Chapter 3

Wireless Interface at 5.7 GHz for Intra-Vehicle Communications:

Sensing, Control and Multimedia

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ABSTRACT

This chapter presents a wireless interface for intra-vehicle communications (data acquisition from sensors, control, and multimedia) at 5.7 GHz. As part of the wireless interface, a RF transceiver was fabricated in the UMC 0.18 µm RF CMOS process and when activated, it presents a total power consumption of 23 mW with the voltage-supply of 1.5 V. This allows the use of only a coin-sized battery for supplying the interface. The carrier frequency can be digitally selectable and take one of 16 possible frequencies in the range 5.42-5.83 GHz, adjusted in steps of 27.12 MHz. These multiple carriers allow a better spectrum allocation and at the same time will improve the channel capacity due to the possibility to allow multiple accesses with multiple frequencies.

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INTRODUCTION

Many automobile manufacturers are aiming efforts to reduce vehicle weight in order to improve the fuel economy. Also, the political, business and social need for fuel-efficient and clean vehicles is clear nowadays in many countries, where it is being demanded high environmental performance without trading-off safety, driving performance or cost (Cramer *et al*, 2002). Since the first Velo's prototype presented by Karl Benz in 1894, until the modern Formula 1's Ferrari F-60, an automobile use sensors. Ever since the introduction of the Manifold Air Pressure sensor for engine control in 1979, followed by airbag sensors in the mid-eighties. Integrated microsystems have been increasingly used throughout the vehicle, and the demand of new sensing and management applications leads undoubtedly cars to be more intelligent, and increasing the need of a networking infrastructure to connect the whole range of sensors and actuators. Thus, the system environment of an automobile is becoming more and more complex (Krueger *et al*, 2003). Today, an average car comprises more than 50 sensors and in the luxury segment more than 100 sensors, roughly one third (1/3) might be based on microsystem technologies. Examples of these systems are listed in Table 1 (Krueger *et al*, 2005). Also, while formerly one single supplier delivered all components of an ABS system or all sensors for airbag control, today the networked architecture allows merged sensor systems for different functions. Ambient intelligence, which means an environment of interacting smart devices, is opening up new information sources for the vehicle. With the growing use of bus-systems, building exclusive systems for each function is becoming more and more difficult and too expensive (Krueger *et al*, 2003). A present day wiring harness may have up to 4000 parts, weight as much as 40 kg, and contain more than 1900 wires for up to 4 kilometers of wiring (Ahmed *et al*, 2007). Thus, these networks bring serious drawbacks like reliability, maintenance and constraints if the manufacturer plans the addition of new functions. These drawbacks can be avoided with wireless transmission infrastructures. Using multi-chip-module (MCM) techniques, it is possible to assemble in the same microsystem, the sensors, radio-frequency (RF) transceiver, electronics for processing and control, memory, and an associated antenna. In the last years, the potential to use wireless interfaces in the vehicular industry became an important goal (Schoof *et al* 2003, ElBat *et al* 2006, Niu *et al* 2009, Leon *et al* 2001, Tsai *et al* 2007, Flint *et al* 2003, Li *et al* 2006, Niu *et al* 2008, Tsai *et al* 2007, Andreas *et al* 1983).

Table 1. Car functions and the respective sensors (Krueger et al, 2003)

System	Number of sensors
Distronic	3
Electronic controlled transmission	9
Roof control unit	7
Antilock braking system	4
Central locking system	3
Dynamic beam leveling	6
Common-rail diesel injection	11
Automatic air condition	13
Active body control	12
Tire pressure monitoring	11
Electronic stability program	14
Parktronic system	12

