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AUTOMATCH

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WHITE PAPER

A LOW COST DYNAMIC ANTENNA TUNING SOLUTION

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SUMMARY:

This paper presents the fundamentals of antenna tuning and impedance matching, and describes an innovative low cost dynamic antenna tuning solution developed by ALCIOM. This approach, applicable in particular to 169MHz, 868 MHz or 2.4 GHz systems (either LoRa, Bluetooth/BLE, Wi-Fi, ZigBee, etc), requires only standard parts. Preliminary tests shows that a typical 60% power budget increase is achievable against a fixed matching solution, reducing power requirements by nearly 50%, with a bill of material cost increase as low as 2$ in volumes.

This solution was developed by ALCIOM through an internal R&D program financed by BPI FRANCE.

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02/09/15	1A	LUCIEN THIRIET	Initial version
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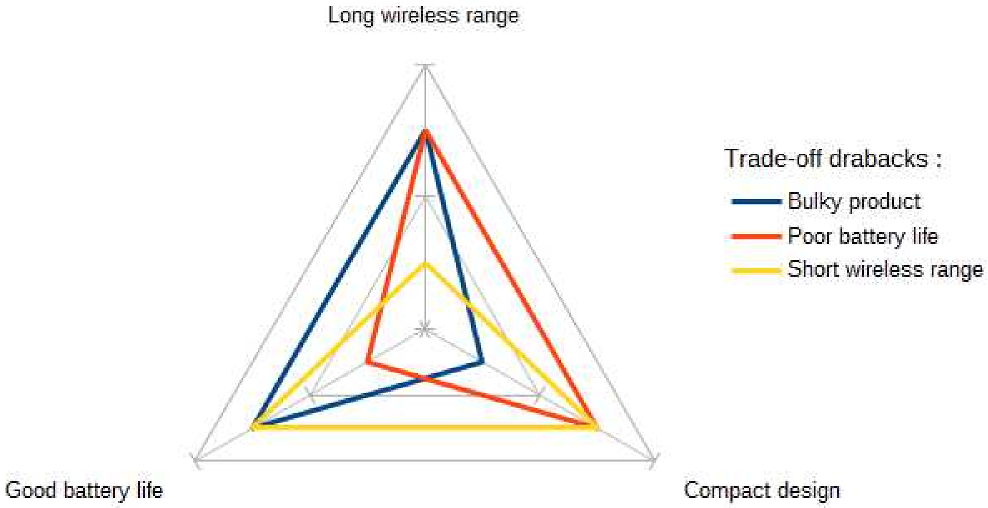
1 Introduction

Internet of Things (IoT) products are a big trend in consumer electronics. More specifically, watches, wristbands and other wearables have hit the market. They are typically wireless, battery-powered, autonomous devices. For such products, the key requirements are usually a long battery life, a good wireless range and a compact design. The same requirements are applicable to industrial projects like smart metering devices.

Unfortunately, those are three opposing factors:



A trade-off usually has to be made between the three.

If more wireless range is needed, RF power can be increased . A bigger battery is therefore needed, but this is often impossible because the device has to keep its compact shape. In that context, **the optimization of the built-in antenna is a key success factor**: a better antenna allows to either achieve a longer communication range or to reduce the power requirement for the same RF performances.

However, IoT and smart metering devices have another constraint related to the antenna: they are physically small. This has two downsides : firstly the antenna must be small (e.g. ceramic antennas), and unfortunately the laws of physics imply that a small antenna with reasonable gain has a high quality factor, meaning the antenna will be very narrow-band. Secondly, due to the small product size, the antenna will inevitably be close to the vicinity and will therefore be **easily detuned** by close-by objects, and this is an issue especially with a narrow-band antenna. For example a wrist-band wireless sensor may have a well-optimized antenna, but will have drastically reduced RF performances when it is not wore on the arm. Similarly a smart meter may have a very well tuned antenna but could have drastically reduced performances if it is installed close to a metallic tube.

How to solve this difficulty ? One of the best solutions is to include in the product a **dynamic antenna tuning** circuit, able to automatically modify the impedance matching network of the antenna depending on its environment. These techniques are **well-known** for professional wireless systems but u**sed to** be costly and are often perceived as **difficult to implement** especially for mono-directional links were no information on the quality of the wireless link is available.

