

**TITLE**

## CONFIGURABLE NESTED PATCH ANTENNA

A patch antenna, which is also known as a rectangular microstrip antenna, comprises a flat rectangular sheet or "patch" of metal that is mounted over a larger sheet of metal called a ground plane. The two metallic surfaces of the patch antenna form a resonant piece of microstrip transmission line with a length of approximately one-half wavelength of the radio waves.

Due to fringe effects, the length of the patch is slightly shorter than one-half a wavelength of an operation frequency. This so-called "resonant length" of the patch depends on the substrate thickness and the dielectric constant of the substrate. The patch antenna radiates mainly in a direction perpendicular to the plane of the patch. A typical opening angle of the radiated beam would encompass about 65 degrees. Radiation toward the back of the substrate is suppressed by shielding effects of the ground plane layer.

A common type of patch antenna is formed out on a dielectric substrate, using the same materials and lithography processes that are used to make printed circuit boards.

Patch antennas are also suitable for use in reconfigurable antennas.

Reconfigurable antennas have the ability to change their behaviour to adapt with changing system requirements or environmental conditions. The behaviour could include the frequency response, radiation pattern, polarization or a combi-

nation of these. This adaptability eliminates restrictions imposed by antennas with fixed characteristics and on the system functionality. A typical scenario for instance is a Software Defined Radio (SDR) system. The essence of SDR / Cognitive Radio is to adapt the communication parameters depending on the dynamic spectrum availability and the wireless channel characteristics.

To achieve efficient performance for an SDR system, an antenna which can adapt its radiation characteristics is essential. Additionally, with growing demand for system miniaturization, it is often desired to achieve the functionality of two or more antennas with one reconfigurable antenna having lower real estate requirement of space. This is not only desired in handheld electronic system miniaturization, but has even greater implications in defence electronics. For instance, in a UAV the available space for mounting antennas is limited due to aerodynamic constraints imposed on the mechanical design. The greater the number of antennas, greater the chances of higher radar cross section which is not desired in defence applications.

It is furthermore desirable to reduce the number of antennas by designing multi-function antennas which can accomplish the functionality of more than one antenna. Reconfigurable antennas are a class of multi-functional antennas where the functionality can be changed dynamically as necessary. Though traditional multi-band and wide-band antennas are key contenders, well-designed reconfigurable antennas may provide other advantages for improved system performance in terms of improved filtering of interfering signals, ability to adapt pattern as necessary and in some cases even vary the polarization of the antenna.

In Xue Xia Yang et al., "A Polarization Reconfigurable Patch Antenna With Loop Slots on the Ground Plane," IEEE Antenna and Wireless Propagation Letters, Vol 11, 2012, a polarization reconfigurable antenna is disclosed. The circularly polarized waves are excited by perturbing loop slots on the ground planes. The slots on the ground plane are located underneath the corner edge of the radiating patch where the electric field is a maximum. Perturbing the slots is achieved by switching elements located on the ground plane. This configuration only allows reconfigurability in terms of polarization and does not offer frequency reconfigurability for a single patch. Furthermore it lacks the adaptability to switch nested patch antennas.

In Tekin Ibrahim, "Reconfigurable dual band microstrip patch antenna for Software Defined Radio applications," IEEE International conference on Wireless Information Technology and Systems (ICWITS), Aug. 28 2010-Sept. 2010, a nested patch antenna is disclosed with DC biasing using quarter wavelength stubs at 2400 MHz. This antenna resonates at 2400 MHz and 5600 MHz. Although using quarter wavelength stubs is effective at high frequencies, they are not feasible to be used for low frequencies such as GSM 900MHz. At low frequencies the stubs would be extremely long making the antenna profile very large.

A nested patch antenna is presented in Iddagoda, Mavidu, "Reconfigurable Antennas for GSM and WLAN Applications", MSc Dissertation report, Nanyang Technological University, Singapore, 2013,. Two patches are nested in a single antenna that operates at GSM (900 MHz) and WLAN(2400 MHz). The feed is realized using a probe feed with a proper feed location identi-

fied based on good impedance match requirements for each of the individual patches.

#### **BRIEF DESCRIPTION OF THE SEVERAL VIEWS OF THE DRAWINGS**

- Figure 1 shows a nested patch antenna with an inner patch and an outer patch,
- Figure 2 shows a side view of the nested patch antenna of Fig. 1,
- Figure 3 shows a cross section through the nested patch antenna of Fig. 1,
- Figure 4 shows a partial cross section through the nested patch antenna of Fig. 1 comprising a feed line,
- Figure 5 shows an enlarged portion of Fig. 4,
- Figure 6 shows a cross section of a connection of a shorting via to a rectangular DC bias pad of the nested patch antenna,
- Figure 7 shows a three dimensional view of shorting via and its connection to the bias pad,
- Figure 8 shows a comparison of reflection coefficients for the nested patch antenna in a GSM mode for two DC bias lines, for the WLAN via connected to the ground plane and for the WLAN via shorted to a bias pad,
- Figure 9 shows a comparison of reflection coefficients for the nested patch antenna in a WLAN mode for the same bias connection designs as in Fig. 16,
- Figure 10 shows a nested patch antenna with three patches,
- Figure 11 shows a reflection coefficient for a GSM mode of a nested patch antenna in which the inner patch is connected to a DC bias pad,

Figure 12 shows a coupling to a mid-point DC bias line for a nested patch antenna in a GSM mode in which no DC bias pad is connected to the inner patch,

Figure 13 shows a reflection coefficient for a GSM mode of a nested patch antenna,

Figure 14 shows a reflection coefficient for a WLAN mode of a nested patch antenna,

Figure 15 shows a comparison of reflection coefficients for nested patch antennas in GSM mode,

Figure 16 shows a comparison of reflection coefficients for nested patch antennas in WLAN mode,

Figure 17 shows a method of designing a nested patch antenna according to the specification,

Figure 18 shows reflection coefficients for four different positions of a bias line for the outer patch,

Figure 19 shows coupling coefficients  $S_{21}$  for a coupling to the bias line of Fig. 16 and for the bias line positions of Fig. 18,

Figure 20 shows a total efficiency for the nested antenna in a GSM mode and in a WLAN mode as a function of frequency,

Figure 21 shows radiation patterns in the E-plane of the nested patch antenna for 900 MHz and 2.4 GHz, respectively,

Figure 22 shows radiation patterns in the H-plane of the nested patch antenna for 900 MHz and 2.4 GHz, respectively,

Figure 23 shows a portion of an outer shell of an unpiloted aerial vehicle in which a configurable patch antenna according to the specification is integrated,

Figure 24 shows an array of nested patch antennas which can be activated selectively, and

Figure 25 illustrates dimensions of a nested patch antenna.

In the following description, details are provided to describe the embodiments of the specification. It shall be apparent to one skilled in the art, however, that the embodiments may be practised without such details.

According to the current specification, a novel design of DC bias lines is presented for nested patch antennas. The realization and performance are demonstrated using a patch antenna of the abovementioned reference Iddagoda, Mavidu, "Reconfigurable Antennas for GSM and WLAN Applications", as an example. The switching elements are placed in the slot between the nested patches at optimal locations. These switching elements could in general be either PIN diodes, RF-MEMs, FETs, varactors etc. Regardless of the switching element used, DC biasing is necessary to switch the elements to different states. For the nested patch configuration, a novel DC biasing circuit with DC connections to both the inner and outer patches while having minimal effects on the RF performance of the patches is presented. The DC bias network has been designed in a systematic approach as follows.

Fig. 1 shows a nested patch antenna 10 according to the present specification. The nested patch antenna 10 comprises a quadratic inner patch 11, also referred to as WLAN patch 11, and a quadratic outer patch 12, also referred to as GSM patch 12, which are provided on a double layer printed circuit board (PCB) 13.

The symmetry of the inner patch 11 is indicated through a first and a second dash dot line which are drawn through the centre of the inner patch 11 and the mid points of opposite edges of the inner patch 11. This symmetry is used as a basis

for a coordinate system with coordinates  $x$ ,  $y$ ,  $z$ , which is centred at the centre point 24 of the inner patch, which is indicated next to Figures 1 to 4. An angle  $\theta$  is used to indicate an orientation relative to the  $z$ -axis. This angle is used in the E-plane and the H-plane diagrams of Fig. 21 and 22.

Fig. 2 shows a cross section through the nested patch antenna 10 of Fig. 1.

