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MEMS Tunable Antennas to Address LTE 600 MHz-bands

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Abstract—The broadcast television spectrum around 600 MHz has been freed in the United States and will be put for auction to wireless carriers in 2015. The newest generation of mobile communication standards will be deployed on these newly available bands, to provide mobile device users with an enhanced connectivity. This paper proposes a novel antenna design that overcomes the bandwidth challenge of such low operating frequencies on handsets.

Index Terms—4G mobile communication, Antenna efficiency, Antenna measurements, Reconfigurable antennas, Mobile antennas, Multifrequency antennas.

I. INTRODUCTION

The fourth Generation (4G) of mobile communications standardized the Long Term Evolution (LTE) and LTE-Advanced (LTE-A) technologies, to provide higher data rates to consumers. 4G is being deployed on new and different frequency bands around the globe. This has led to band proliferation; consequently, mobile phone antennas need to cover nearly 40 bands in Frequency Division Duplex (FDD) and Time Division Duplex (TDD) [1]. World-wide mobile data access has multiplied the number of bands allocated to mobile communication by a factor 10, compared to speech-only specifications. 14 bands are defined in the low frequency range of the 4G spectrum and represent nearly all the frequencies between 699 MHz and 960 MHz. Additionally, part of the frequency spectrum previously used for television broadcasting is put for auction to carriers, specifically frequencies ranging from 600 MHz to 698 MHz [2].

Designing a handset antenna in the low bands of 4G is a real challenge for antenna engineers, as the antenna bandwidth and the operating frequency are inversely proportional with the antenna volume [3], provided a constant efficiency. Thus, to both lower the antenna resonance frequency and to enhance its bandwidth, the antenna volume needs to be increased. However, the antenna footprint must to be ever decreasing as newer generations of smart-phones appear on the market, promoting smaller and slimmer designs. Over the past decade, antenna engineers have pushed the lower bound of their design from 824 MHz, to 699 MHz, while reducing the antenna volume, which often caused efficiency degradation [4]. With the new bands at 600 MHz, the lower bound has to be pushed by an extra 100 MHz.

Tunable antennas have a great potential for enhancing the antenna bandwidth while keeping a low profile. Micro-Electro-Mechanical Systems (MEMS) are state of the art in terms of insertion loss, footprint and voltage handling, thus they are a great candidate for tunable antennas. This paper uses MEMS tunable capacitors and proposes a novel design to address 600 MHz-bands.

II. ANTENNA DESIGN

A. Antenna concept

Enabling world-wide roaming, i.e. calling services and high-speed mobile internet, requires the mobile device antenna to cover all LTE-A bands. Tunable antennas are very promising for fulfilling this requirement in mobile phones, since they can keep a low profile, while being reconfigured to a wide range of frequencies. Especially the low frequencies of the spectrum are challenging to address with a passive antenna design, due to the constrained volume dedicated to the antenna in modern smart-phones. Therefore, the use of tunable antennas is particularly relevant for the low-bands of 4G. The drawbacks of tunable antennas are the component insertion loss and the high unloaded Quality factor (Q) of the resulting antenna structure. The feasibility of a tunable antenna design lies in the trade-off between insertion loss and level of miniaturization.

While the channel bandwidths for the 600 MHz-bands are still unspecified, the LTE standard can support channel bandwidths ranging from 1.4 MHz to 20 MHz [1], specifically 1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz. Additionally, the spacing between the Transmitting (TX) channel and the Receiving (RX) channel (i.e. the duplex spacing) is likely to be between 10 MHz and 40 MHz, such that the minimum required antenna bandwidth could be as wide as 60 MHz. For operating frequencies as low as 600 MHz, a fractional bandwidth of 10 % is challenging to realize, while keeping an acceptable volume for a typical smart-phone. In the following, a tunable antenna is used to address these frequencies.