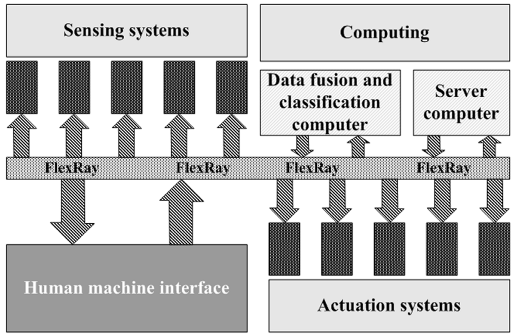
THE STATE OF THE ART AND SYSTEM OVERVIEW

Advances made in the electronics industry in general, and government legislation towards the increase of comfort and safety in cars, were the main driving forces that leaded to the development of vehicle network technologies. At not so long time ago, the auto-radio was considered the only electronic device in an vehicle, but now almost every existing component in the vehicle has some sort of electronic feature. The engine control module (ECM), the anti-lock braking system (ABS), the transmission control module (TCM) and the body control modules (BCM) are some of the most common electronic systems on the today's vehicles. Electronic modules are placed in the automobile, in order to acquire the measures of the sensors (speed, temperature, pressure, among others) and to be used in computations. The orders received by the various actuators, are given by these same modules, which are responsible for actions, where the switching on the cooling fan, changing gear (in the case of automatic gears) constitutes some examples of actuation. These modules must exchange data between each other, during the normal operation of the vehicle. An example of such a data exchanging, is when a communication between the engine and the transmission of a car, is needed in order to exchange information with other modules when a gear shift occurs. This need of a fast and reliable data exchange lead to the development of vehicle network concept. Moreover, the use of microcomputers, electronic display, and voice output in motor vehicles means greater scope not only for the gathering and processing data, but also for making such data available to the driver (Andreas *et al* 2000). Some years ago, the increased demand for these new applications and needs of electronics in order to increase the passenger's safety and reliability of the vehicles, lead the Toyota company to introduce the model Soarer in the market. For this model was developed a multidisplay system, which employs a 6-inch colour cathode ray tube (CRT) newly developed for automobile application, in which various kinds of useful information such as vehicle conditions and diagnostic data that may be used by service mechanics are compactly and expediently displayed with high legibility (Torri *et al* 1988).

In order to make the different blocks in a car to exchange data between them, some kind of communication network are needed. There are several network types and protocols used in vehicles by various manufactures. Many companies are encouraging a standard communication protocol, but one has not been settled on. There are several network types and protocols used in vehicles by various manufactures, but the CAN (Controller Area Network), which is an inexpensive low-speed serial bus for interconnecting automotive components, is the most used of all by the vehicular industry. CAN has been running in cars for more than ten years now. But unlike the telecom industry, which has managed to establish a GSM standard where every service provider can use components from the worldwide supplier ecosystem, the car industry has not moved beyond a component standard for CAN. This is going to change with the introduction of LIN (Local Interconnect Network) and FlexRay (adopted in 2007 by BMW), which are defined on a systems level for interoperability of modules (see Figure 1).

Not only are the physical and logical interfaces specified, but in addition the higher protocol software layer APIs, the messaging sequence generation mechanism, diagnostics and conformance test. With these mechanisms in place, it will be possible to generate truly exchangeable electronic components that are independent from the underlying technology. Then the carmaker will be able to source from an ecosystem of suppliers, just like a computer maker is able to source the latest disk-drive technology for its system, thus managing transparent technology transitions (Snook, 2008). The assimilation of multimedia and multimedia communication by industry for applications in design, manufacturing, and training marks a significant turning point. This important and constantly evolving area comprises a number of technologies, including multimedia compression, computer networks, and the transport of multimedia over these networks. The standards and technology for multimedia and multimedia communication are evolving quickly and, therefore, it is challenging to keep pace with the wide spectrum of this rapidly advancing technology.

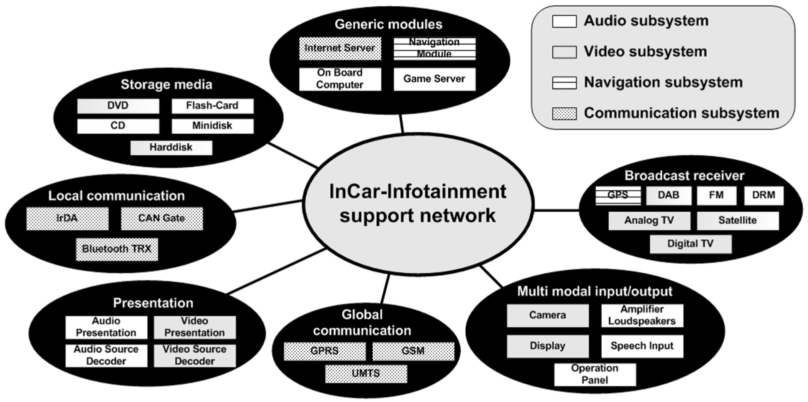
Figure 1. A backbone-based (on FlexRay) architecture for automotive