The inner patch 11 and the outer patch 12 are separated via a slot 14 between an outer boundary 15 of the inner patch 11 and an inner boundary 16 of the outer patch 12.

The inner patch 11 and the outer patch 12 are connected via shorting pins 17, 18, 19, 20, 21, 22, which are provided in the slot 14 between the inner patch 11 and the outer patch 12. The shorting pins 17 - 22 are provided as switching elements 17 - 22, such as pin diodes or RF-MEMS.

A resistance to electric current of the shorting pins 17 - 22 depends on a direct current (DC) bias between the inner patch 11 and the outer patch 12. According to a first alternative, the switching elements are normally closed and are opened by applying a bias voltage to terminals of the switching element. Thereby, the terminals of the switching elements are connected. According to a second alternative, the switching elements are normally open and are closed by applying a bias voltage to terminals of the switching elements. Thereby, the terminals of the switching elements are disconnected. According to a third alternative, a forward bias is applied to open the switching elements and a reverse bias is applied to close the switching elements.

In particular, the inner patch 11 can be used as a WLAN patch 11 for transmitting and receiving WLAN signals and the outer patch 12 can be used as a GSM patch 12 for transmitting and receiving GSM signals. The frequency of GSM signals is typically around 900 MHz, for example for the GSM 900 band, but can also be around 380 MHz (GSM 400) to around 1.9 GHz (GSM 1900). The frequency of WLAN according to the various IEEE 802.11 standards may be around 2.4 or around 5 GHz, for example. For the use of the nested antenna as WLAN and GSM patch, a typical dimension of the inner patch is in the range of 3.5 cm x 3.5 cm and a typical dimension of the outer patch is in the range of 10 cm x 10 cm.

A first DC bias line 23 is connected to a first via 26 through the PCB 13. The first via 26 is connected to the inner patch 11 at a mid-point 24 of an edge of the inner patch 11. A second DC bias line 25 is connected to a second via 27 through the PCB 13. The second via 27 is connected to the outer patch 12 at a mid-point 28 of an outer edge of the outer patch 12. The bias lines are connected to respective bias voltage sources which are not shown in Figs. 1 and 2.

According to one embodiment of the application, a via may be provided for the bias line of the outer (GSM) patch 12.

By contrast, the methodology of drawing a DC bias line using a via as in the GSM patch case is not feasible for the WLAN patch in the nested antenna. If the same methodology is adopted in the nested antenna case for the WLAN patch, there will be significant RF energy in the GSM band coupling to the DC bias line connected to the WLAN patch. To illustrate this,

the configuration with both DC bias lines realized using vias is simulated.

While observing the reflection coefficient, it is noticed that the return loss is lower for both the GSM and WLAN cases. However, looking at the coupling to the DC bias lines, it is realized that the low return loss in the GSM case is not due to radiation but due to strong coupling to the DC bias line connected to the WLAN patch. To better evaluate the design as to whether the low return loss is due to radiation or due to coupling to the DC bias lines, the radiation efficiency metric is defined as given in equation (1)

$$Q_R = 1 - |S_{11}|^2 - |S_{21}|^2 - |S_{31}|^2 \quad (1)$$

Where in  $S_{11}$ ,  $S_{21}$  and  $S_{31}$  are components of a 3x3 scattering parameter matrix which are defined as

$S_{11}$ : reflection coefficient

$S_{21}$ : coupling to the bias line connected to the outer (GSM) patch 12

$S_{31}$ : coupling to the bias line connected to the inner (WLAN) patch 11.

Since in the simulations, only lossless substrates and perfect electrical conductors are considered, so there is no power loss due to dissipation. The radiation efficiency in (1) indicates the amount of net power radiated by the antenna excluding the reflected power and the power coupled to the DC bias lines. A well designed DC bias line will have minimum coupling with RF and hence at the frequencies with good impedance match, the radiation efficiency is high.

All simulation results were obtained using a commercially available 3D EM simulation software, CST-MWS (<http://www.cst.com/>).

The suitable location for a DC bias line is determined by evaluation of a radiation efficiency metric  $Q_R$  with only 2 ports (RF and 1 DC bias line port connected to the outer patch) when the reconfigurable nested patch antenna is in the GSM mode of operation and in the WLAN mode of operation, respectively.

Due to the non-alignment of the centres of the outer patch 12 and the inner patch 11, further optimization to move the inner patch 11 with respect to the outer patch 12 while maintaining the shorting pin at the centre 24 of the inner patch 11 is necessary for improved impedance matching and higher radiation efficiency when the nested patch antenna is in the GSM mode of operation. This method of DC biasing is suitable for two nested patches, but it is less suitable for more than two nested patches.

A first end of a feed line 29 is connected to a feed point 30, which is located at a distance  $d$  from the centre of the inner patch 11. A second end of the feed line 29 is connected to a centre conductor 31 of a coaxial cable 32.

The centre of the inner patch 11 is offset with respect to the centre of the outer patch 12 by a centre offset. The offset is directed away from the x-direction of Fig. 1. Likewise, the location of the feed point 30 of the inner patch 11 is offset opposite to the x-direction by a distance  $d$ . A direction of an electrical field of the nested patch antenna 10 is indicated in Fig. 1 by a double arrow 9.

Fig. 2 shows a side view of the PCB 13 with the patches 11 and 12 in which vias 26, 27, 29 and the slot 14 are indicated by dotted lines. The PCB 13 comprises an upper copper layer 33 and insulating layer 34 and a lower copper layer 35.

The inner patch 11 and the outer patch 12 are formed out on the upper copper layer. In the embodiment of Fig. 1 and 2, the upper copper layer 33 is only comprises the inner patch 11 and the outer patch 12 but in other embodiments it may also comprise further regions on the insulating layer 34.

Fig. 3 shows a cross section of Fig. 1 along the line A-A in which the connection of the bias line 23 to the centre point 24 of the inner patch 11 is shown.

Fig. 4 shows a cross section of Fig. 1 in which the connection of the inner patch to the feed line 29 is shown. An outer conductor of the coaxial cable 32 is soldered to the ground plane 35 while an inner conductor of the coaxial cable is connected at location 30 a distance  $d_{\text{GSM}}$  from the centre of the outer patch 12. This location is equivalent to a distance  $d_{\text{WLAN}}$  from the centre of the inner patch 24. The outer conductor and the inner conductor of the coaxial cable are separated by an inner insulating layer of the coaxial cable in a known way.

In a further embodiment, a feed is provided by a microstrip transmission line instead of a coaxial cable. Other designs for providing a feed to a patch antenna, which may also be used in a nested patch antenna according to the present specification, include an aperture-coupled feed and a proximity-

coupled feed In yet a further embodiment, more than one feed is provided, for example to achieve a circular polarization.

Fig. 5 shows an enlarged portion of Fig. 4. The coaxial cable 32 comprises a centre conductor 29, which is often made of a copper wire, a plastic insulation layer 36 and a woven copper layer 37. The woven copper layer 37 is soldered to the ground plane 35 via solder joints 38.

According to one embodiment of the present specification, the ground plane 35 is used as part of the DC biasing circuitry. In this embodiment, the inner patch 11 is shorted to the ground plane 35 through a shorting pin placed at a suitable location.

For more than two nested patches, an arrangement similar to Fig. 7 is more appropriate, in which biasing vias of the outer patches are connected to bias pads of the ground plane 35.

According to further embodiment of the present specification, which is illustrated in Figs. 6 and 7, the outer patch 12 is connected to a bias pad 42 of the ground plane 35.

According to the present specification, a novel method is proposed in order to allow multiple patches (more than two) in the nested configuration, which is illustrated by Figs. 6 and 7. The via of the inner (GSM) patch is shorted to the ground, and a square slot is cut around the WLAN via to provide electrical isolation between the two shorting pins. Cutting of this slot creates a small pad onto which the WLAN shorting pin is connected. With this configuration, biasing is achieved by the potential difference between the pad and the ground plane.

Figure 7 illustrates the concept of creating a pad. The pad should not be too large as otherwise the currents on the ground plane would be affected. Furthermore, since the slot for the pad is located at the centre of the patch where the electric field is weak, the effect on the RF performance of WLAN patch is minimal.

Fig. 6 shows a connection from the outer patch 12 to the rectangular DC bias pad 42 of the ground plane 35 through a shorting via 27. The rectangular DC bias pad 42 is separated from the remainder of the ground plane 35 by a slot 46.

Fig. 7 shows a three dimensional view of the ground plane 35, the DC bias pad 39 and the via 27 of Fig. 6.

