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Implementing Wideband Monopole/Dipole Antennas on Paper Substrates

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Abstract — **Advanced internet and multimedia set-top boxes are today massively based on 4*4 MIMO systems, with multi-sub-bands standards (Wifi bands, LTE, Bluetooth,…). Multiple antennas spatially distributed on the plastic casing become therefore a great challenge for cost and performances motivations, thus promoting flexible technology and substrate, for assembling sub-systems, under compactness considerations, as well as electrical performances improvement.**

In this paper, we discuss about the characterisation of Multi-band antennas designed on an ultra-low cost material (a cellulosic substrate, i.e. a paper) with design challenges in terms of radiation efficiency maximization and wideband properties under compactness constraints. Simulation and measurements are proposed to validate the designs.

Keywords – **wideband antennas, Flexible Printed Circuit, paper substrates, conformable structure, integrated balun**

I. INTRODUCTION

Antennas are usually processed on substrates external to the main PCB (Printed Circuit Board) of electronics devices. This is mainly due to the limited electrical properties (in terms of losses and high frequency operations) of conventionnal low cost PCBs usually considered as mechanical supporting structures only for digital sub-systems (processors, memories, basic electronics modules). Nevertheless, with the extensive use of multi-antennas wireless links, especially for internet of multimedia set-top-boxes which have to support simultaneously an increasing number of standards, specific constraints such as radiation efficiency (thus using low-loss cost effective thin substrates), spatial diversity for MIMO schemes (with up to 4*4 colocated antennas per standards) are expected, leading to multiple input-output interconnections from the main PCB. In addition, antennas are usually processed on substrates external to the main PCB, so as to address specific constraints such as radiation efficiency (thus using low-loss cost effective thin substrates), spatial diversity for MIMO schemes (then requiring up to 4*4 colocated antennas per standards and multiple interconnections towards external substrates preselected for their electrical performances at high frequencies, up to 6GHz).

The flexibility is also required regarding geometrical implemenation of those different antennas, with spatial diversity for MIMO scheme performances, and drastic constraints in terms of decoupling and environment perturbations with surrounding elements of set-top boxes such as radiators and other metalized parts (display, batteries,..).

For such purpose, flexible substrates produce new opportunities and are widely used today to adress theses different integration and interconnection challenges. Nevertheles, cost has to be considered to remain compatible with well-controled low cost industrial process (for instance stamped metal antennas mechanically inserted in plastic casing).

The "Stick'It" project ("Printable passive antenna system in a conformable structure") aims to develop innovative low-cost technologies for the design of 2D and 2.5D RF interconnection components and sub-systems printed on flexible materials such as paper substrates and plastic films. The development of such substrates will make paper, in the near future, an excellent candidate for ultra-low-cost, flexible, and environmental friendly electronic systems.

We have tested different metallization methods and cellulosic based substrates for evaluating a new family of ultra-low cost interconnection substrates. In [1], we presented the design and characterisation of microstrip transmission lines screen-printed on a 240 μm thick E4D paper substrate (experimental dielectric properties: ε r = 2.54 and tanδ = 0.05), with a 7μm thick silver ink metallization. The next step consists here in the design of multi-frequency antennas (either multi-band or ultra-wide frequency band) on these flexible substrates (paper and PET). Antennas such as Vivaldi and monopole type are good candidates for wireless multimedia applications due to their wideband property.

In this work, we present different topologies of antennas processed on a E4D paper substrate, with multiband frequency performances covering the 2.4 and 5GHz Wifi frequencies. Part II describes a bi-band monopole antenna, with a double C configuration. An improved and original configuration of a wide band dipole is proposed in Part III.

II. DUAL-BAND MONOPOLE ANTENNA (2.4 GHZ/5.5 GHZ)

We have developed monopole or dipole type antenna with multi-frequencies performances in order to satisfy the multi-standard communication requirements of advanced multimedia set-up boxes.

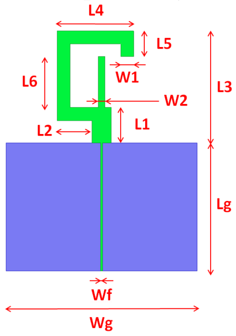
The antenna must cover at least two frequency bands 2.4 – 2.5 GHz and 5.15 – 5.85 GHz, with omnidirectional radiation pattern and minimum 60% radiation efficiency. Of course, manufacturing constraints are to be considered regarding the available fabrication technology. Most importantly, the antenna size is very limited to permit its integration into a set-top-box by sticking it on plastic sidewalls of the casing. Specifically, the length of the radiator and ground should not exceed 3cm (height of the electronic box).

