A Rectangular Monopole Filtenna with U-shaped Slot for 5G Applications

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Abstract: A filtering antenna for 5G applications is proposed in this study, where the resonant element has a U-shaped slot embedded into the microstrip feed line so that no extra size is required. The proposed filtenna has a very compact size of only 35 * 47 mm$^2$. Using CST Microwave Studio Suite, a comprehensive parametric analysis was done to evaluate and optimize the characteristics of the proposed filtenna. The filtenna is aimed for the 5G 3.4-3.8 GHz, as it covers a bandwidth of 412MHz (3.395 -3.807GHz) with a good reflection coefficient of -22.96dB at the center frequency. The U-shaped slot enhances the lower shoulder of the antenna frequency response and has no effect on the radiation at the desired band.

1. Introduction
In late 2016, the European Commission and the Radio Spectrum Policy Group (RSPG) identified the 3.4–3.8GHz band as the “primary band suitable for the introduction of 5G-based services in Europe even before 2020”[1], thus allocating this band for use in a rapidly growing system. This band offers adequate bandwidth for the 5G systems, and recent developments such as massive MIMO have further increased the importance of this band.

Filters and antennas are the most common and integral parts of all wireless communication systems, where transmitters and receivers are fitted with antennas. Some frequencies in the received signal need to be removed such that to reduce interference and/or noise. These signal processing functions are performed by filters that block particular frequencies while allowing others to pass.

The integration of filters and antennas, where the antenna acts as the filter’s last resonator, is the filtering antenna. Filtering antennas can be used to reject a certain frequency band or to enhance bandwidth and selectivity [2]. The design, fabrication, and testing of a compact filtering antenna with a second-order quasi-elliptic response was proposed in [3]. A U-shaped radiating patch is excited by an inset-coupled T-shaped resonator. The antenna achieved a fractional bandwidth of 2% at center frequency 5 GHz. In another work [4], two planar, efficient, wideband, compact, monopole filtennas were presented. The first one was developed from the common planar capacitive loaded loop (CLL)-based filter, while the second filtenna consisted of a driven element augmented with a CLL structure and with a slotted ground plane. The fractional bandwidth was expanded from 6.28% up to 7.9% for the first one at center frequency 2.34GHz.

In [5], a combined filtering planar dipole antenna having an edge-coupled feed was presented to show a second-order filtering response. The first stage of the filter is a U-shaped half-wavelength resonator that is followed by a simple planar dipole, whose bandwidth is controlled by the edge-coupling between the two stages. The antenna offered a21% bandwidth extending from 4.2 GHz to 5.2 GHz with a sharper roll-off than that of the conventional planar dipole. A low-profile planar dipole filtering antenna having an omnidirectional radiation pattern was presented in [6]. The antenna is
formed of a planar dipole radiator, which is fed by a microstrip-to-slot transition structure. By adding non-radiative components, including a coupled U-shaped microstrip line and two I-shaped slots, to the feed network, the filtering characteristics are accomplished. Moreover, a novel dual-polarized filtering patch antenna without an extra circuit was suggested as filtenna[7]. With split-ring resonators (SRR) located within the antenna aperture, this proposed antenna achieved four radiation nulls. A wideband planar filtering dipole antenna is presented in [8] for 5G communication. Two rectangular radiating patches, that are fed by an inverted L-shaped feedline, compensate the dipole antenna. On the radiating rectangular patches, two complementary step impedance resonators (CSIRs) branches and two complementary split-ring resonators (CSRRs) are etched such that the antenna out of the operating band produces under and upper resonant zeros. The antenna has an operating frequency range of 3.08 to 5.15 GHz and gain > 2 dBi.

Low reciprocal coupling between antenna elements is required for the successful implementation of MIMO systems to reduce the envelope correlation coefficient (ECC). An open stub meandered (OSM) band-stop filter (BSF) architecture was used in [9] for MIMO applications, which implemented a mutual coupling suppression technique. A two-element patch array was optimized and applied on the ground-plane side of the OSM-BSF.

In this study, the analysis and design of a filtering antenna for the 5G (3.4-3.8 GHz) band is presented. The antenna consists of a rectangular monopole fed by a microstrip line that offers more than the desired bandwidth. The filtering action is thus needed to limit the bandwidth to the desired 3.4-3.8 GHz range. The proposed filter is in the form of a U-shaped slot etched in the feed line, thus no extra space is needed, as seen in many conventional designs. The various stages of the design were investigated by the CST microwave Suite.