According to the embodiment of Figs. 6 and 7, the via 27 of the outer patch 12 is shorted to the ground plane 35, and a square slot 46 is cut around the end point of the via 27 of the outer patch 12 to provide electrical isolation between the two shorting pins 26, 27. The square slot 46 surrounds a small bias pad 42 onto which the shorting pin 27 of the outer patch 12 is connected. With this configuration, biasing is achieved by applying a potential difference between the bias pad 42 and the ground plane 35.

According to a further embodiment of the nested patch antenna, the via 28 of the inner patch 11 is connected to a second bias pad 39, which is cut out of the ground plane 35 in a similar manner as the bias pad 42 of the outer patch 12.

The bias pads 39 and 42 of Fig. 6 and 7 are made sufficiently small such that there is little or no influence on the ground plane currents and they are physically realizable.

The slot 40 for the bias pad 39 of the inner patch 11 is located close to the centre of the inner patch 11 where the electric field is weak. Thereby, the effect on the RF performance of the inner patch 11 is small.

Using shorting pins with pads on the ground plane, as shown in Figs. 6 and 7, paves the way for the design of DC bias circuitry for multiple nested patch antennas, as shown in Fig. 10, for an example. According to this design, each of the nested patches is to be shorted to a pad on the ground plane through a shorting pin and operation of the intended frequency band of radiation is achieved by applying suitable potential difference between the shorting pad of the innermost patch 11, which is the patch to which the RF feed is connected, and shorting pads of all the subsequent patches needed for the antenna to operate in the particular band of interest.

In the Figs. 8, 9 and 11 to 22, simulated antenna properties are shown. For the simulations, the switching elements are modelled as ideal switches. When a diode is used instead of an ideal switch, a shift in frequency can be observed in the reversed biased state that is caused by a reactive loading effect. This occurs because the diode, in reversed biased state, exhibits a parasitic reactance whereas in the forward biased state the diode primarily exhibits a resistance. A resistance in forward bias and a capacitance in reversed bias state represent an equivalent model for a diode. The shift in resonance frequency depends on the magnitude of the parasitic

capacitance. Hence, a diode with very low parasitic capacitance is preferable (typically less than 0.1 pF). The forward bias resistance lowers the amount of radiated power. Hence, a diode with low forward bias resistance is preferred.

Furthermore, only lossless substrates and perfect electrical conductors are considered. Therefore, the simulated model does not include power loss due to dissipation. The substrate between the conducting layer was chosen as a Roger RT 5880 substrate, which has a dielectric constant  $\epsilon$  of 2.20  $\pm$  0.02 and a substrate thickness of 8 mm. A high substrate thickness was used to improve frequency bandwidth.

In summary, the following dimensions were used for the simulations:

1. Patch dimensions
  - a. GSM square patch: 105 mm
  - b. WLAN square patch: 35 mm
2. Distances:
  - a.  $d_{\text{GSM}}$ : 19 mm
  - b.  $d_{\text{WLAN}}$ : 15 mm
3. Thickness of substrate: 8 mm
4. Thickness of upper layer (thickness of patches): 0.05 mm
5. Thickness of ground layer: 0.05 mm
6. Extension of the slot: 2 mm
7. Distance of the diodes from the inner edge of the slot
  - a. on the side of the feed and opposite to it: 17.5 mm  
on the sides which are parallel to the distance between the feed and the inner patch centre:
  - b. 11.66 mm for the diodes 18 and 20 that are further away from the feed
  - c. 11.66 mm for the diodes 17 and 21 which are nearer to the feed
8. Diameter of the bias line vias: 1mm

These dimensions are illustrated in Fig. 25.

Figure 8 and Figure 9 show the reflection coefficient performance for GSM band and WLAN band respectively for the bias pad configuration compared with the structure having two DC bias lines and with the WLAN via shorted to the ground.

Figs. 8 and 9 show a reflection coefficient for GSM band and WLAN band respectively for

- the bias pad configuration with separate bias pads connected to the inner patch 11 and to the outer patch 12, for
- a structure having two DC bias lines and for
- a structure having a bias line for the outer patch 12 and the via of the inner pad 11 shorted to the ground plane.

Herein, the reflection coefficient is shown in decibel as a function of frequency.

A comparison of the reflection coefficients of Figs. 8 and 9 shows that creating a slot for the pad on the ground plane 35 does not affect the performance significantly for the respective frequency bands at 900 MHz and at 2.4 GHz. In particular, it can be seen in Fig. 8 that the relevant minima 50, 51, 52 for the GSM mode are almost congruent.

Generally, it is not desirable to have low reflectivity outside the frequency range of interest. Then, higher oscillation modes, such as the resonances 56, 57 of Fig. 8 will contribute to the emission of the antenna.

For the GSM mode of Fig. 8, there is a minimum below 500 MHz for the case with the ground shorted WLAN bias line due to the length of the bias line. For the configuration with the

WLAN bias line that is shorted to a DC bias pad, there is a minimum above 1.5 GHz which is more pronounced than for the ground-shortened via and for the configuration with two DC bias lines. On the other hand, the high frequency reflectivity minima above 2.5 GHz are much smaller for the WLAN via that is shorted to a bias pad than for the other two configurations.

For the WLAN mode shown in Fig. 9 there is only little reflectivity difference for the last two configurations. Hence, shorting the WLAN bias line to ground or to a bias pad makes only little difference in terms of reflectivity as far as the WLAN mode is concerned.

It is noted that creating a slot for the pad on the ground plane does not degrade the performance for both of the frequency bands. The concept of etching out slots on ground plane, creating pads for the shorting pins to reach the inner patch 11 allows to design multiple patches in a nested configuration. To demonstrate this, similar to the WLAN case, a pad is created for the shorting pin connected to the GSM shorting pin. This isolates the ground plane from the DC current entirely and weakly perturbing the RF currents on the ground plane. Biasing is achieved by the potential difference applied across the two pads. The final design is shown in Figure 1.

The DC bias vias are shorted to the DC pads created on the ground. Hence, the potential differences are to be applied between these DC pads as needed for proper biasing of switches.

Fig. 10 shows a nested patch antenna 10' with three patches 11, 12, 41. The nested patch antenna 10' of Fig. 10 illus-

trates a conceptual nested patch antenna with three patches to demonstrate the scalability in design of the proposed DC bias circuit. Similar to the nested patch antenna of Fig. 1, the patches 11, 12, 41 are separated by slots 14, 43, which are bridged by switching elements.

In the embodiment of Fig. 10, the switching elements are provided by diodes. Four diodes are provided along the x-direction, wherein two diodes are provided at opposite edges of the inner patch 11 and two diodes are provided at opposite edges of the intermediate patch 12. Six diodes are placed along the y direction and symmetrically to the mid-points of the patch edges. Therein, two groups of two diodes are provided at opposite edges of the inner patch 11 and two other groups of two diodes are provided at opposite edges of the intermediate patch 12.

Similar to the case for the two-patch nested patch antenna, a distance between the switching elements along the slot is chosen such that it does not correspond to half of a predetermined wavelength that corresponds to a wavelength of the inner patch, thereby avoiding the creation of a resonant cavity.

The nested patch antenna of Fig. 10 comprises an outer patch 41 that surrounds an intermediate patch 12 and an inner patch 11. The inner patch 11 is connected to a first DC bias pad 39 through a via 26, the intermediate patch 11 is connected to a second DC bias pad 42 through a via 27 and the outer patch 41 is connected to a third DC bias pad 44 through a via 45. Similar to the first bias pad 39, the second bias pad is isolated against the remainder of the ground plane 35 by a slot 46

and the third bias pad 44 is isolated against the remainder of the ground plane 35 by a slot 47.

The first bias pad 39 and the second bias pad 42 are connected over a first controllable voltage source 48. Likewise, the second bias pad 42 and the third bias pad 44 are connected over a second controllable voltage source 49.

The DC bias pads can be manufactured by etching out a rectangular slot from the ground surface 35. The design principle of Fig. 4 can also be used to produce nested patch antennas with more than three nested patches, wherein the patches are connected to bias voltage source.

Fig. 11 and 12 show antenna parameters for a nested patch antenna in which a DC bias line with a bias pad is connected to the mid-point of an outer edge of the outer patch 11, but in which the inner patch is not connected to a bias line.

Fig. 11 shows a simulated reflection coefficient  $S_{11}$  in dB (decibel) as a function of the frequency of an input signal in GHz for a nested patch antenna in a GSM mode, which has a GSM mid-point DC bias line.