The work presented in this paper proposes to use a dual-resonance antenna in order to optimize the minimum required bandwidth, hence reduce the antenna volume. In the following, an example illustrates the above-mentioned, using a duplex spacing of 40 MHz, as well as channel

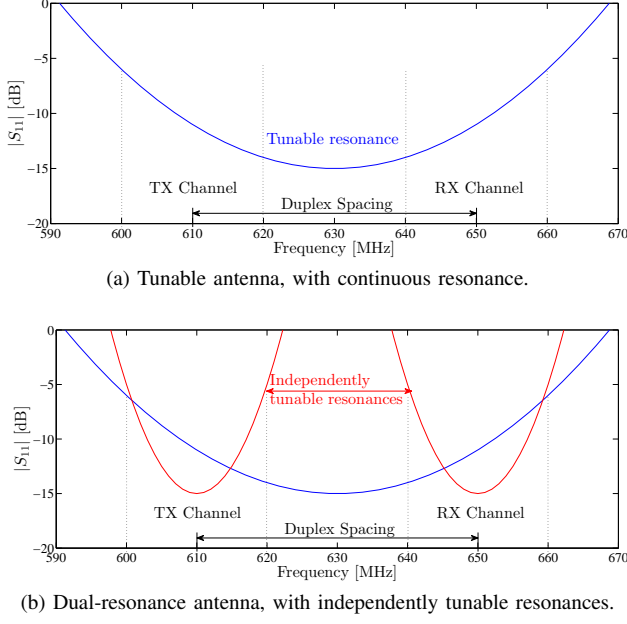


Fig. 1: Examples of antenna resonance behavior addressing the 600 MHz-bands.

bandwidths of 20 MHz each. Fig. 1a shows a typical antenna frequency response exhibiting a bandwidth of 60 MHz. Hereafter, the bandwidths are specified at a return loss of -6 dB, i.e. $|S_{11}| = -6$ dB. The resonance of Fig. 1a can be tuned, in order to cover all of the LTE low-bands. Implementing tunability and reducing the antenna resonance to its minimum required bandwidth (i.e. 60 MHz on this example) is interesting for antenna designers, as it allows them to reduce the volume occupied by the antenna. However, even within the minimum bandwidth there still are unused frequencies. For example, when the antenna transmits in the channel [600 - 620] MHz and receives in the channel [640 - 660] MHz the frequencies between 620 MHz and 640 MHz are not used. Nevertheless, they are still covered in the antenna resonance. This is shown in Fig. 1a. Additionally, if the channel bandwidths are narrower, e.g. 3 MHz or even 1.4 MHz, an even larger portion of the minimum required bandwidth is unused, if the duplex spacing remains 40 MHz.

In order to further optimize the minimum required antenna bandwidth, this paper suggests to use a dual-resonance antenna instead. A dual-resonance antenna covers only the channel bandwidths, and not the frequencies in between. An example of such an antenna frequency response is shown in Fig. 1b. Both resonances are tunable in order to address different operating bands. The resonances are also independently tunable in order to cope with different duplex spacings. In this way, the unused frequencies between 620 MHz and 640 MHz are not covered by the antenna resonance. In other words, the volume occupied by the antenna is optimized for the relevant frequencies of operation. The design illustrating this idea is part of a patent, the publication is in progress.

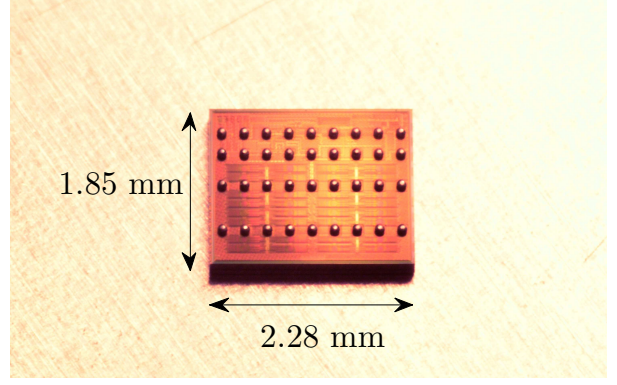


Fig. 2: MEMS tunable capacitors.