Multimedia and multimedia communication can be globally viewed as a hierarchical system. The multimedia software and applications provide a direct interactive environment for users. When a computer requires information from remote computers or servers, multimedia information must travel through computer networks (Wu *et al*, 1998). The stringent requirements associated to multimedia applications that can't be achieved with traditional automotive networks (the CAN is an example), leaded the automotive industry to respond with the proposition of the MOST (Media Oriented Systems Transport) action. The MOST cooperation is based on a partnership of carmakers, setmakers, system architects and key component suppliers. MOST is a multimedia network optimized for multimedia and infotainment applications. It is a network originally developed by the automotive industry for the automotive industry but with wide-ranging applications in many other industries. Its design allows it to provide a low-overhead and low-cost interface for the simplest of devices, such as microphones and speakers. At the same time, more intelligent devices can automatically determine the features and functions provided by all other devices on the network and establish sophisticated control mechanisms to take away distractions from the driver of the car as different subsystems try to communicate information to him (Allan, 2006). The technology was designed from the ground up to provide an efficient and cost-effective fabric to transmit audio, video, data and control information between any devices attached even to the harsh environment of an automobile. The Figure 2 illustrates an application scenario with a possible MOST-system for a typical in-car infotainment.

In respect of vehicle communication protocol prior art, multiplex vehicle control systems currently use a single channel (wire) for both transmitted and received signals. Such systems are usually microprocessor based and require a slave or satellite module to generate an interrupt function before a particular operation can be undertaken. For example, the operation of braking would entail a signal to be generated upon movement of the brake pedal, the signal serving as an interrupt to the microprocessor, who thereafter would take whatever steps are necessary, such as activation of brakes and/or brake lights. The type of communication used in such systems is usually either all synchronous or all asynchronous. Coupled with the provision of only one transmission/recep-

Figure 2. An exemplary MOST-system view of a typical in-car infotainment application scenario



tion channel between the master and each slave module, there has been a need to speed up the rate of data flow. This increased data flow rate has proved necessary as a result of the relatively limited time available for a multiple system to receive, issue and act on commands, for example in the act of braking of the vehicle (Hansen *et al*, 1994). The result of increasing the data flow rate in prior arrangements has been the adoption of higher and more costly technology, and hence relatively more expensive components. Thus, on the whole, vehicle manufacturers have remained with more traditional wiring looms or harnesses as these have proven to date to be more reliable and/or cost effective than multiplex systems previously developed for vehicle application.

The idea to apply wireless links to cable replacement is not new. General Motors Company was the first, if not the only one up to now to got the idea to install wireless links in vehicles, in order to replace cables (Ahmed *et al*, 2007). Mainly, these cables are based in low-current loops that simultaneously feed and acquire data from the sensors. However, the specificity of the environment in a car addresses aspects that are not present in other type of wireless networks. Thus, a wireless network to connect sensors in a car is not just another type of wireless sensor network. Previous studies conducted in vehicular environment revealed a set of issues, which can't be discarded (Krueger *et al.,* 2003; ElBatt *et al.,* 2006). The most important aspects to be considered when mounting a wireless network in a car include questions like heterogenity, where different sensors and different communications profiles are present (ElBatt *et al.*, 2006). The complete characterization of the wireless channel and the selection of the most suitable modulation are other important and definitive tasks (Niu *et al.,* 2009; Leon *et al.,* 2001; Tsai *et al.,* 2007; Flint *et al.,* 2003; Li *et al.,* 2006; Niu *et al.,* 2008). The work presented conducted by Tsai *et al* (Tsai *et al.*, 2007) showed (at least) for the 915 MHz, using a forward error correction (FEC) code, the network support at least 98% packet reception rate. Moreover, Tsai *et al* also suggest that sacrificing the throughput, by using an automatic repeat request (ARQ) scheme will result in a better packet