$S_{11}$  refers to the component  $S_{11}$  of the scattering matrix, also known as S-parameter matrix. In the GSM mode, a bias is applied such that the inner patch 11 and the outer patch 12 are connected. The inner patch 11 of the nested patch antenna 10 that was used for the measurement of Fig. 7 is connected to a DC bias pad of the ground surface while the outer patch is not.

It is desirable to have a low reflectivity in a frequency band of interest in order to maximize the radiation efficiency in this frequency band. A low reflectivity shows up as a large negative value in the decibel scale of  $S_{11}$ . Under the conditions of Fig. 9, there is a first reflectivity minimum 93 with low reflectivity slightly below 1 GHz, a second reflectivity minimum 94 slightly below 2 GHz, a third reflectivity minimum 95 above 2 GHz and a fourth reflectivity minimum 96 slightly above 2.5 GHz.

Fig. 12 shows a coupling to a mid-point DC bias line for a nested patch antenna in a GSM mode. The coupling can be defined as the component  $S_{21}$  of a 3x3 S-parameter matrix, wherein  $S_{11}$  is the reflection coefficient,  $S_{21}$  is the coupling to the bias line connected to the outer (GSM) patch 12 and  $S_{31}$  is the coupling to the bias line connected to the inner (WLAN) patch 11. When the modulus of  $S_{21}$  is small, the radiation efficiency is increased.

A first coupling minimum 97 can be observed at around 0.9 GHz and a second coupling minimum at 2 GHz. The coupling minimum at 0.9 MHz coincides with the reflectivity minimum of Fig. 11. Thereby, in the GSM mode little energy is lost to reflection as well as to coupling into the GSM midpoint bias line in the immediate vicinity of the GSM frequency of 900 MHz. However, coupling is relevant outside the coupling minima. Further coupling minima can be found at 1.7 GHz and slightly above 2 GHz.

Fig 13 shows a simulated reflection coefficient  $S_{11}$  in dB (decibel) as a function of the frequency of an input signal in GHz for a GSM mode of a nested patch antenna in which, in

addition to the GSM bias line, a WLAN bias line is shorted to a DC bias pad.

A first reflectivity minimum 98 is observed around 0.9 GHz, a second reflectivity minimum 99 is observed around 1.7 GHz and a third reflectivity minimum 100 is observed slightly above 2 GHz. Other reflectivity minima are much less pronounced. Most valuable for the GSM mode is the minimum around 0.9 GHz, which is also the most pronounced.

These minima are similar to the minima of Fig. 11, but they are less pronounced, as can also be seen from the dB range. Another minimum above 2.5 GHz, which is present in Fig. 11, is only very weakly developed in Fig. 13. It can be seen that the minimum at 900 MHz is only slightly less pronounced than for Fig. 11. The GSM performance is hence only slightly affected with respect to the reflectivity by placing a bias connection on the inner (WLAN) patch 11.

Fig. 14 shows a simulated reflection coefficient  $S_{11}$  in dB (decibel) as a function of the frequency of an input signal in GHz for the nested patch antenna of Fig. 13 in a WLAN mode. In the WLAN mode, the bias is applied such that the inner patch 11 and the outer patch 12 are disconnected.

A first reflectivity dip 100 is observed 0.3 GHz and a second dip 101 at around 0.8 GHz. A first reflectivity minimum 102 is observed below 2.5 GHz and a second minimum at about 2.7 GHz, more pronounced minimum 103. These minima transition into each other, allowing a broadband operation in the WLAN mode.

The effect of connecting a GSM bias pad to the outer pad 12 on the reflectivity is further investigated in Fig. 15, while the effect of connecting a WLAN bias pad to the inner patch 11 is further investigated in Fig. 16. The reflectivity curves of Fig. 15 refer to the GSM mode while the reflectivity curves of Fig. 16 refer to the WLAN mode.

For the comparisons of Fig. 15 and Fig. 16, the straight line curves indicate performance for GSM and WLAN bands for the nested patch antenna without any DC bias lines, and the broken lines indicate the same for the nested patch antenna complete with the proposed DC bias pads.

From Figure 15 it can be seen that the GSM performance is very much preserved. In particular, the reflectivity minima 104, 105 at 900 MHz almost coincide for both configurations.

Further, the higher order modes, which would potentially interfere with the WLAN band while the configurable antenna is in a GSM mode, are suppressed. In particular, the minimum 106 at about 1.8 GHz is strongly suppressed and shifted to lower frequencies to a minimum 107, the minimum 108 is suppressed by about 5 dB, and the double minimum 110 is strongly suppressed and appears as minimum 112 in the configuration without DC bias pads.

For the WLAN mode it can be seen that the impedance matching of the WLAN band degrades slightly in that the reflectivity minimum 113 below 2.5 GHz is slightly less pronounced and shifted to a higher frequency minimum 114. However, the minimum 116 develops into a more pronounced second minimum 115 above 2.5 GHz. Thereby, a more pronounced double resonance is

formed, which has a potential to be utilized as a wide band in WLAN mode.

Further low frequency minima 117, 118 are found between 0.5 and 1 GHz and further high frequency minima 119, 120 are found below 2 GHz, wherein the minimum 120 of the configuration with bias pads is suppressed as compared to the minimum 119 of the configuration without bias pads.

Low frequency resonances, which could interfere with GSM mode are very small. This is mainly due to the disconnection of the outer patch, which interacts only weakly with the inner patch due to coupling across the slot between the inner patch 11 and the outer patch 12.

According to a further aspect, the present application discloses a method of designing a nested patch antenna with an inner patch and an outer rectangular patch. Therein, the inner patch has a higher resonance frequency than the outer patch. In one embodiment, the inner patch is a WLAN patch and the outer patch is a GSM patch.

The design method takes into account design considerations for the nested patch which, among others, comprise

- a. placement of the smaller patch 11 (WLAN)
- b. a common feed location 30 for both patches 11, 12
- c. choice of a slot width for the slot 14 isolating the inner patch 11 (WLAN) against the outer patch 12 (GSM)
- d. choice of a strategy for placing shorting pins 17 - 22 between the inner patch 11 (WLAN) and the outer patch 12 (GSM)

Taking the first two design considerations in to account, the WLAN patch was nested within the GSM patch such that the probe feed location for both the patches coincides. Furthermore this common location is the same location for both the patches which was determined separately each of the single patches.

This way of nesting ensures that

- a. the feed location of WLAN is optimum for its operation
- b. the feed location of GSM is optimum for its operation
- c. the feeding is achieved using only one feed point

The resulting structure is shown in Figure 1. Without any shorting pins in the slot, the antenna would operate in the WLAN frequency. It is essential to determine a proper slot width such that, it would ensure sufficient isolation between the WLAN and GSM patches. A large slot width provides high isolation (less parasitic coupling) to the GSM patch. However, it is infeasible to arbitrarily keep increasing the slot width, since when the antenna structure operates in GSM mode, a lower surface area of the GSM patch would result in a reduced radiation efficiency. Using simulations, a proper slot width is found which would be a trade-off between the amount of parasitic coupling tolerable and sufficient patch area for the GSM patch.

In order for the antenna to work in GSM mode, the shorting pins, eventually realized using switching elements such as pin diodes or RF-MEMs need to be placed in the slot between the nested patch. It is important that the locations of shorting pins are chosen properly to ensure a good coupling between the two patches. It was done so, by considering the current distribution around the slot and WLAN patch. The num-

ber and location of the shorting pins is chosen to avoid any additional slot resonances over the patch resonance within the interest frequency bands of operation. Guidelines for the locations of the shorting pin can be obtained from the current distributions induced in the nested patch.

A design method according to the present specification is shown in Fig. 17.

In a first step 61, centre frequencies are chosen for a frequency band of the outer patch 12 and for a frequency band of the inner patch 11. In a second step 62, a parameter sweep is performed for the distances  $d_{\text{GSM}}$ ,  $d_{\text{WLAN}}$  of a feed location on the respective patches from the edges of the respective patches. In a third step 63, the distances  $d_{\text{GSM}}$  and  $d_{\text{WLAN}}$  are chosen such that an impedance match is within a predetermined interval around a maximum impedance match for the respective patches.

