SP3T switch.

The feeding network functionality and its integration with the proposed antenna structure were evaluated with the use of ADS (Agilent Technologies 2000), using both electromagnetic simulation and circuit analysis algorithms. Figure 12 shows the transient response of the proposed circuit when it is switched from one radiation pattern to another. Switching time between the diverse patterns is equal to the sum of the switching delays of the two switches used, since the passive 3 dB quadrature hybrid does not induce any significant delay to the signals.

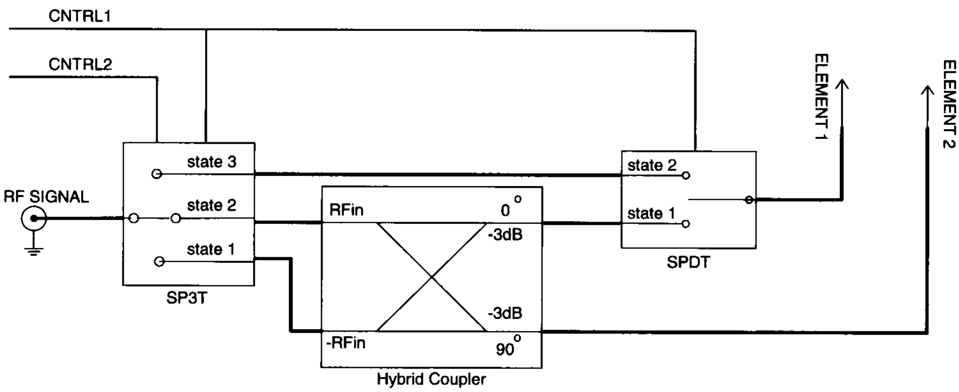

Figure 11. Feeding circuit block diagram.

CNTRL1	CNTRL2	SPDT state	SP3T state	Pattern
0	0	1	1	Directional 1
0	1	1	2	Directional 2
1	X	2	3	Omnidirectional

Table 3. Switch control logic.

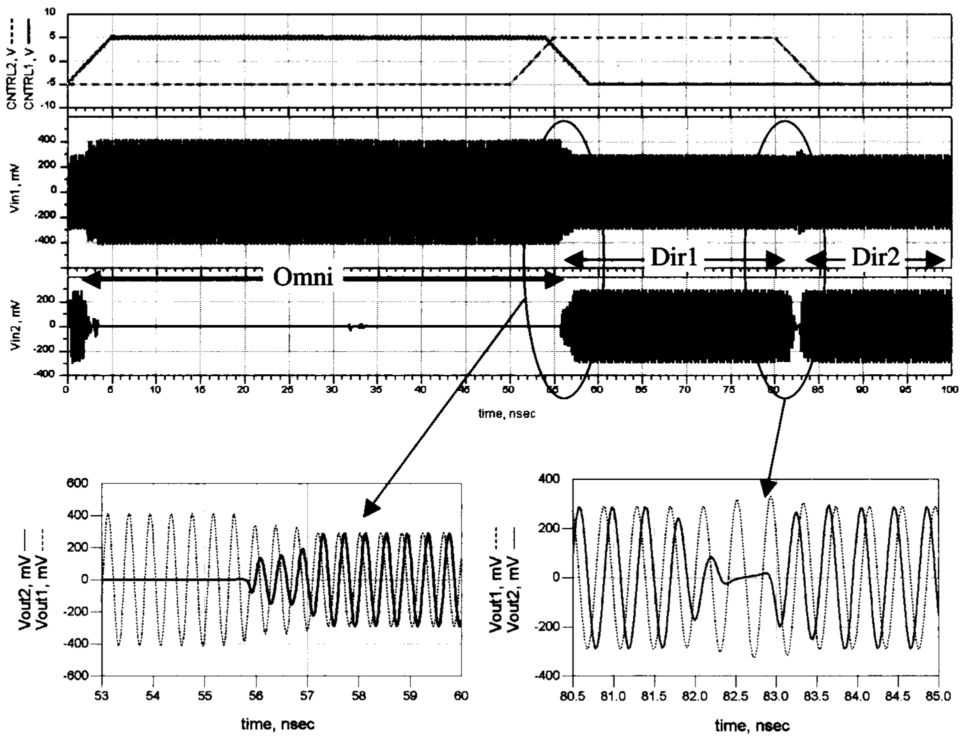

Figure 12. Feeding circuit transient response.

5. Conclusions

A dual switched antenna array operating in the 2.4 GHz ISM band was described in this paper. The array is capable of increasing the performance of a mobile computing network without affecting the wireless protocol's functionality. Unlike current mobile diversity scheme implementations, the proposed antenna introduces true angle diversity to the mobile terminals by producing directional patterns with very large nulls in the azimuth plane. Moreover, the proposed diversity scheme does not affect the functionality of the wireless protocol, since it also produces an omnidirectional pattern that the system designer can use to support the functions of existing wireless protocols. The proposed array is driven by a low-cost feeding network that is controlled only by two digital logic lines. Future work in this field will involve further study of the proposed array on a finite ground plane, on different dielectric substrates and with a larger number of elements, in order to achieve higher diversity gain for mobile and base-station computing network terminals.

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