2. Monopole antenna

This section presents the monopole antenna aiming to cover 5G (3.4 to 3.8 GHz) band. The initial structure of the proposed antenna is shown in Figure 1, where the FR4 (glass epoxy) substrate having dielectric constant $\varepsilon_r = 4.3$, loss tangent of $\tan \delta = 0.025$, and a thickness of 1.6 mm is used. The copper coating for the ground plane and monopole antenna is $t=0.035$ mm. The overall dimensions of the proposed antenna are $L_s \times W_s \times h$, where a rectangular radiating patch of $L_p \times W_p$ is denoted as MA1 and is connected to a 50-Ohm microstrip feed-line.

![Figure 1](image-url)  
**Figure 1.** The geometry of the proposed monopole antenna; (a) front view, (b) side view, and (c) rearview.

The antenna parameters (patch width $W$ and patch length $L$) can be found from the following equations (1-5)[10]:

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2
\[ \varepsilon_{\text{eff}} = \frac{(1 + \varepsilon_r)}{2} \]  
\[ W = \frac{c}{2f_r} \times \left( \frac{2}{\varepsilon_r+1} \right)^{0.5} \]  
\[ \Delta L = 0.412 \times h \times \left( \frac{\varepsilon_{\text{eff}}+0.3(W/h+0.264)}{\varepsilon_{\text{eff}}+0.258(W/h+0.6)} \right) \]  
\[ L_{\text{eff}} = c/2 \times f_r \times (\varepsilon_{\text{eff}})^{0.5} \]  
\[ L = L_{\text{eff}} - 2\Delta L \]  

For the desired band of 3.4 – 3.8 GHz, the center frequency \( f_c = 3.6 \) GHz, thus, the patch width \( W_p = 25.6 \) mm, effective dielectric constant \( \varepsilon_{\text{eff}} = 2.65 \), and patch length \( L = 24 \) mm. The width of the feed line can be calculated from equation (6) to obtain line impedance of \( Z_o = 50 \) Ohm[10]:

\[
\frac{W}{h} = \begin{cases} 
\frac{2}{\pi} \left[ B - 1 - \ln(2B - 1) + \frac{\varepsilon_r - 1}{2} \times \left( \ln(B - 1) + 0.39 - \frac{0.61}{\varepsilon_r} \right) \right] & \text{for } W/h < 2 \\
8\varepsilon^A/e^{2A} - 2 & \text{for } W/h > 2 
\end{cases} 
\]  

Where

\[ A = \frac{Z_o}{60} \sqrt{\varepsilon_r+1} + \frac{\varepsilon_r - 1}{2} \times \left( 0.23 + \frac{0.11}{\varepsilon_r} \right) \]  
\[ B = \frac{377\pi}{22\sqrt{\varepsilon_r}} \]  

Then equation (7) can be used to determine the characteristic impedance of the microstrip line[10]:

\[
Z_o = \begin{cases} 
\frac{60}{\sqrt{\varepsilon_{\text{eff}}}} \left( \frac{8h}{W} + \frac{W}{4h} \right) & \text{for } W/h \leq 1 \\
\frac{120\pi}{\sqrt{\varepsilon_{\text{eff}}}} \left[ W/h + 1.393 + 0.667\ln(W/h + 1.444) \right] & \text{for } W/h > 1 
\end{cases} 
\]  

The calculated dimensions of the antenna are listed in Table 1. Figure 2 illustrates the effect of the ground plane length \( L_g \) or the effect of the gap length (\( L_d - L_g \)) between the radiating patch and the ground plane. This part of the feed-line works as a matching section between the radiating monopole and the 50-Ohm line. The matching is achieved by varying the gap length as has been used in [11,12, 13]. It can be seen that a shorter gap leads to shifting the frequency of best matching towards lower frequencies. The influence of the gap length on the frequency for best matching is larger than that on the bandwidth. The best value of \( L_g \) that realizes better matching at the required center frequency was found to be 8.8mm, where the minimum reflection coefficient \( S_{11} \) is -38.7 dB. However, the achieved bandwidth is 2GHz that is much larger than the desired value of 400 MHz.