In a fourth step 64, a relative location of the patches is determined such that the feed locations of the inner patch 11 and the outer patch 12 essentially coincide. In a fifth step 65, a parameter sweep is performed for a slot width  $d$  between the inner patch and the outer patch. The slot is cut around the edge of the inner patch. In a sixth step 66, a slot width  $d$  is chosen such that a parasitic coupling between the inner patch and the outer patch is low enough so that the parasitic coupling from the WLAN patch to the GSM patch does not interfere with GSM band.

The abovementioned method can also be applied for the design of a nested patch antenna with more than two nested patches. For example for three nested patches 11, 12, 41, the distanc-

es of a feed point 30 to the patch centre 24 are determined separately for each of the three patches 11, 12, 41 and the three patches 11, 12, 41 are aligned such that the feed points 30 coincide.

Figs. 18 and 19 illustrate the effect of placing a bias via of the outer patch 12 at the mid-point of the outer pads' 12 edge.

According to the cavity model for patch antennas, the ground modes of resonance  $TM_{010}$ ,  $TM_{001}$  for a rectangular patch antenna have a minimum of the electric field at a mid-point of those edges that are oriented in the oscillation direction of the electric field. Due to the placement of the feed point, the oscillation direction is mainly along the connection line between the centre point 24 of the inner patch and the feed point 30.

For these reasons, the bias via of the outer patch 12 is placed at the mid-point of one of the two outer edges of the outer patch 12, which are oriented in the oscillation direction of the electric field in order to reduce RF coupling into the bias wire. Higher oscillation modes, which do not have a minimum of the electric field at the edge mid-points, could occur in principle but they can be suppressed by placing a bias via of the inner patch at the centre of the inner patch 11.

In particular, for a rectangular patch antenna, the frequency of the ground mode is a function of the patch side length and can be approximated by the expression

$$f_r = \frac{1}{2L\sqrt{\mu\epsilon}} = \frac{v_0}{2L\sqrt{\epsilon_r}}$$

L stands for the length of the longer edge,  $v_0$  for the velocity of light in vacuum, and  $\epsilon_r$  for the dielectric constant of the substrate. The last expression holds for  $\mu_r$  close to 1. For  $\epsilon_r = 2$ , the side length L depends on the frequency as

$$L = \frac{299,792,458 \frac{m}{s}}{2\sqrt{2}} \frac{1}{f_r} \approx 105,992,640 \frac{1}{f_r}$$

which yields for 900 MHz a length L of  $105,992,640 / 900 * 10^{-6} = 0.118$  m and for 2.4 GHz a length L of  $105,992,640 / 2.4 * 10^{-9} = 0.044$  m. This is in agreement with the specified lengths of 10 cm and 3.5 cm for a substrate with  $\epsilon_r = 2.2$ .

Although the abovementioned formula provides an approximate patch size, fine tuning of the patch dimensions by means of simulations is needed to adjust the patch dimension to resonate at desired frequencies.

Figure 18 and Figure 19 show the reflection coefficient  $S_{11}$  and the coupling  $S_{21}$  to the GSM via, respectively, for different locations A, B, C, D of placing the GSM via pin. These locations are indicated in the inset of Fig. 18.

Fig. 18 shows simulated reflection coefficients for four different positions of a bias line for the outer patch. The inset of Fig. 18 shows three different locations for a bias line of the outer (GSM) patch 12.

The bias line, which is indicated in the inset of Fig. 18, is drawn from the outer (GSM) patch 12 through a via from the upper layer 33 to the substrate below the ground plane 35, as can be seen in more detail in Fig. 2, for example.

The reflection coefficient of Fig. 18 is simulated in a GSM mode in order to simulate the effect of placing the GSM bias line at different locations. In the GSM mode, the minimum at 900 MHz is most important. It can be observed that the minimum 119 at 900 MHz is most pronounced when the bias line is placed at the midpoint of the edge of the outer (GSM) patch 12 along the y-direction. The low reflectivity at 900 MHz in Fig. 18 means that less energy is lost by back reflection into the feed line.

For all four positions A, B, C, D of the GSM bias line, further minima of the reflectivity can be observed, which include a minimum 120 at 1.8 GHz, a minimum 121 slightly above 2 GHz and a minimum 122 slightly above 2.5 GHz, but the minimum above 2 GHz is only noticeable at position C. The minimum 120 at 1.8 GHz and the minimum 121 slightly above 2 GHz are most pronounced for position C. By contrast, the reflectivity minimum 122 above 2.5 GHz is most pronounced for position B and similarly pronounced for position A and D but less pronounced for position C.

The electric field at the mid-point of a patch along the oscillation direction of the electric field is a minimum. This midpoint corresponds to location C shown in Fig. 18. From the reflection coefficients observed in Fig. 18 for GSM mode of operation, it could be seen that the performance in GSM mode of operation is best when the via is location C. This is further demonstrated by the minima occurring in coupling of the

RF power to the DC bias line at 900 MHz as shown in Fig. 19. Therefore, location C was chosen for the design of Fig. 1.

Fig. 19 shows simulated coupling coefficients  $S_{21}$  for a coupling to the bias line of Fig. 18 and for the bias line positions of Fig. 18 for GSM mode of operation. For position C of the via location, the coupling shows a pronounced minimum 123 at the GSM frequency band of 900 MHz. This minimum 123 means that less energy is lost by coupling into the bias line at the GSM frequency. A further minimum occurs above 2 GHz due to higher order modes.

By contrast, there is no minimum at the same frequency as the main minimum 120 of the reflectivity  $S_{11}$  in the WLAN range below 2 GHz, which shown in Fig. 18. Instead, there is a coupling minimum 124 slightly above 2 GHz.

For the positions A and B, the minimum 123 is shifted to lower frequencies while for the position D it is shifted to higher frequencies and forms a double minimum with a second minimum at 1.3 GHz, which is also present for the location A and B but not as pronounced.

Based on the minima occurring in reflection coefficients at 900MHz obtained in Figure 18 and minima occurring in coupling to GSM via at 900MHz in Figure 19 it is seen—that choosing the midpoint on the edge of the patch for DC biasing lines minimizes the effects on the GSM performance.

Fig. 20 shows a simulated total efficiency in decibel for the nested antenna 10 in a GSM mode (full line) and in a WLAN mode (dashed line) as a function of frequency. The total efficiency performance metric of an antenna is defined as

$$\text{total efficiency} := \frac{\text{Power radiated from the antenna}}{\text{total input power of the antenna}}$$

A high efficiency close to one is observed for the two bands of design, notable the GSM band 60 at 900 MHz and the WLAN band 61 at 2.4 GHz. In particular, the efficiency is close to one for 900 MHz in the GSM mode and it is also close to one for a range around 2.5 GHz that includes the 2.4 GHz frequency for the WLAN mode. Thus, the efficiency in the decibel scale is close to zero.

The efficiency maximum 62 around 900 MHz is sharply peaked, which provides a good frequency selectivity. The frequency maximum 63 of the WLAN mode, on the other hand, extends over several hundred MHz, allowing a broadband operation in the WLAN range.

Similar to the GSM mode, there is a sharply peaked efficiency maximum in the WLAN mode which is close to 900 MHz but which is shifted slight to lower frequencies with respect to the first minimum 62 of the GSM mode.

For both the GSM and the WLAN mode, the efficiency drops above 900 MHz and rises again above 1.5 GHz. For the GSM mode, there are further maxima of efficiency around 1.7 GHz and 2.1 GHz.

Figs. 21 and 22 show simulated radiation patterns in the E-plane and in the H-plane of the nested patch antenna for the 900 MHz (GSM) and 2.4 GHz (WLAN) modes, respectively.

The location of the E-plane, the H-plane and the angle theta is indicated in an inset of Figs. 21 and 22. For the configuration of Fig. 21, the E-plane lies in the x-z plane of Fig. 1. It is perpendicular to the patch surfaces and goes through the centre of the inner patch and the feed point. The H-plane lies in the y-z plane of Fig. 1. It is perpendicular to the E-plane and goes through the centre of the inner patch 11.

The angle theta of Figs. 18 and 19, which takes on values in the range of -180 to 180 degrees, refers to an angle relative to the z-axis, which is perpendicular to the patch surfaces 11, 12 and points away from the ground plane 35, and which lies in the E-plane or in the H-plane, respectively.

The E-plane of the WLAN band pattern is more asymmetric as the WLAN patch is not placed symmetrically along the E-plane with respect to the outer patch.