B. Antenna design

The antenna design used for this investigation rests on a rectangular ground plane of dimensions $120 \times 55 \text{ mm}^2$, in order to represent a typical smart-phone form factor. The volume occupied by the antenna is 1.4 cm^3 . The antenna exhibits a single feed and a dual-resonance behavior. Each of the resonances are independently tunable in order to cope with low-band tuning and with variable duplex spacings. Additionally, a wide-band resonance can be achieved by constructive addition of the two resonances, in a Chebyshev-like manner.

C. Antenna tuning

The tuning of the antenna resonance is realized with Micro-Electro-Mechanical Systems (MEMS) tunable capacitors from WiSpry [5], namely the die 1041. The dimensions of the die are $1.85 \times 2.28 \times 0.59 \text{ mm}^3$, as shown in Fig. 2. The supply voltage is 3.3 V and the power consumption of the tuner varies depending on the status of the device. At start-up, the tuner draws 6 mA for a duration of $200 \mu\text{s}$. While writing to the device, the consumption is $60 \mu\text{A}$. When it is in stand-by, it holds the capacitance set and draws typically $1 \mu\text{A}$. The power consumption of the MEMS tuner is very low compared to other tuning technologies.

The device consists of 4 independent tunable capacitors, each of them providing 2.30 pF with a resolution of 62.5 fF and a minimum capacitance of 0.46 pF. The antenna design uses a single device to tune from 960 MHz to 600 MHz, thus the two independent resonances share the tuner. That is to say, each of the independently tunable resonances uses half the total tuning range, specifically [0.92 - 4.61] pF can tune each resonance from 960 MHz to 600 MHz. The MEMS tuner exhibits a Q of 120 at 1 GHz and 200 at 600 MHz.

III. MEASUREMENT RESULTS

A dual-resonance antenna was manufactured and tested in order to measure the achievable efficiency of the proposed antenna concept in the low-bands of 4G. The measurements were done with the Stargate from Satimo, and the efficiency was computed with 3D pattern integration

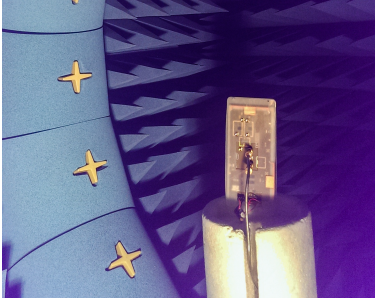


Fig. 3: Demonstrator in the measurement facility.

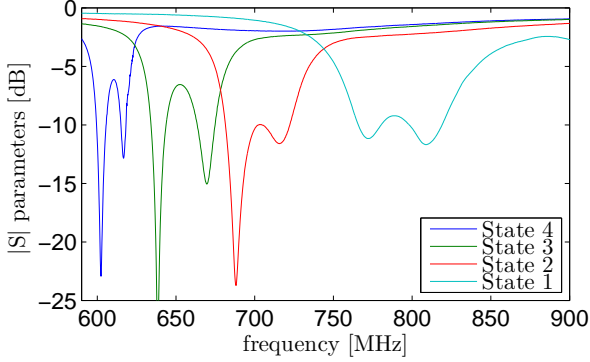


Fig. 4: Measured return loss in different tuning stages.

TABLE I: Bandwidths of Fig. 4

State	Total continuous bandwidth [MHz]
1	79
2	54
3	49
4	23

technique. Fig. 3 shows a picture of the demonstrator in the measurement facility. It can be seen that the coaxial cable is taken out from the center of the antenna ground plane, in order to minimize the currents running on it.