This paper presents the fundamentals of antenna tuning and impedance matching, and describes an innovative low cost dynamic antenna tuning solution developed by ALCIOM : AUTOMATCH. This approach, applicable in particular to 169MHz, 868 MHz or 2.4 GHz systems (either LoRa, Bluetooth/BLE, Wi-Fi, ZigBee, etc), requires only standard parts. Preliminary tests shows that a typical 60% power budget increase is achievable (2dB) over a traditional fixed matching network, reducing power requirements by nearly 50%, with a bill of material cost increase as low as 2$ in volumes.

This solution was developed by ALCIOM through an internal R&D program financed by BPI FRANCE.

2 Antenna tuning and impedance matching

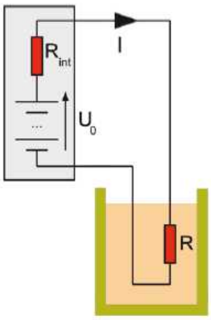
2.1 *Why impedance matching is a concern ?*

A source and a load are said matched when **the power transfer from the source to the load is maximised**. As it will be explained here below, this is achieved when there is a precise relation between the impedance of the load and the impedance of the source. Matching therefore is a must for minimum power losses, and is often referred as **impedance matching**.

In the case of wireless devices, power is a scarce resource : the lower the losses then better the wireless link in terms or coverage and/or error rate. So **taking care of impedance matching is critical for good RF performances**. And the most critical matching issue is usually between the antenna and the electronics, meaning the receiver and/or transmitter chipset. Why ? Simply because the impedance of an antenna could be quite different from design to design, whereas the impedance of an electronic design is usually well defined (and commonly set to the 50-ohm standard impedance).

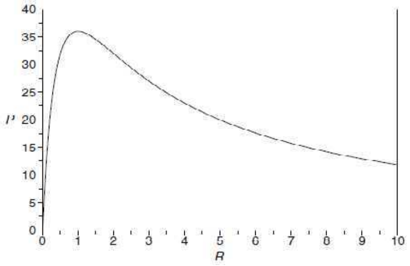
2.2 *A DC matching example*

Let’s take the most basic example first: a DC-powered heater. Suppose that you have a battery pack with an internal resistance Rint equal to 1 ohm and you want to use it to heat your coffee during a cold winter night. You could connect a heating resistor between its two terminals, but what would the optimal value R for this resistor have to be to enable you to use your battery’s energy in the most effective way?



If you use a high-value resistor, the current going through it will be small, so dissipated power will be low. Conversely, if you use a very low-value resistor (close to a short circuit), then the current will be very high; but the power dissipated in your resistor, which is the current times the voltage, will be very low because the voltage across a short circuit will be nearly zero. In fact, in this last case, a lot of power will be dissipated, but it will happen in the battery’s internal resistance and not in your heating resistor. So, there is an intermediate optimal resistor value for maximum power transfer from the battery to your resistor. This value is 1 ohm, the same as the source resistance. It’s easy to calculate:

$$P = R \cdot I^2 = R \cdot \left(\frac{U_0}{R_{int} + R} \right)^2 = \frac{R}{(R_{int} + R)^2} \cdot U_0^2 \qquad I = \frac{U_0}{R_{total}} = \frac{U_0}{R_{int} + R}$$



When the load impedance is 1 ohm, the power transferred to the load is maximum (36 W). R is therefore matched with Rint. **For any other load value the transferred power will be lower.**

2.3 AC impedance matching

The same calculation is applicable in AC, though there are some minor differences:

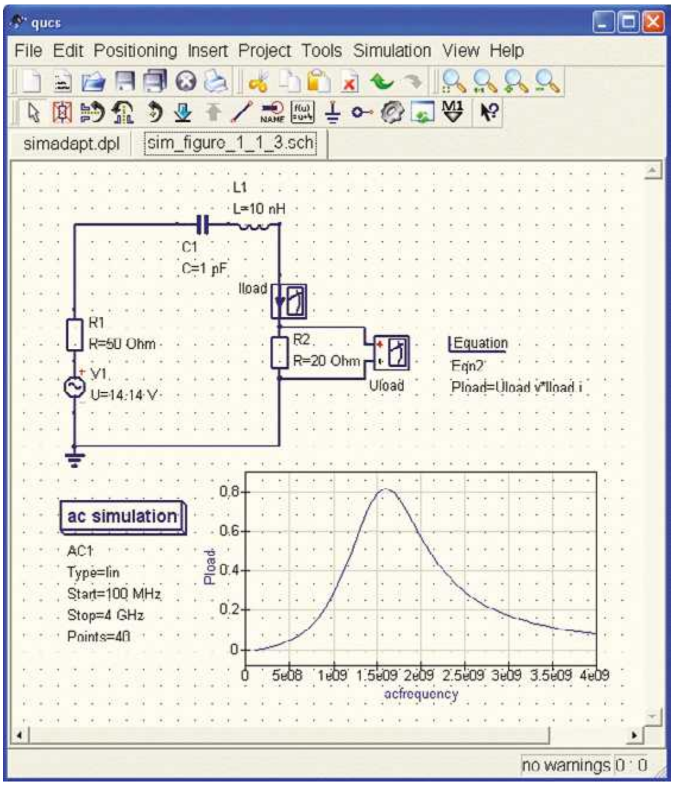
- Resistance becomes **impedance** (real resistance R + complex reactance X, giving R+jX)
- Matching is achieved when the source impedance Zs is the **complex conjugate** of the load impedance Zl, meaning that both resistances are equal (Rs = Rl), but both reactances are equal in value but with an opposite sign (Xs = –Xl).

It is worth nothing that reactance is function of frequency, that is to say an impedance measured at freq A may not be the same if measured at freq B. For example, here is how to calculate the impedance of a capacitor and an inductor:

$$Z_C = \frac{1}{j\omega C} \quad Z_L = j\omega L$$

Consequence is that an impedance matching in AC is dependent on the frequency. This must be kept in mind when designing a circuit or matching impedance.

Let's see an example. Every antenna is in fact a complex load, involving a real and a complex value, which vary following frequency, and can be modelled as a series RLC circuit. Assume that we have an antenna that behaves like a 20 Ω resistor, in series with a 10 nH inductor and a 1 pF capacitor. Let's assume that the antenna can't be changed. It is easy to calculate the power transfer from a 50-ohm source to this antenna for a varying carrier frequency. Here is a QUCS simulation:

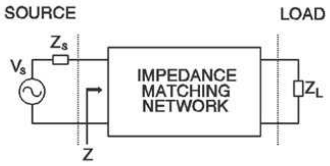


Can we use this antenna at a frequency of 2.4 GHz? What will be the transmitted power? As shown on the simulation, this antenna resonates at 1.59GHz. This is the frequency where the capacitor and the inductor impedances cancel out each other and the power transfer is maximal. The antenna is said to be tuned for 1.59GHz. At that frequency, the antenna behave like a 20 Ω resistor, so the matching isn't perfect : The power transfer is 80 % of the available power. But what about using this antenna at 2.4 GHz? Only 35 % of the power would be transmitted, as can be seen on the simulation. 65 % of the power is then lost, this is the mismatch loss.

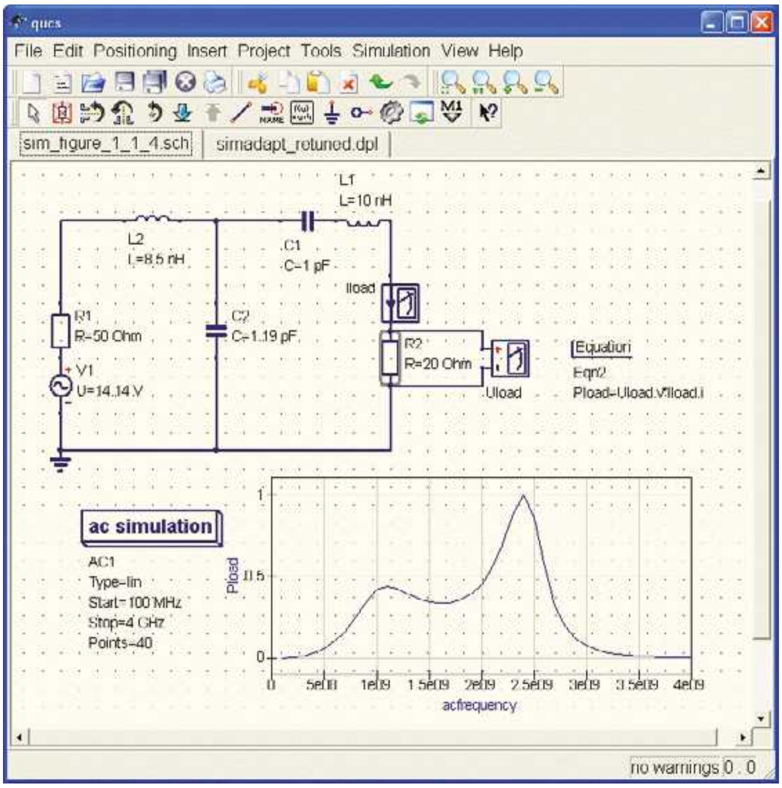
This mismatch loss is directly related to two other measurements of the antenna mismatch, namely VSWR (standing wave voltage ratio) and return loss. The following table gives the correspondence :