Many solutions of planar dual-band monopole have been reported in the literature for wireless applications [2] [3]. All these antennas have two frequency bands which can be controlled independently. However, many of them have a quite large size not compatible with the required compactness feature. Therefore, we have chosen a folded monopole, inspired from Jyoti et al, 2011 [2] to implement a dual-band monopole structure. The expected bandwidths for WLAN applications can be reached, considering also miniaturization criterias (use of meandered lines) with simple geometry. The main drawback is probably its non-ideal monopole-like radiation pattern at 5.5 GHz due to the influence of the long C branch.

1) *Dual frequency behaviour*

This dual-band Wi-Fi monopole has been designed by parametric optimization for WLAN applications at 2.4 - 2.5 GHz and 5.15 - 5.85 GHz. The layout and the prototype of this antenna screen-printed on E4D-100µm paper are shown on *figure 1*.

This monopole, with a compact size (17.5 x 12 mm^2), exhibits two resonance frequencies and two associated bandwidths that can be controlled independently.



Wf	0.33mm
Wg	30mm
W1	2mm
W2	1mm
Lg	20mm
L1	5.5mm
L2	5.5mm
L3	17.5mm
L4	12mm
L5	4mm
L6	8mm

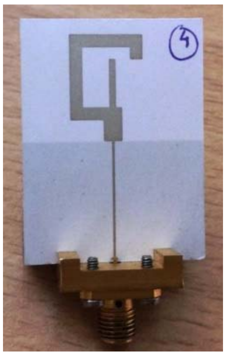
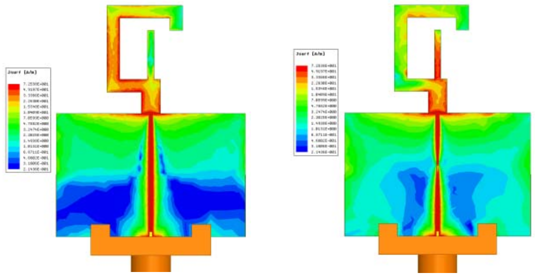


Fig. 1. Layout and prototype of the dual-band Wi-Fi monopole antenna, screen-printed on E4D-100µm paper

It has two radiating elements: a hook-shaped branch for the low frequency band and a straight branch for high frequencies. Its structure is also simple, appropriate for the double-sided printing process on paper substrate, and there are no special technical requirements for antenna fabrication (no via holes realization, for example).

The behavior of the antenna has been studied through the visualization of current distributions using HFSS EM-simulations in order to verify the independence of the two frequency bands (2.4 and 5.5 GHz - see *figure 2*). It can be seen that the hook-shape branch has a high current density and appears to be “active” at 2.4 GHz (see *figure 2a*). On the other hand, the straight branch is more “active” at 5.5 GHz. It can be seen that the current is concentrated mostly around the straight branch (see *figure 2b*).

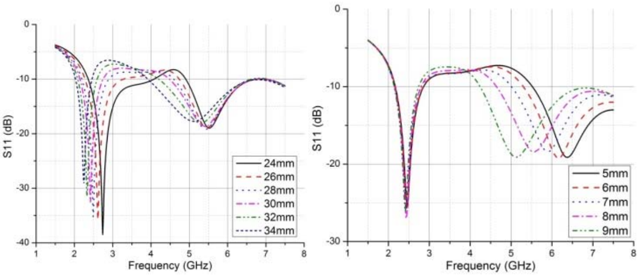


(a) (b)

Fig. 2. Simulated current distribution at: (a) 2.4 GHz and (b) 5.5 GHz.

2) *Parametric study*

The two branches appear as quite independent in terms of electrical behavior in the two sub-bands. Thus, a parametric analysis has been carried out by varying one of the effective length parameters while keeping constant the other length parameters of the antenna to reach the optimized dimensions, as illustrated in *figure 6a & b*.



a) b)

Fig. 3. Effects of changing L3 and L6 on the 2.4 GHz and 5.5 Ghz frequencies

The resonance frequencies, as well as the associated bandwidths of the antenna, are sensitive to the length of each branch. Hence, the performance of this antenna could be sensitive to the fabrication process tolerances. However, considering the printing technology accuracy (about ±0.05 mm), a negligible impact has been observed.

The return loss S_{11}, radiation patterns and gains of this antenna at 2.4 GHz and 5.5 GHz were measured to be compared with the EM simulations. A small metallic support (10x30x10 mm^3) was used to attach the SMA connector to the antenna for measurements.

A reasonably good concordance was obtained between the measurement and the simulated S_{11} parameter. Obviously, the agreement is improved when the connector and the attached cable is considered. The simulated, respectively measured return loss, are displayed in figure 4, yielding a 1st frequency at 2.4 GHz (0.64 GHz bandwidth, respectively 0.44GHz @TOS=2) and a 2nd frequency at 5.5 GHz (2.22 GHz bandwidth, respectively 1.55GHz @TOS=2).