The above design was developed by choosing other substrate parameters of (\( L_d = 46 \) mm, \( W_d = 60 \) mm, and \( L_g = 18 \) mm) to be compatible with the filtenna design which will be discussed in section 4. Simulations were then performed to find the best value for the gap length (\( L_d - L_g \)). The obtained reflection coefficient \( S_{11} \) is shown in Figure (3), the best value of \( L_g \) that realizes good matching at the required center frequency is 14.5 mm, where the reflection coefficient \( S_{11} \) is -32 dB and the bandwidth is approximately 2.28 GHz.
Table 1. The dimensions of the proposed antenna.

| Parameter | Value in mm | Name                        |
|-----------|-------------|-----------------------------|
| $W_g$     | 35.2        | Ground plane width          |
| $W_f$     | 3.1         | Feed linewidth              |
| $W_s$     | 35.2        | Substrate width             |
| $W_p$     | 25.6        | Patch width                 |
| $L_s$     | 39          | Length of the substrate     |
| $L_f$     | 11.5        | Length of the feed line     |
| $L_g$     | Variable    | Length of the ground plane  |
| $L_p$     | 24          | Length of the patch         |
| $t$       | 0.035       | Thickness of copper         |

The simulated peak gain and the radiation efficiency of the designed antenna-1 are plotted in figure 4. The peak gain of 1.85 to 1.9 dBi in the operating band can be seen, while the efficiency is better than 85% across the band of operation, although a low-cost substrate of FR4 is in use. Higher values of efficiency can be obtained if another substrate of lower loss tangent has been used. The far-field radiation patterns in the E-Plane and H-Plane for the antenna are shown in Figure 5 for the two frequencies of 3.5 GHz and 3.7 GHz. The antenna has the usual monopole pattern exhibiting the figure 8 shape in one plane and omnidirectional pattern in the other plane. The patterns are stable over the band of operation.

Figure 2. Variation of the reflection coefficient $S_{11}$ with frequency for various values of $L_g$, ($L_f$= 11.5mm).

Figure 3. Variation of the reflection coefficient $S_{11}$ with frequency for various values of $L_g$, ($L_f$= 18mm).
Figure 4. Variation of antenna gain and radiation efficiency with frequency for the monopole antenna-1, (Wp=25.6mm, Lp=24mm, and Lg = 14.5mm).

(a) 

(b) 

Figure 5. Far-Field E-Plane and H-Plane pattern;(a) at 3.5GHz(b) at 3.7GHz.

3. Filter design
The designed antenna offers the required radiation pattern, but it has much more than the required bandwidth. Thus, a filter is needed to limit the bandwidth to the required 400MHz. The proposed filter is to use a U-shaped slot etched on the microstrip line as shown in figure 6. This filter that was proposed in [14] has a compact design as it can be embedded into the microstrip line itself. This design was formerly used to achieve band-notched characteristics as in [12] and antenna isolation by filtering the coupled signal in[13]. The U-shaped slot has also shown a similar behavior in Frequency Selective Surface (FSS) applications [14]. The U-shaped slot resonates at a frequency $f_r$ where its length equals multiple of the effective wavelength in the slot [14].

$$f_r = \frac{Nc}{2 \times LS \times \sqrt{\varepsilon_{eff}}}$$

$$LS = 2Lu + d$$
Where \( N \) is an integer, \( c \) is the speed of light, \( L_s \) is the slot length, and \( d \) is the separation between the two legs of the slot. The FR4 substrate was used for the construction of the filter, where the filter dimensions of 35mm*20mm*1.6 mm was used, and a feed line width (\( W_f = 3.1 \)) was calculated from Equation 6 to achieve 50-Ohm impedance.

Using equations (8) and (9), the slot dimensions that realized a frequency of 3.6 GHz were found to be (\( L_u = 12.5 \) mm, \( W_u = 0.55 \) mm, and \( d = 1 \) mm) hence the total length is 26 mm. The obtained scattering parameters \( S_{11} \) and \( S_{21} \) for the proposed filter are shown in figure 7. A band-notch property of 15.6dB insertion loss at 3.598GHz has been achieved by the U-slot design.