SWR	ρ	Return Loss (dB)	Mismatch Loss (dB)	Power To Load[1]
1.1	0.05	26.44	0.01	100%
1.2	0.09	20.83	0.04	99%
1.5	0.20	13.98	0.18	96%
2	0.33	9.54	0.51	89%
2.5	0.43	7.36	0.88	82%
3	0.50	6.02	1.25	75%
5	0.67	3.52	2.55	56%
10	0.82	1.74	4.81	33%
20	0.90	0.87	7.41	18%
50	0.96	0.35	11.14	8%

Now how to improve the situation, assuming once again that the antenna can't be physically changed and that the source is and stay a 50-ohm source ? Simply by introducing an impedance matching network between the antenna and the RF source. This will tweak the impedance seen by the source, leading it to be as near to 50 Ω as possible, thus maximizing power transfer.



In the example above we could add a well calculated serial inductor and parallel capacitor. As shown on the simulation below this has two effects : firstly the antenna and its matching network will now resonate at 2.4GHz (we have retuned the antenna thanks to the matching network), and secondly the impedance of the antenna plus matching network is now 50 ohm at the resonant frequency, providing a 100% power transfer efficiency :



Equation
Eqn2
Pload=Uload.v*Iload.i

AC1
Type=lin
Start=100 MHz
Stop=4 GHz
Points=40

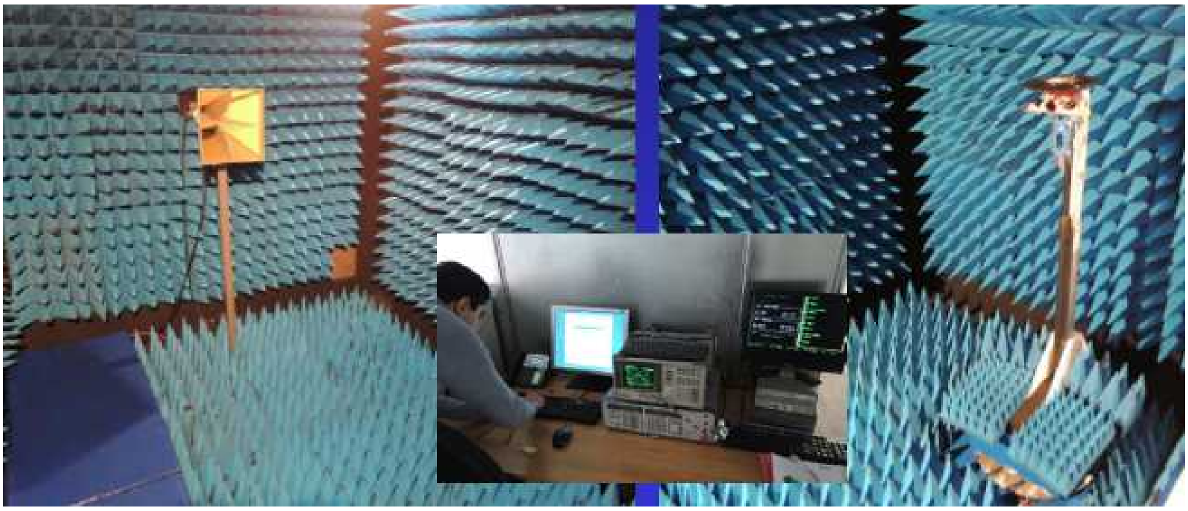
2.4 Standard antenna tuning method

Adding such a matching network is theoretically always possible and could always gives a 100% efficiency. Unfortunately this is far from exact in real life, as the matching parts could be impossible to buy and have never a perfect quality factor : Parasitic components like wire inductance, pad capacitance etc jeopardize the theory quite often. More importantly such a matching network is narrow band : The antenna will have the proper impedance matching only at a precise frequency. And **the higher is the initial mismatch the narrower will usually be the matching**...