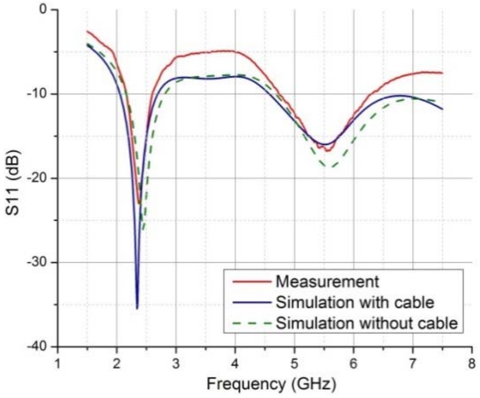
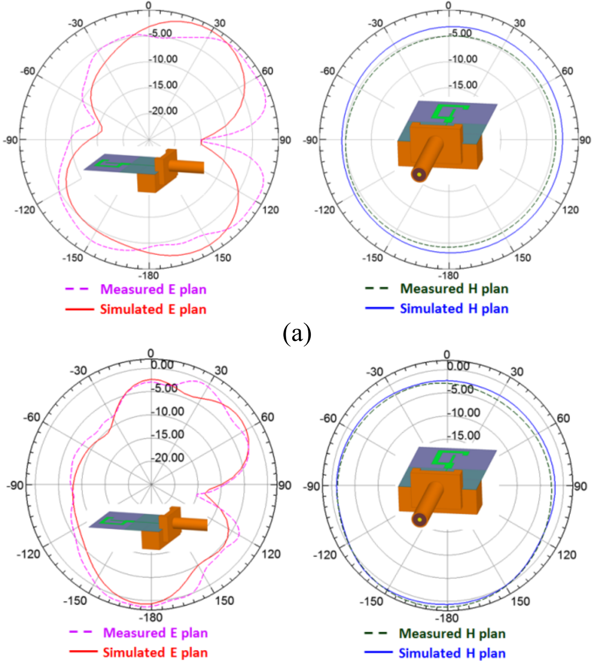


Fig. 4 Return loss S_{11} of this dual-band Wi-Fi monopole antenna

3) *Radiation patterns measurement*

The radiation patterns measured at 2.4 GHz and 5.5 GHz with a MVG Stargate® system (SG-24) show a good agreement with the HFSS simulations (cf. *figure 5*). It can be observed that the H-plane radiation patterns are almost omnidirectional at both resonant frequencies. At 2.4 GHz, the simulated and measured results exhibit a bi-directional monopole-shape radiation pattern in the E-plane. The E-plane graph is slightly tilted and distorted due to the influence of the attached connector with the metallic support. At 5.5 GHz, we have no longer a bi-directional monopole behavior in the E-plane due to the influence of the hook-shaped branch into the radiation pattern of the straight branch.



(a)

(b)

Fig. 5 E-Plane and H-Plane radiation patterns of dual-band Wi-Fi monopole antenna at: (a) 2.4 GHz and (b) 5.5 GHz

The simulated and measured max realized gains versus frequency (*figure 6*) are also fairly consistent: 1.42dBi and 1.87dBi at 2.4 GHz, 3.21dBi and 4.1dBi at 5.5 GHz, respectively (excluding insertion losses in the 20 mm feed line: 2.1 dB at 2.4 GHz and 3.1 dB at 5.5 GHz).

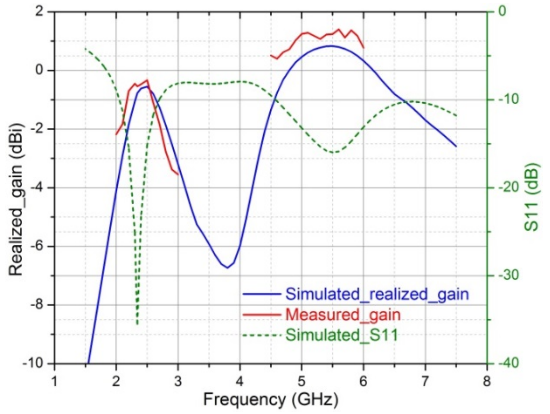


Fig. 6 Simulated and measured realized gain of the antenna versus frequency

III. PLANAR DUAL-BAND DIPOLE ANTENNA (2.4 GHZ/5.5 GHZ)

Dipole antennas usually exhibit a wider impedance bandwidth than monopoles. We consequently investigate a dual-band dipole prototype that is intended to be stuck on the sidewall of a set-top-box for WLAN applications (2.4 GHz and 5.5 GHz). We have developed a new model of broadband dipole antenna, which was screen-printed on E4D-210µm paper. The form factor was optimized, as depicted in *figure 7*, to extend the bandwidth while reducing the overall size. Considering such wideband dipole antenna, the innovation lies also on the implicit integration of the balun.