The U-slot filter's characteristics, such as resonance frequency and band rejection depend on the dimensions of the U-slot. The slot length, slot width, and distance between the slot's legs are the parameters that control the characteristics of the filter. Simulated transfer characteristics for the U-slot filter are plotted in figure 8 for various slot lengths while keeping \( W_u = 0.45 \) mm and \( d = 1 \) mm unchanged. The frequency of resonance decreases as the slot length increases, which confirms equation (8).

The influence of the slot width is demonstrated in figure 9 when \( d = 1 \) mm and \( L_u = 12.5 \) mm. As can be seen, the width of the slot influences the width of the reject band, so that larger width results in wider bandwidth, while \( S_{11} \) gets slightly higher and \( S_{21} \) decreases slightly. Thus, the desired filter characteristics can be obtained by the proper choice of the filter dimensions guided by equations (8) and (9).

![Figure 6](image1.png)

**Figure 6.** The geometry of the proposed band-stop filter using a u-slot etched on a microstrip line.

![Figure 7](image2.png)

**Figure 7.** Transfer characteristics of the U-slot filter.
4. Design of the Filtering antenna
A U-slot resonator is placed on the feed line of the antenna designed in section 2 to limit its bandwidth to the desired 3.4–3.8 GHz range. The geometry of the proposed filtenna is shown in figure 10, and the optimized dimensions are listed in table 2. In this design, various values of the ground plane length $L_g$ were considered to obtain the optimum values that achieve the required bandwidth (3.4–3.8 GHz).

Figure 11 illustrates the reflection coefficient $S_{11}$ of the filtenna, where it covers a bandwidth of 412 MHz (3.3952 GHz to 3.8072 GHz), and achieves a reflection coefficient $S_{11}$ of -22.96 dB at 3.676 GHz. The figure also displays the frequency responses of the two-monopole antenna-1 and antenna-2 (without the U-shaped slot) that were designed in section 2, where much more than the desired 400 MHz bandwidth is shown. The introduction of the U-shaped slot has clearly improved the left part of the response, and a sharper response is also noticed at the right edge of the band.

Figure 8. The frequency response of the U-shaped filter for various slot lengths at (Wu=0.45mm, $d=1$mm): (a) the reflection coefficient, (b) the transmission coefficient.

Figure 9. S-parameters of the U-slot filter for various slot widths.
The simulated peak gain of the proposed filtenna is displayed in figure 12. The peak gain of 3.1477 dBi is seen in the operating band. The figure also shows that the antenna achieved an efficiency higher than 73% across the desired band. The gain and efficiency drop to smaller values outside the band. Table 3 shows a comparison between various parameters of the three designed antennas. The filtenna has offered the required bandwidth with a small decrease in the gain.

![Figure 10. The geometry of the proposed filtenna, (a) front view, (b) rear view.](image)

![Table 2. The dimensions of the proposed filtenna.](image)

| Parameter | Value in mm | Name          |
|-----------|-------------|---------------|
| $W_u$     | 0.45        | U-slotwidth   |
| $W_f$     | 3.1         | Feed linewidth|
| $W_s$     | 35          | Substratewidth|
| $W_p$     | 25.6        | Patch width   |
| $W_g$     | 35          | Ground plane width |
| $L_u$     | 10.9        | Length of the U slot |
| $L_f$     | 19          | Length of the feed line |
| $L_g$     | 18.3        | Length of the ground plane |
| $L_p$     | 24          | Length of the patch |
| $a$       | 2.2         | Distance from the port to U-slot |

![Figure 11. The reflection coefficient ($S_{11}$) of the proposed filtenna compared to antenna-1 and antenna-2(without the U-shaped slot).](image)
Table 3. Comparison between the characteristics of antenna1-, antenna-2 and filtenna.

|         | Gain (dBi) | Bandwidth (GHz) | $S_{11}$ (dB) |
|---------|------------|-----------------|---------------|
| Antenna 1 | 3.1        | 2.06 (2.2613-4.3172) | -38.75        |
| Antenna 2 | 2.72       | 2.282 (1.9523-4.2341) | -32           |
| Filtenna | 2.577      | 0.412 (3.3952-3.8072) | -22.96        |

Figure 12. Gain and Radiation efficiency of the proposed filtenna.

The radiation patterns in the H-planes and E-planes are shown in figure 13. The antenna has the normal monopole pattern exhibiting the figure 8 shape in one plane and omnidirectional pattern in the other plane. The patterns are stable over the band of operation.