The maximum of the E-plane radiation pattern 125 of the GSM mode, which is shown in Fig. 21, has a sine-like shape and extends over a range of approximately -100 degrees to 100 degrees, while the maximum of the E-plane radiation pattern 126 of the WLAN mode is peaked between -50 to + 50 degrees. It shows an ascending plateau left of the peak between -120 degrees and -50 degrees and a plateau-like feature right to the peak between 50 degrees and about 140 degrees. Dips of radiation intensity are observed at - 130 and + 120 degrees for the GSM mode and at -150 and + 150 degrees for the WLAN mode.

The maximum of the H-plane radiation pattern 127 of the GSM mode, which is shown in Fig. 22, has a sine-like shape and extends from about -130 degrees to +130 degrees. The maximum of the H-plane radiation pattern 128 of the WLAN mode is sim-

ilar to the maximum of the radiation pattern 127 but slightly more pronounced. Intensity dips can be observed at about -130 degrees and about 130 degrees. These dips are more pronounced for the WLAN mode.

The GSM mode has a realized gain of 6.05 dB and directivity of 7.08 dBi at 900MHz and WLAN mode has realized gain of 8.96 dB and a directivity of 9.45 dBi at 2.4 GHz. These results can be derived from the three dimensional antenna pattern. Figs. 18 and 19 are cross sections of the three dimensional antenna pattern, which is not shown for simplicity.

Fig. 23 shows a portion of the outer shell 70 of an unpiloted aerial vehicle. A nested patch antenna 10 according to the present specification is provided on the outer shell 70. A control unit 72 comprises a frequency switch unit 73 and a bias control 71. The bias control 71 is connected to a bias electronic at the ground plane 35 of the nested patch antenna 10. The bias electronic is not shown in Fig. 23. Furthermore, the bias control is connected to the switch unit 73.

A signal line 74 is connected to a signal generator, which is not shown, and to a GSM frequency converter 75 and to a WLAN frequency converter 76 of the switch unit 73. A controllable switch 77, which is controllable by the bias control 71, is connected to the coaxial cable 78.

Fig. 24 shows an antenna array 80 of nested patch antennas 81, 82, 83, 84 according to the present specification, with respective feed connections 85, 86, 87, 88.

The nested patch antennas 81, 82, 83, 84 of the antenna array 80 are connectable to a signal source and a receiver elec-

tronic, which are not shown in Fig. 24. In a first mode, only one antenna at a time is active. For example, the emission characteristic of the antennas 81, 82, 83, 84 may point in different directions and an antenna is activated according to a selected directivity.

The application provides a configurable nested patch antenna which comprises a substrate that can have the form of a printed circuit board 34. The substrate comprises a metallic upper surface and a metallic ground surface that can act as a ground plane 35. The upper surface of the printed circuit board comprises an inner patch and an outer patch, wherein the outer patch surrounds the inner patch and is separated from the inner patch by a gap that can have the form of a slot. The substance of the metallic surfaces may comprise copper, silver, gold or aluminium, for example.

The outer patch and the inner patch can have any shape. They can have, among others, a rectangular shape, a square shape, a round shape, or an oval shape. The shape of the outer patch and the inner patch can influence the radiation pattern of the antenna.

The nested patch antenna further comprises a feeder section, that can be provided as a feed line 29, which is connected to a feed point of the inner patch. The feed point may be located at a distance  $d_{\text{WLAN}}$  from a centre of the inner patch to facilitate impedance matching.

There is at least one electrically switching element provided, that is provided as a diode 17, 18, 19, 20, 21, 22, as an RF MEMS, as a varactor or as any other suitable component. The switching element is provided in an area of the outer

circumference of the inner patch and in an inner circumference of the outer patch, thereby bridging the gap. It can be advantageous if a resistance or an impedance of the switching element changes when a bias voltage is applied to terminals of the switching element, e.g. between a first and a second end of the switching element. Hence, the impedance  $Z$  may comprise capacity and/or inductivity components which can be changed in a pre-determined manner by applying a pre-determined bias voltage to the terminal of the switching element.

According to the application, the inner patch, the outer patch or both of them are connected to a separate DC bias pad. A particularly simple way to provide the DC bias pads comprises forming the bias pad from the ground surface such that the bias pad is separated from the ground surface by a surrounding gap, which surrounds the bias pad.

A first DC bias via through the substrate is connected to the inner patch, and it may be provided at a centre of the inner patch or at a midpoint of an outer edge of the inner patch. This supports application of a bias voltage from behind the ground plane to the inner patch and therefore to one terminal of the switching element. The placement at the centre or at the midpoint of an edge can contribute to the suppression of undesired higher oscillation modes, especially if the oscillation modes have an amplitude maximum at the location of the connection between the bias via and the patch.

A second DC bias via is connected to the outer patch, for example to a mid-point of one side of the outer patch or even to a mid-point of an outer edge of the outer patch. A placement at the mid-point is particularly advantageous when a ground mode of oscillation of the antenna has zero amplitude

at this location. Then, little or no energy of the ground mode is lost through the bias via. Placing the DC bias via close to the outer edge moves the DC bias via further away from the radiation source and further reduces coupling into the bias via. The effect on the coupling is illustrated in particular with respect to Figs. 18 and 19.

In one embodiment, the first DC bias via, which is connected to the inner patch, is connected to a first bias pad. Similarly, the second DC bias via may be connected to a second bias pad.

The first bias pad and the second bias pad are each provided by a plane portion of a metallic layer to which an end of the bias via is connected. In particular, each of the patches may be provided by a portion of the ground plane that is separated from the ground plane by a slot, which surrounds the bias pad.

In particular, the first DC bias via may be connected to a centre point of the inner patch. Thereby, undesirable higher modes can be suppressed, which, unlike the basic modes, have no minimum of the electric field at the centre point location, e.g. the TM<sub>020</sub> and TM<sub>002</sub> modes of the cavity model. Higher modes would lead to radiation or reception in undesired frequency bands.

More specifically, the inner patch may have a rectangular shape and the outer patch may have the shape of a rectangular frame which surrounds the inner patch. The rectangular patch shape is easy to analyse and manufacture as compare to circular, elliptical or other irregular shapes. For ease of refer-

ence, a patch in the form of a rectangular frame is also referred to as a rectangular patch.

In particular, the inner patch may have a quadratic and the outer patch may have the shape of a quadratic frame. This embodiment is shown in Fig. 1, for example. The quadratic frame provides a good ratio of radiated power to surface area.

In one embodiment, a dimension of the inner patch (11) is approximately 3.5 x 3.5 cm and a dimension of the outer patch (12) is approximately 10 cm x 10 cm. These dimensions are particularly suitable for a frequency of the ground modes of about 900 MHz and 2.4 GHz, respectively, under the condition that the dielectric constant  $\epsilon_r$  is approximately 2 and the relative magnetic permeability  $\mu_r$  is approximately equal to 1.

In one embodiment with rectangular patches, the second DC bias via is connected to a mid-point of a side of the outer patch. This location may comprise any mid-point location between an inner circumference and an outer circumference of the patch.

In particular, the second DC bias via can be connected to a mid-point of an outer edge of the outer circumference of the outer patch. When placing the DC bias via at the outer circumference or close to it, it is further removed from the source of radiation than for a location further inside. Thereby, a possible coupling into the second bias via is smaller.

In particular the switching elements may comprise diodes 17, 18, 19, 20, 21, 22 which are cheap and easy to attach to the antenna patches.

In one arrangement having nested rectangular patches there are at least four switching elements provided. Two of the switching elements are aligned along the connecting line between the centre point of the inner patch and the feed point of the inner patch, hence in the x-direction of Fig. 1. This placement is advantageous for providing a good current flow. By contrast, in the y-direction it is advantageous not to place the diodes at the mid-point of the edges as the electric field amplitude and hence the current flow is small there. Furthermore, placing switching elements at the mid-point along y-direction would result in a slot length of half a wavelength in resonance frequency of the smaller patch. (i.e. WLAN band for the two patch system) . This results in unwanted radiation in frequency of the smaller patch (i.e. WLAN band) even when the antenna operates at the frequency of the larger patch (i.e. GSM band).

In order to control the switching elements, a controllable voltage source, such as the controllable voltage source (48) is connected to at least one of the first DC bias via (26) and the second DC bias via. In particular, the controllable voltage source may be included in a bias electronics, which is provided on the ground plane.

In a further embodiment, the concept of the nested patch antenna is extended to a multiple patch antenna with at least three nested patches. The multiple nested patch antenna comprises the aforementioned nested patch antenna. Furthermore, a third patch is provided which surrounds the outer patch of

the nested patch antenna. The third patch is separated from the outer patch of the nested patch antenna by a second slot. Furthermore—switching elements are provided between the outer patch and the third patch in the second slot at appropriate locations determined by the current distribution on the slot.