A. Antenna performance in the low bands of 4G

In this section the tunability over the low-bands of 4G is demonstrated. The demonstration focuses on low frequencies, as these are the most challenging ones to address on a small platform. Fig. 4 shows the frequency response of the tunable antenna between 597 MHz and 834 MHz. In this figure, the two resonances are juxtaposed, in order to show the maximum continuous bandwidth of every state. That is to say, the total antenna bandwidth exhibits a return loss lesser than -6 dB, for every state. The achievable bandwidths can be seen in Table I. It is clear that, the bandwidth shrinks, as the antenna is tuned towards lower frequencies. At the highest tuning state (state 4), the maximum continuous bandwidth is only one fourth of its value for the lowest tuning state (state 1).

For this particular antenna design, fitting in a 1.4 cm^3 volume, the continuous bandwidth configuration leads to certain limitations. For example, state 1, state 2 and state 3 can support all the channel bandwidths of the 4G standard.

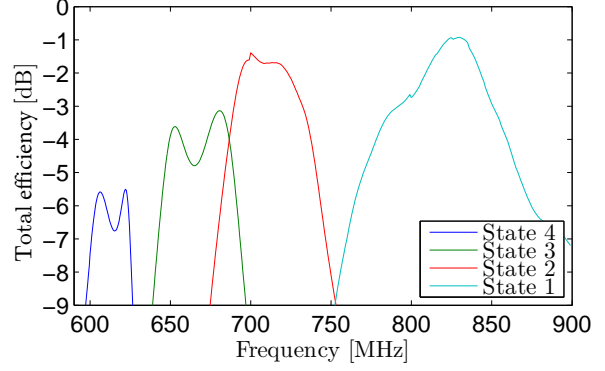


Fig. 5: Measured efficiency in different tuning stages.

However, state 4 can only support channel bandwidths of a maximum of 10 MHz. Moreover, the maximum duplex spacing that can be supported in state 4 is only 13 MHz, for the given antenna volume and for the configuration shown in Fig. 4. With a typical antenna design, exhibiting a single resonance (as shown in Fig. 1a), widening the duplex spacing would mean enlarging the antenna volume. That is undesirable for antenna engineers, when designing for small platforms, e.g. mobile phones. With the proposed dual-resonance antenna design, the authors show in the next section that it is possible to both keep the antenna volume (1.4 cm^3) and widen the duplex spacing, thanks to the implementation of independent tuning of the two resonances.

The total efficiency of the states 1–4 is shown in Fig. 5. As expected, the efficiency decreases, as the antennas are tuned towards lower frequencies. That is, as the antenna is tuned further away from its natural resonance, higher currents run to the tuner, causing a higher insertion loss. The antenna Q is not shown for the proposed design, since the formula relating the Q to the inverse of the bandwidth does not apply to dual-resonance antennas. At 600 MHz the total efficiency is -5.5 dB. Compared to phones on the market [4], [6], this is an acceptable performance for such low operating frequency. The peak efficiency of the tuned resonances is shown in Table II for all four states.

TABLE II: Efficiencies of Fig. 5

State	Peak efficiency [dB]
1	-0.9
2	-1.6
3	-3.2
4	-5.5

B. Antenna performance in the 600 MHz-bands

In order to cope with wide duplex spacings, the proposed antenna exhibits a dual resonance, where each resonance is independently tunable. In that way, the antenna can adapt to different duplex spacings, as it is tuned throughout the low-bands of 4G. In this section, different duplex spacing are investigated for the 600-MHz bands. The antenna performance is evaluated, as the duplex

spacing is varied, in order to assess whether the efficiency is deteriorated by widening the total bandwidth (sum of the TX channel bandwidth, the duplex spacing and the RX channel bandwidth).

In order to test different duplex spacings, one of the resonances is fixed at 600 MHz, while the other one is tuned to different frequencies, up to 650 MHz. This is equivalent to a maximum duplex spacing of 50 MHz. The MEMS tunable capacitor controlling the resonances exhibits the following characteristics for each resonance: a minimum capacitance of $C_{min}=0.92$ pF, a maximum capacitance of $C_{max}=4.61$ pF and capacitance steps of $C_{step}=0.0625$ pF. To test different duplex spacing on the 600 MHz-bands, the settings summarized in Table III are applied. The TX capacitor controls the resonance placed on the TX channel. In this case it is assumed that the TX channel is centered at 600 MHz. As this resonance is fixed, the capacitor value is fixed. It is set to 3.795 pF. The second resonance is tuned and it is assumed to be the RX channel. Therefore, this resonance is controlled with the RX capacitor, which varies from 3.295 pF to 3.67 pF.