Nevertheless, **antenna matching is a vital step in the development of nearly all wireless devices**. Usually a matching network is planned at the schematic and routing phase, and then the actual antenna impedance is measured thanks to a vectorial network analyzer (VNA) as soon as a prototype is ready. Such an equipment can deduce real and complex values of an unknow impedance, through measurement of the phase and amplitude of the reflected signal.

An example of ALCIOM's VNA : the MS2036C from Anritsu

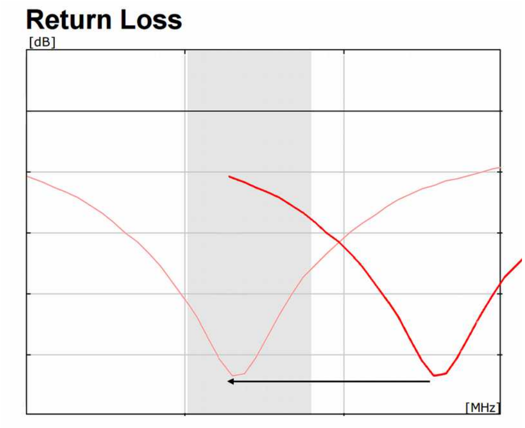
The proper matching network is then calculated, populated on the board and verified. Lastly the resulting performance of the antenna is measured in an anechoic chamber.



ALCIOM's anechoic chamber

2.5 *Antenna de-tuning in real life*

But what happens to the antenna impedance in real life ? What happens for example if we get our hand close to an antenna?



As soon as the hand enters the so-called close-field area of the antenna, the hand becomes in fact part of the antenna. The antenna couples to the hand, which has a given dielectric constant very different than air (and is conductive to some degree). This creates a change in its impedance, and the calculated matching network is no longer efficient. Maximum power is then no longer delivered to the load (antenna + matching circuit) and the far-field received signal strength is reduced.

The problem is not minor. If 3 dB are lost by mismatch, then half the power is lost. This reduces wireless range and/or signal quality. In real life, way more than 3 dB can be lost... This phenomenon is especially important in two application areas where ALCIOM is very active :

- **IoT devices**, which are usually very small products with huge variations in their surroundings (carried in a pocket, weared, put on a wall, etc).

- **Smart meters**, which requires very efficient wireless links and which are very susceptible to antenna detuning due to the small antenna size as compared to the wavelength and complex installation scenarios.

In a nutshell an antenna impedance varies as soon as its vicinity changes. This is especially true for small antennas, which are inherently very narrow-band due to the laws of physics, and thus are very sensitive to near-field disturbance. Therefore :

1. **Measuring the actual impedance of an antenna on a prototype and adding the proper impedance matching network is an imperative step in the development of nearly all wireless devices, and especially the small ones. If not, RF efficiency could be drastically lower than expected ;**

2. **This measurement must be done with the product installed in a “typical configuration” with a reasonable simulation of its vicinity.**

3. **In real life the antenna will be detuned as the vicinity will very probably not stay stable. This will be a problem for narrow band antennas, and the smaller the antenna the narrower the bandwidth for the same antenna gain...**

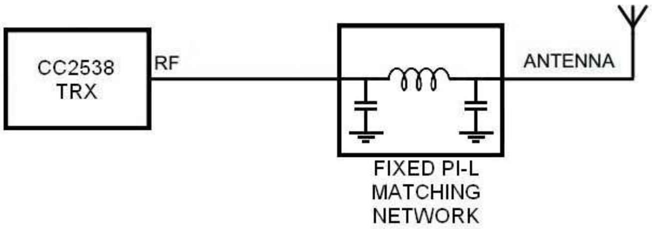
3 Dynamic antenna tuning

3.1 Introduction to dynamic matching

As discussed before, matching networks must be calculated with the antenna placed in its final nearby environment (e.g. within the product enclosure, on the skin...). With a fixed matching network, especially with high-Q, optimum performance cannot be guaranteed in all use cases. For products with well-known and fixed surroundings, this is not a problem. However, this is an issue for products with unknown or varying use environment.