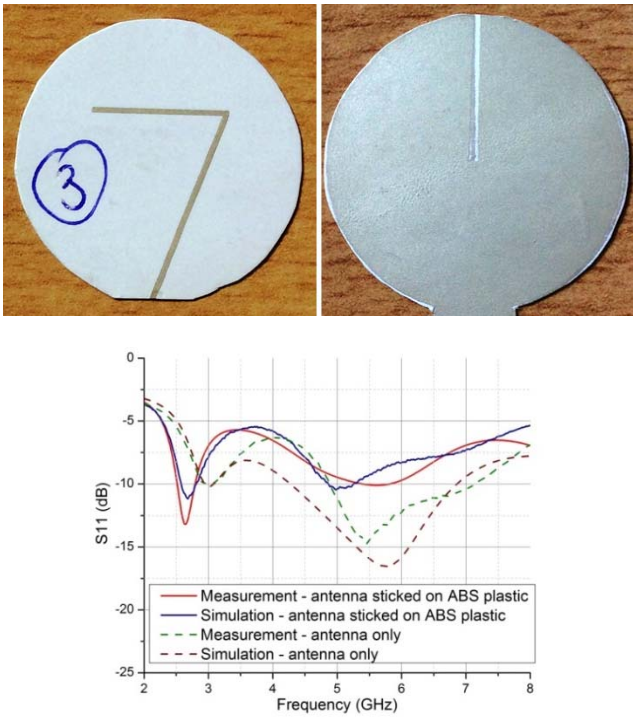


Figure 7: *Prototype and return loss of a modified ultra-wideband dipole*

The structure was then adjusted to improve the impedance matching and to add a second sub-band for the dual-band Wi-Fi dipole antenna. Two slots are inserted to modify the current distribution and generate a second resonance at 5.5GHz. The second dipole is inserted into the first one to create two dipole antennas (one operates at 2.45 GHz and the other at 5.5 GHz) on the same radiation structure, as presented in *figure 8*. The circular ground plane was also truncated to reduce the overall size of the antenna and to decrease the length of feeding line to 21 mm (so, reducing the insertion losses in the feed line) [4].

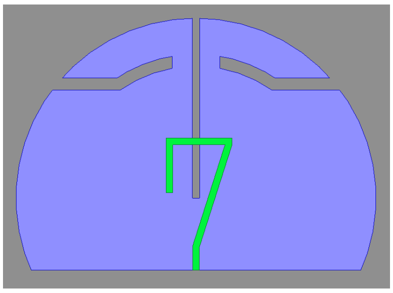


Fig. 8 New Prototype of the dual-band Wi-Fi dipole antenna, screen-printed on E4D-200µm paper

This dual-band Wi-Fi dipole exhibit two bandwidths @ [2.4 - 2.63 GHz] (9.2% @ROS=2) and [4.59 - 6.43 GHz] (36.1%). A fairly good agreement was obtained between the measurement and the HFSS simulation of S_{11}.

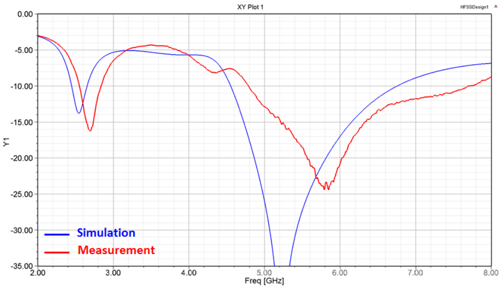


Fig. 8 - S11 measured and simulated dual-band Wi-Fi dipole antenna

The simulated max realized gain of this dipole is -0.23dBi at 2.5 GHz and 3.3dBi at 5.5 GHz, respectively. The simulated total efficiency was 54.8% at 2.5 GHz and 92.2% at 5.5 GHz, respectively (excluding losses in the 21mm feed line). The planar dual-band dipole shows also a good performance in terms of radiation pattern, gain and efficiency and appears as a good solution for the final antenna system

IV. CONCLUSION

During the conference, we will present the complete experimental and simulation results concerning both transmission lines and antennas performed on paper substrates. The simulations are almost in good agreement with the measurement results. Antennas printed on paper operates up to at least 6 GHz. The next issue of the work will concern a final demonstrator using spatially distributed antennas for radiation patterns and consequently special diversity and multi-standards capabilities.

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