TABLE III: Capacitance values for different values of duplex spacing

State	TX capacitor [pF]	RX capacitor [pF]
4.1	3.795	3.295
4.2	3.795	3.42
4.3	3.795	3.545
4.4	3.795	3.67

The frequency responses of these different configurations is shown in Fig.6. The channel bandwidth remains 10 MHz while the duplex spacing varies from 20 MHz to 50 MHz. For each of these configurations, the total antenna efficiency is measured. It is plotted in Fig. 7. One can observe that the antenna efficiency is rather stable, with respect to varying duplex spacing. The peak efficiency remains around -5.5 dB in the 600 MHz-bands. Using a dual-resonance design with independently tunable resonances allows to cover the required bandwidth for LTE technology at 600 MHz, while keeping a small size and an acceptable total efficiency. Note that in a typical single resonance design, widening the bandwidth would result in enlarging the antenna volume and maintaining the efficiency, or in keeping the antenna volume but sacrificing the efficiency. It is demonstrated here that the dual-resonance antenna can widen its total bandwidth, keep its volume and maintain its efficiency.

IV. CONCLUSION

A dual-resonance antenna is being used to address LTE at 600 MHz. This behavior allows to cope with wide duplex spacings, while keeping a low profile antenna design, i.e. a volume of 1.4 cm^3 and a peak efficiency of -5.5 dB or better. LTE services at 600 MHz are possible on a handset, and nowadays high-Q tuning technology makes it an attractive solution for commercial phones.

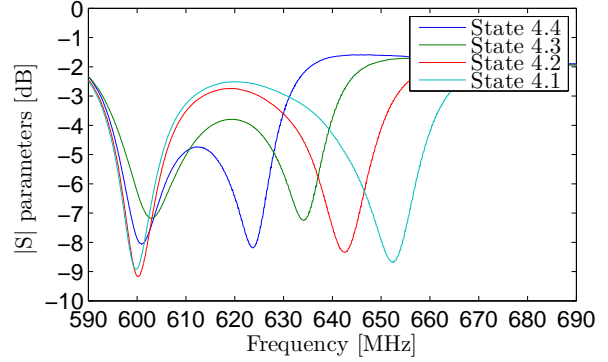


Fig. 6: Measured return loss in 600 MHz-bands.

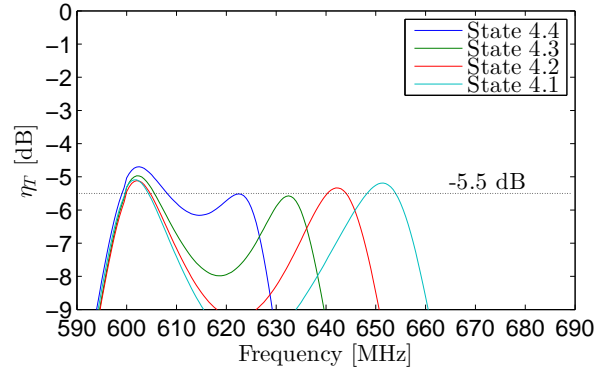


Fig. 7: Measured total efficiency in 600 MHz-bands.

V. FUTURE WORK

The low-band antenna design will be combined with another antenna that can address the high bands of 4G. The high-band antenna does not necessarily need to exhibit a dual-resonance, since the trade-off between volume and bandwidth is not an issue for high frequencies. Additionally, multiple antenna systems will be investigated, especially the antenna coupling at 600 MHz.

ACKNOWLEDGMENT

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