For example, a watch connected via Bluetooth to a smartphone can have a good wireless link when wore on the wrist, but lose signal when left on a table or on its charging stand. Because of antenna detuning, the designer can be forced to increase RF power, which is often achieved by adding a range extender/booster IC (PA+LNA) right after the radio TX/RX. This kind of solution implies an extra cost for the booster (approx. 1 to 2 € in medium volume), and has a drastic downside effect on the battery life. Moreover, as the antenna mismatch occurred both on the RX and TX paths this leads to increased radiated powers and therefore radio spectrum pollution. This could be problematic on the regulatory side as well.

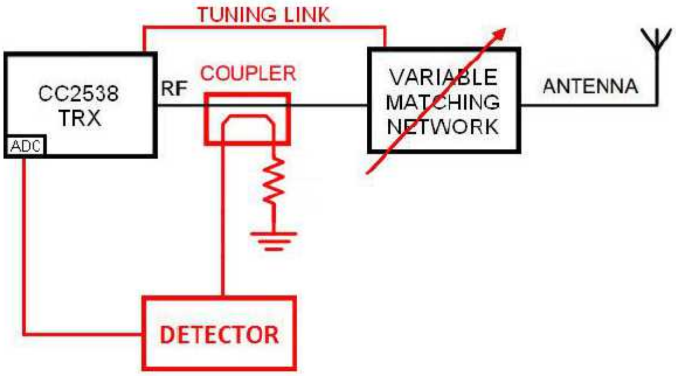
Here is an example of a typical ZigBee (2.4 GHz) transceiver circuit, with a PI antenna matching network:



To tackle the problem at source, we must correct the antenna impedance as it changes with the vicinity. In order to ensure this, the circuit must includes two modifications :

1. The matching network must not be fixed, but variable : As nearby environment changes, a **variable antenna matching network** can be employed so as to always ensure maximum power transfer to or from the antenna.

2. To automate the process, a way of **measuring the actual matching performance** is needed. For two-way systems this could be done by monitoring the received signal strength (as long as the initial matching is good enough to establish the link), however for one-way systems or high mismatch configurations then the device must integrate a way to measure the power reflected by the antenna, ie a kind of build-in network analyzer.



Such a technique is commonly referred to as **dynamic antenna tuning**. It avoids mismatch losses for transmission **and** reception, avoids the need for increased power use and spectrum pollution. It can even be employed in the event of frequency shifts (different channel or RF band), for example to use a narrow-band antenna on a wide frequency range.

3.2 ALCIOM's work on dynamic matching : The AUTOMATCH project

The idea of a dynamic antenna tuning is not new, it is **well-known** both for ham-radio and for professional wireless systems. However it used to be costly and often perceived as **difficult to implement** especially for mono-directional links. This explain why it is not very common in consumer electronics so far except in some mobile handsets. Dynamic matching solutions used to be out of budget for cheap small devices and in particular IoT devices and smart meters.

Ealy 2015, ALCIOM has launched an internal R&D project, named AUTOMATCH, to investigate low cost alternatives potentially applicable to these kind of devices. It should be emphasized that this R&D project was funded by BPI FRANCE thanks to the SRC certification of ALCIOM.

Our goal was to design a technological demonstrator with the following targets :

- Ability to correct typical antenna detuning for small-size devices ;
- Applicable to all ISM frequency band (typically 169MHz/868MHz/2.4GHz) ;
- Low incremental transmission loss as compared to fixed matching solution (1dB maximum)
- And last but not least incremental cost close to the cost of a range extender (2Eur typically).

The solution we designed relies on the following architecture :

1. Design of a low loss variable matching network using MEMS technology.

2. Design of an ultra-low cost reflection bridge and detector, using discrete components for flexibility and cost-efficiency

3. Use of the computing resources of the SoC TRX, which typically integrates a programmable microcontroller with digital and analog I/Os, avoiding the use of an external microcontroller to handle the dynamic tuning algorithm and variable network operation.