The multiple patch antenna may also comprise further patches, wherein each further patch surrounds a neighbouring patch inside the further patch and is connected to a neighbouring patch antenna that is nested inside the further patch by switching elements in a similar manner as shown in Fig. 10.

Furthermore, the current specification discloses an antenna device comprising one of the abovementioned nested patch antennas. The nested patch antenna is arranged within a plastic housing of the antenna device, for example positioned or also moulded. The antenna device may be configured to provide services to multiple consumers in a room or outdoors. In particular, the antenna device may comprise a transceiver element and further elements for controlling the patch antenna, such as the bias control 71, the control unit 72, the frequency switch unit 73, the GSM frequency converter 75, the WLAN frequency converter 76 or the controllable switch 77 of Fig. 23.

Moreover, the application discloses an electronic device, such as a mobile phone, a laptop computer, a palmtop, a monitoring station, a printer, a screen, a portable electronic device, a transceiver device etc., comprising the abovementioned nested patch antenna.

The nested patch antenna is arranged within a casing of the electronic device or on the outside of the casing. A signal generator of the electronic device is connected with the

feeder section of the nested patch antenna. At least one switching element is connected with a control section of the electronic device. The control section may comprise a bias electronic or the bias electronic may be provided at the ground plane of the nested patch antenna.

Furthermore, the current specification discloses a motor vehicle with a nested patch antenna wherein the nested patch antenna is attached to an outer body of the motor vehicle. A control section of the motor vehicle that is arranged within the body of the vehicle is connected the bias line of the nested patch antenna. The control section may be included in a communication device or a car radio, for example.

Moreover, the present specification discloses a flying apparatus such as an aircraft, an unpiloted aerial vehicle, a glider plane, a balloon, a toy plane with a nested patch antenna, wherein the nested patch antenna is attached to an outer shell of the flying apparatus and connected to a control section of the flying apparatus.

In a further aspect, the current specification discloses a method for designing a configurable nested patch antenna which comprises an inner patch and an outer patch that surrounds the inner patch and that is separated from the outer patch by a gap, such as a slot.

The method comprising choosing a first operating frequency for the inner patch, such as a WLAN frequency and choosing a second operating frequency for the outer patch, such as a GSM frequency. When the dielectric constant and the magnetic permeability of the substrate material is known, this can al-

ready allow to fix the outer dimensions of the patches according to the ground modes of the patches.

A first parameter sweep is performed for a distance  $d_{\text{GSM}}$  of a feed location from a centre of the outer patch and thereby quality indicators for an impedance match are obtained, such as reflectivity, coupling coefficient, standing wave ratio, antenna efficiency etc.

A second parameter sweep is performed for a distance  $d_{\text{WLAN}}$  of a feed location from a centre of the inner patch and quality parameters for an impedance match are obtained.

Values for the distances  $d_{\text{GSM}}$  and  $d_{\text{WLAN}}$  are chosen such that an impedance match is within a predetermined interval around a maximum impedance match for the respective patches, wherein the maximum impedance match is derived from the quality parameters.

The distances  $d_{\text{WLAN}}$  and  $d_{\text{GSM}}$  are determined by running simulations on individual patches, as opposed to running a simulation on the nested patch. After determining  $d_{\text{WLAN}}$  and  $d_{\text{GSM}}$  individually, the two patches are nested in such a way that the distances  $d_{\text{WLAN}}$  and  $d_{\text{GSM}}$  are superimposed on one another.

The locations of the inner patch and the outer patch are aligned such that the feed locations coincide. According to a further embodiment, the slot width, or gap width, between the inner and the outer patch is determined as well by performing a parameter sweep for a slot width of the slot between the inner patch and the outer patch. When adapting the slot width, a pre-determined size of the inner patch is kept con-

stant. In particular, the predetermined constant size may include a pre-determined constant length, a pre-determined constant width and a pre-determined constant surface area.

The slot or gap could be etched out on the larger patch giving the smaller patch. While the outer length and width of the larger patch is a constant, by etching out the slot, the surface area of the larger patch is reduced. The smaller patch has the same size as determined in advance.

The slot width  $d$  is chosen such that a parasitic coupling between the inner patch and the outer patch is lowest, taking into account that the size of the inner patch is larger than a pre-determined minimum admissible size of the inner patch. This minimum admissible size corresponds to a desired frequency of radiation for the inner patch.

Furthermore, the patch antenna design method may comprise forming out, especially etching out, an inner patch and forming, especially etching out, an outer patch from a surface layer of a substrate according to the determined design parameters.

Furthermore, the patch antenna design method may comprise forming out, especially etching out, a first bias pad and a second bias pad on a ground surface layer of the substrate and connecting the first bias pad to the inner patch and connecting the second bias pad to the outer patch, and in particular to a mid-point of an edge, especially an outer edge of the outer patch.

The connection is achieved for example by drilling a through hole through the substrate/printed circuit board and the con-

ducting layers of the printed circuit board. The through hole is filled out with a conducting material and solder joints are provided at each end of the through hole for better connection with the conducting layers.

A reconfigurable nested patch antenna according to the present specification may be controlled to adapt its behaviour to changing system requirements or environmental conditions. The behaviour could include the frequency response, radiation pattern, polarization or a combination of these. This adaptability eliminates restrictions imposed by antennas with fixed characteristics and on the system functionality. A typical scenario for instance is a Software Defined Radio (SDR) system. The essence of SDR / Cognitive Radio is to adapt the communication parameters depending on the dynamic spectrum availability and the wireless channel characteristics. To achieve efficient performance for an SDR system, a nested patch antenna according to the present specification may be provided.

With growing demand for system miniaturization, it is often desired to achieve the functionality of two or more antennas with one reconfigurable antenna having lower real estate requirements of space, such as the nested patch antenna according to the present specification. This is not only desired in handheld electronic system miniaturization, but has even greater implications in defence electronics. For instance, in a UAV the available space for mounting antennas is limited due to aerodynamic constraints imposed on the mechanical design. The greater the number of antennas, the greater the chances of a higher radar cross section which is undesirable in defence applications. It is then desired to reduce the

number of antennas by designing multi-function antennas which can accomplish the functionality of more than one antenna.

Reconfigurable antennas are a class of multi-functional antennas where the functionality can be changed dynamically as necessary. In comparison to conventional multi-band and wide-band antennas remain key contenders, but reconfigurable antennas may provide advantages for improved system performance in terms of improved filtering of interfering signals, ability to adapt antenna patterns as necessary and in some cases even varying the polarization of the antenna.

A nested patch antenna according to the present specification may provide, among others, the following benefits:

- By introducing pads on the ground plane that are surrounded by slots, an unwanted coupling to bias lines is reduced greatly. The design has inherently high RF-DC isolation.
- Ability to house the DC biasing circuitry anywhere below the ground plane as this has little or no effect on the RF performance.
- DC bias pads on the ground plane lead to scalability in design allowing design of multiple nested patches antennas with more than 2 frequencies (or states) of operation.
- The nested patch configuration allows switching of the antenna between bands that are separated widely apart in frequency.

- By placing the shorting pin or the shorting pins at appropriate locations, higher order modes of the low frequency band(s) that could potentially interfere with high frequency band/s are suppressed.