The surface current distribution for antenna-1 and the proposed filtenna are shown in figure 14 for the two frequencies; the center of the operating band (3.6 GHz) and the frequency of 4 GHz (outside the band). Comparing the results of antenna-2 that are shown in figures 14(a) and 14(c), it can be seen that the current distribution on the radiating patch is basically similar at the two frequencies in the operating band (3.6 GHz) and outside the band (4 GHz). On the other hand, looking at the current distributions of the proposed filtenna, which are shown in figures 14(b) and 14-d, it is evident that outside the operation band (i.e., at 4 GHz), the density is limited on the radiating patch. This leads to small radiation efficiency and gain as confirmed by the results shown in figure 12, where the gain drops to -4 dB, and the efficiency drops to less than 20%. The influence of the U-shaped slot is to reduce the signal fed to the radiating patch drastically as can be seen in figure 14(d). Therefore, filtenna has fulfilled the requirement of low radiation/receiving properties outside the designated band of operation.
Figure 13. The far-field patterns of the filtenna at various frequencies, (a) E/H-planes at 3.5GHz and (b) E/H-planes at 3.7GHz.

Figure 14. Simulated surface current distribution; (a) antenna MA1 at 3.6GHz, (b) Filtenna (proposed antenna) at 3.6GHz, (c) antenna MA1 at 4GHz, (d) Filtenna (proposed antenna) at 4GHz.
5. Comparison with other designs
The characteristics of the proposed filtenna are compared with those of other antennas presented in the literature, as listed in Table 4. In [4], the last resonator element was replaced by a fan-monopole antenna with a compact size of 0.36 x 0.34λg^2, but the bandwidth is less than 150MHz, and its achieved gain is 1.75dBi. In [6], the dipole antenna with a U-shaped microstrip-line and two I-shaped slots lead to a larger size compared to [4], but both antennas have a smaller size compared to the antenna proposed in this work. However, the proposed filtenna has a larger gain of 2.58 dBi, and a bandwidth of 412MHz satisfying the requirement of 400 MHz. Instead of filtering loops, short pins have been used in [16], but due to its large ground plane, the antenna is of considerable size (1.1 * 1.1 λg^2). A filter of the multi-stub method has been used in [17] in the feed line of a conventional inset-fed square microstrip patch antenna. However, this design needed twice the area occupied by the proposed filtenna. The proposed design shows various advantages compared to the other filtenna designs mentioned above, such as simple construction, compactness by using the feed line to achieve the filtration characteristic, and controllable bandwidth by easily adjusting the length of the U-slot.

Table 4. Comparison with other published designs of the proposed band-notch filtennas.

| Ref. | Band frequency GHz | Dimension mm | ε_r / tanδ | S_11in dB | Resonant element |
|------|--------------------|--------------|------------|-----------|------------------|
| [4]  | 2.264-2.46         | 29*27        | 3.48 /0.0037 | -21.9     | Capacitive loaded loop (CCL)+ monopole |
| [6]  | 3.82-4.49          | 28*40        | 3.38/N.A.   | -16.1     | U-shaped and two I-shaped slots + Dipole |
| [16] | 4.3-4.7            | diameter= 99 | 2.65/N.A.   | -22.6     | Ring slot + Triangular patch |
| [17] | 2.4-2.1            | 70*40        | 4.5 /0.022  | -30       | Multi-stub + Rectangular patch |
| This work | 3.395-3.807  | 35*47        | 4.3 /0.025  | -22.96    | U-slot + Monopole |

6. Conclusions
The design and characterization of a filtering antenna (Filtenna) with a compact size of 35 x 47 mm^2 for the 3.4-3.8 GHz 5G applications has been demonstrated. The design consists of a conventional monopole antenna having a center frequency of 3.6 GHz, and a U-shaped slot embedded in the feed line of the monopole. The U-shaped slot provides the filtering property that is needed to limit the bandwidth to the desired value of 400MHz, and its length can be adjusted to control the bandwidth of the filtenna. Using CST Microwave Studio Suite, a comprehensive parametric analysis was performed to evaluate and optimize the characteristics of the proposed filtenna. The filtenna achieved a 412MHz band covering the frequency range (3.395-3.807) GHz. The filtenna showed a maximum gain of 2.577 dBi, a reflection coefficient of -22.96dB, and high rejection outside the operating band.

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