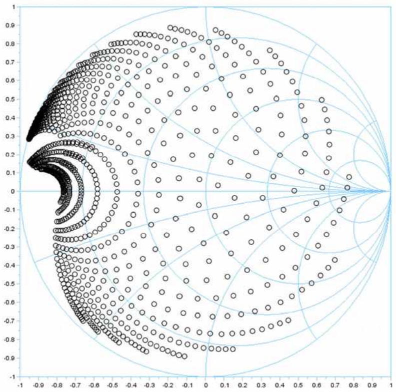
4. Development of automatic tuning algorithm to achieve a proper tuning as fast as possible. This tuning can even be done during the sending of the preamble RF frame, so without any significant impact on the transmitted on-time.

We developed a demonstration prototype at 2.4GHz, using as an example a Texas Instrument CC2538 IEEE802.15.4 SoC as a transceiver, and verified that the performances could be reproducted at 868MHz and 169MHz. Here is a picture of the full prototype. The parts added for automatic tuning occupy only 1cm^2 of board estate (red square on the picture), very similar to the area that would be required for a range extender :

ALCIOM's AUTOMATCH 2.4GHz prototype

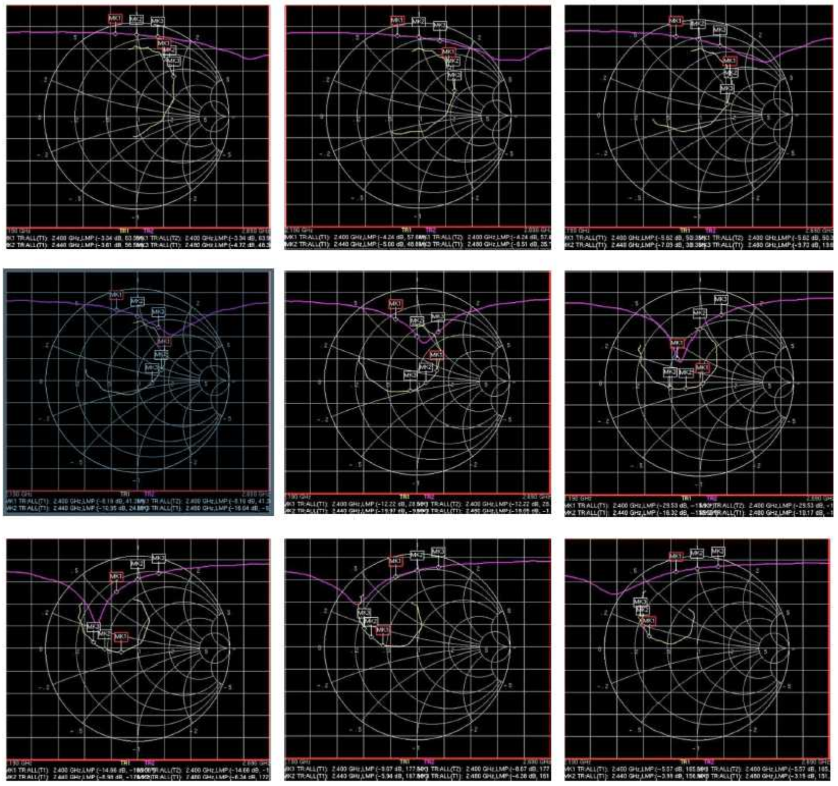
3.3 AUTOMATCH performances

Several simulation and design iterations were required to balance the flexibility of the matching, the cost of the network and its insertion loss. In particular the parasitics of all components need to be included in the design in order to get good results. The following Smith chart is an illustration of the possible antenna impedances that could be matched with a full-featured matching network based on AUTOMATCH architecture :



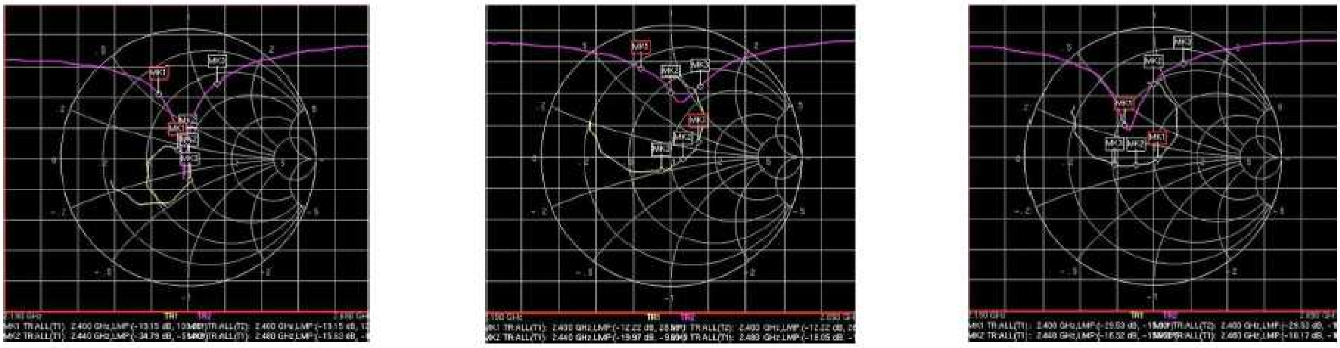
SciLab simulation of the full AUTOMATCH network