## Reference numbers:

|    |                                             |         |                                                       |
|----|---------------------------------------------|---------|-------------------------------------------------------|
| 9  | direction of electric field                 | 30      | feed point                                            |
| 10 | nested patch antenna                        | 32      | coaxial cable                                         |
| 11 | inner patch                                 | 33      | upper layer                                           |
| 12 | outer patch/intermediate patch              | 34      | isolating layer (circuit board)                       |
| 13 | circuit board                               | 35      | ground plane/lower layer                              |
| 14 | rectangular slot                            | 36      | plastic insulation layer                              |
| 15 | outer circumference of inner patch          | 37      | woven copper layer                                    |
| 16 | inner circumference of outer patch          | 38      | solder joints                                         |
| 17 | switching element                           | 39      | bias pad of inner patch                               |
| 18 | switching element                           | 40      | slot of bias pad 39                                   |
| 19 | switching element                           | 41      | outer patch in three patch arrangement                |
| 20 | switching element                           | 42      | bias pad of outer patch/intermediate patch            |
| 21 | switching element                           | 43      | second slot                                           |
| 22 | switching element                           | 45      | bias via of outer patch (for three patch arrangement) |
| 23 | bias line of inner patch                    | 46      | slot of bias pad 42                                   |
| 24 | centre of inner patch                       | 48      | controllable voltage source                           |
| 25 | bias line of outer patch                    | 49      | controllable voltage source                           |
| 26 | bias via of inner patch                     | 50 - 57 | minima of Fig. 8                                      |
| 27 | bias via of outer patch                     | 60      | GSM range                                             |
| 28 | mid-point of the outer patches' outer edge  | 61      | WLAN range                                            |
| 29 | centre conductor of coaxial cable/feed line |         |                                                       |

62 GSM range efficiency  
maximum 127, 128 radiation patterns  
63 WLAN range maximum of Fig. 22  
70 outer shell  
71 bias control  
72 control unit  
73 frequency switch unit  
74 signal line  
73 switch unit  
74 signal line  
75 GSM frequency converter  
76 WLAN frequency convert-  
er  
77 controllable switch  
78 coaxial cable  
81 nested patch antenna  
82 nested patch antenna  
83 nested patch antenna  
84 feed connection  
85 feed connection  
86 feed connection  
87 feed connection  
88 feed connection  
90, 91, 92 double minima  
of Fig. 9  
93 - 96 minima of Fig. 11  
97 minimum of Fig. 12  
104 - 112 minima of Fig. 15  
113 - 118 minima of Fig. 16  
119 - 122 minima of Fig. 18  
123, 124 minima of Fig. 19  
125, 126 radiation patterns  
of Fig. 21

**CLAIMS**

1. Configurable nested patch antenna (10), comprising
  - 5 - a substrate (34), the substrate (34) comprising a metallic upper surface (33) and a metallic ground surface (35), wherein the upper surface (33) of the substrate (34) comprises
  - an inner patch (11) and
  - 10 - an outer patch (12), wherein the outer patch (12) surrounds the inner patch (11) and is separated from the inner patch (11) by a gap (14),the nested patch antenna (10) further comprising
  - a feed line (29) which is connected to a feed point
  - 15 (30) of the inner patch (11),
  - at least one switching element (17, 18, 19, 20, 21, 22) which is provided between an outer circumference (15) of the inner patch (11) and an inner circumference (16) of the outer patch (12),
  - 20 - a first DC bias via (26) which is connected to the inner patch (11),
  - a second DC bias via (27) which is connected to the outer patch (12), wherein at least one of the inner patch (11) or the outer patch (12) is connected to a metallic DC bias pad (39, 42) that is separated from the
  - 25 ground surface (35) by a surrounding gap (46).
2. Configurable nested patch antenna (10) according to claim 1, wherein the second DC bias via (27) is connected to a bias pad (42), the bias pad (42) being separated
- 30 from the ground surface (35) by a gap (46) which surrounds the bias pad (42).

3. Configurable nested patch antenna (10) according to claim 1 or claim 2, wherein the first DC bias via (26) is connected to a bias pad (39), the bias pad (39) being separated from the ground surface (35) by a gap (40) which surrounds the bias pad (39).  
5
4. Configurable nested patch antenna (10) according to one of the claims 1 to 3, wherein the first DC bias via (26) is connected to a centre point (30) of the inner patch (11).  
10
5. Configurable nested patch antenna (10) according to one of the claims 1 to 4, wherein the inner patch (11) has a rectangular shape, and wherein the outer patch (12) has the shape of a rectangular frame.  
15
6. Configurable nested patch antenna (10) according to one of the claims 1 to 4, wherein the inner patch (11) has a quadratic shape, and wherein the outer patch (12) has the shape of a quadratic frame.  
20
7. Configurable nested patch antenna (10) according to claim 6, wherein a dimension of the inner patch (11) is approximately 3.5 x 3.5 cm and a dimension of the outer patch (12) is approximately 10 cm x 10 cm.  
25
8. Configurable nested patch antenna (10) according to one of the claims 5 to 7, wherein the second DC bias via (26) is connected to a mid-point (28) of a side of the outer patch (12).  
30
9. Configurable nested patch antenna (10) according to claim 8, wherein the second DC bias via (26) is connect-

ed to a mid-point of an outer edge of the outer patch (12).

10. Configurable nested patch antenna (10) according to one  
5 of the preceding claims, wherein the at least one switching element (17, 18, 19, 20, 21, 22) comprises a diode.
11. Configurable nested patch antenna (10) according to one  
10 of the claims 5 to 7, wherein at least four switching elements (17, 18, 19, 20, 21, 22) are provided, and wherein two of the switching elements (19, 22) are aligned along the connecting line between the centre point (24) of the inner patch (11) and the feed point  
15 (30) of the inner patch (11), and wherein a distance between each pair of two adjacent switching elements (17, 18, 19, 20, 21, 22) is different from a pre-determined resonant wavelength of the inner patch (11).
12. Configurable nested patch antenna (10) according to  
20 claim 11, wherein at least six switching elements (17, 18, 19, 20, 21, 22) are provided, and wherein a distance between each pair of two adjacent switching elements (17, 18, 19, 20, 21, 22) is different from a pre-  
25 determined resonant wavelength of the inner patch (11).
13. Configurable nested patch antenna (10) according to one  
of the claims 1 to 12, wherein a controllable voltage source (48) is connected to at least one of the first DC  
30 bias via (26) and the second DC bias via (27).
14. Multiple patch antenna (10') comprising a configurable nested patch antenna (10) according to one of the claims

- 1 to 12, the multiple patch antenna (10') further comprising (at least) a third patch (41) which surrounds the outer patch (12) of the nested patch antenna (10), wherein the third patch (41) is separated from the outer patch (12) by a second gap (43) and wherein at least one switching element is provided in the second gap (43) and between the outer patch (12) and the third patch.
- 5
15. Antenna device comprising a nested patch antenna (10) according to one of the claims 1 to 14, wherein the nested patch antenna is arranged within a plastic housing of the antenna device.
- 10
16. Electronic device comprising a nested patch antenna (10) according to one of the claims 1 to 14, wherein an antenna connector of the electronic device is connected with the feeder section of the antenna and wherein the at least one switching element is connected with a control section of the electronic device.
- 15
17. Motor vehicle with a nested patch antenna (10) according to one of the claims 1 to 13, wherein the nested patch antenna is attached to an outer body of the motor vehicle and connected to a battery of the motor vehicle.
- 20
18. Flying apparatus with a nested patch antenna (10) according to one of the claims 1 to 14, wherein the nested patch antenna is attached to an outer shell of the flying apparatus and connected to a power supply of the flying apparatus.
- 25
19. Method for designing a configurable nested patch antenna (10, 10'), the nested patch antenna (10, 10') comprising
- 30

an inner patch (11) and an outer patch (12), the outer patch (12) surrounding the inner patch (12) and being separated from the outer patch by a gap (14), the method comprising

- 5       - choosing a first operating frequency for the inner patch (11),
  - choosing a second operating frequency for the outer patch (12),
  - performing a parameter sweep for a distance  $d_{\text{GSM}}$  of a  
10       feed location (30') from a centre of the outer patch (12),
  - performing a parameter sweep for a distance  $d_{\text{WLAN}}$  of a feed location (30) from a centre of the inner patch (11),
  - 15       - choosing values for the distances  $d_{\text{GSM}}$  and  $d_{\text{WLAN}}$  such that an impedance match is within a predetermined interval around a pre-determined suitable impedance match for the respective patches (11, 12),
  - aligning the inner patch (11) and the outer patch (12)  
20       such that the feed locations(30, 30') (essentially) co-incide. (30' not shown currently)
20. Design method according to claim 19, comprising
- 25       - performing a parameter sweep for a gap width  $d$  of the gap (14) between the inner patch (11) and the outer patch (12),
  - choosing the gap width  $d$  such that a parasitic coupling between the inner patch (11) and the outer patch (12) is lowest under the condition that the size of the  
30       inner patch (11) is larger than a pre-determined minimum admissible size of the inner patch (11).

21. Design method according to one of the claims 19 or 20 comprising  
- forming an inner patch (11) and an outer patch (12)  
from a surface layer (33) of a substrate (34) according  
5 to the determined design parameters.

22. Design method according to claim 21, comprising  
- forming a first bias pad (39) and a second bias pad  
(42) on a ground surface layer (35) of the substrate  
10 (34),  
- connecting the first bias pad (39) to the inner patch  
(11),  
- connecting the second bias pad (42) to the outer patch  
(12).  
15