From this reference architecture, ALCIOM has gone one step further and investigated potentially simplified matching networks, that proved to provide **nearly as good matching performance with a significantly reduced insertion loss**. The optimal solution is of course application dependant. Extended measurements and optimizations have been realized in ALCIOM's lab on the AUTOMATCH prototype. Both 868MHz and 2.4 GHz prototypes have shown very good results, and application to 169MHz seems realistic. The following plots shows the tuning range of a PCB 2.4GHz F-antenna through the full scale of the AUTOMATCH variable matching network ; Up to 300MHz of tuning was achieved.



Tuning range of the AUTOMATCH solution

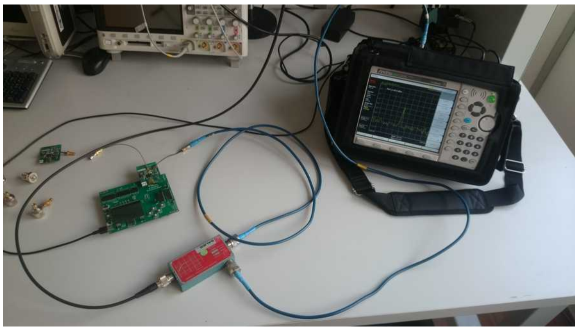
With dynamic antenna tuning, changes in the vicinity (hand, plastic box...) still slightly detune the antenna, while it would be severely detuned with a simple fixed impedance matching network. The following plots shows, with the same 2.4GHz F-shaped antenna, the actual matching achieved with ALCIOM's AUTOMATCH prototype after execution of the automatic matching and on three different environmental conditions (respectively open air, 1cm from a table, 5mm from the hand)



AUTOMATCH performances with three different environmental conditions, 2.4GHz printed antenna

As shown on these plots, our solution achieve in these examples a return loss lower than 8dB in all these situations. We voluntarily selected a non optimal matching network to reduce the insertion loss, as 8dB return loss gives only a reasonable mismatch loss (lower than 1dB). **This leads to more than 2 dB radiated improvement over a classic fixed matching network solution when the environmental conditions are changing.** This represents more than 63 % of power that would have been wasted. Moreover the gains are doubled if the dynamic matching solution is used on both nodes.

On the firmware side, ALCIOM developed a fast tuning algorithm, which tracks and corrects the antenna impedance variations. AUTOMATCH automatically retunes the antenna in **less than 200 µs**.



AUTOMATCH test bench

Last but not least, our work proved that it is possible to **integrate dynamic antenna matching with great results into low-cost products**, for the same BOM cost than a classical range extender, Indeed, the cost of the dynamic tuning subsystem on our prototype is **between 1 and 2 Euros** depending on volume, while range extenders generally start at 2 Euros in large quantities.

4 Conclusion

AUTOMATCH is not an off-the-shelf product but one of ALCIOM's internal R&D projects. Our results prove that, thanks to the advances in MEMS and SoCs, dynamic antenna tuning is now a solution for compact wireless devices. Improvements of more than 60% in radiated power were demonstrated with an incremental bill of material cost lower than 2Eur in volume. Contrarily to range extenders, this gain is intrinsic and doesn"t increase the power drawn from the battery.

Even if project-per-project customisation will very probably be required, this technological is now available to ALCIOM's customers for 2.4GHz band but also for 868MHz and 169MHz. As compared to a traditional fixed impedance matching, this solution could provide drastic improvements for products with complex or varying environments, and in particular for IoT and smart metering devices. For additionnal informations please contact us : contact@alciom.com