reception. Also, further works suggest that with ultra-wide-band (UWB) transmission is possible to achieve high data-rates, despite the noisy and fading characteristics of the vehicular environment (Liu *et al.,* 2006; Niu *et al.,* 2008). In spite of an extensive number of studies related to the channel characterisation, it is evident the worry to use the emerging and established technologies, such as the ZigBee and the Bluetooth to put in connection the different sensors, controllers and multimedia systems (Schoof *et al.,* 2003; Flint *et al.,* 2003; Tsai *et al.,* 2007). These two standards have strong points and drawbacks. The ZigBee is a set of protocols (e.g., corresponding to the two lowest layers in the OSI model) that allows to mount a real wireless sensor network in topologies ranging from a simple star to complex meshes with the advantage to work for years. This working mode is obtained at the cost to have the wireless nodes to operate in low-duty-cycles. Low-duty-cycles are not tolerable in real-time systems, so the advantage of the ZigBee will fast turns in something to avoid. Alternatively, the Bluetooth allows the use of high-baud-rates, e.g., baud-rates up to 1 Mbps to exchange data between the wireless nodes. However, it is very difficult to have complex mesh topologies and worse, the Bluetooth is a very heavy protocol with a lot of rules, where despite the high-baud-rates available, it will result in high latencies. High latencies are also unacceptable in real-time monitoring and control systems. Thus, the Bluetooth is more suitable in applications such as hand-free systems that allow drivers to keep their hands on the wheel while staying connected to cellular phones. Furthermore, the use of high density of nodes and simple protocols in the vehicular environment was also tried before (Niu *et al.,* 2009; Hill *et al.,* 2000). Several variants for the same solution were proposed and all of the implementations use third-party products such as radios (motes) and sensor interfaces (Hill *et al.*, 2000). The motes are battery-powered devices that run specific software. These motes are ready-to-use wireless modules, where boards with sensors are attached. Their primary advantage rapidly fades and turns into a severe drawback, because the primary goal is to have wireless platforms integrating the vehicular environment. Thus, more compact and low-sized modules are needed. Also, these solutions are much too expensive for high-mass production and thus, for use in cars.

The advantages to have RF transceivers with dimensions comparable to the other elements of the microsystem, such as the sensors and the electronics of processing and control are enormous. Miniaturised microsystems contributes to the mass production with low prices, favoring the spread of applications for these microsystems. Moreover, solutions relying in wireless microsystems, offer a flexibility such as it is possible to chose how many and which are the sensors to be integrated together with the RF transceiver and the remain electronics. Also, it can control the power during the transmission and to select what subsystem must be enabled. In terms of project and design, it is easier to provide the supply, when all the system-blocks are integrated together in the same microsystem. Because the feeding points are reduced and the battery coupling is more effective, thus, the key of effective wireless interfaces for vehicles rely on a trade-off between the best possible baud-rates and the best-control features, as it is the case of high-performance embedded systems.

Wireless interfaces can be used to connect the sensors spanned in the car and to transmit the acquired values to a base-station, which stores, process and display the most suitable physical measures, such as the oil level, water temperature in the cooling system, pressures in the tires, beside others. These measures can be monitored and displayed in the front panel of the car, to give information to the driver, while the car is rolling in the road. Another way to use these wireless sensors networks, is when car driver wants to see in a PDA, for example, the oil level of the engine, without the need to move close the car. The Figure 3 shows the system architecture of a wireless interface to mount a wireless sensors network in a car. The wireless interfaces must be deployed closely to the sensors, in order to reduce the interferences caused by the electromagnetic noise generated by the car electrical system and to minimize measuring errors. It is advantageous to have wireless interfaces with plug-and-play features (the modules can be easily placed/removed on/from where and when it is desired without special concerns) for overcoming the gap brought by the previously network standards for cars, thus making possible to have a real network infrastructure coexistent with the sensing subsystem and the Information Communication and Entertainment system (ICE). This allows a common multimedia system platform for integrated information, communication and entertainment applications for use in automotive environments. Typically, the systems offered to the consumer, are made in separate devices for very specific applications (the DVD players is an example). However, the integration of such applications in automotive environments comes with major challenges, such as, system space requirements and overall costs will be too high. Therefore, the use of wireless links to make the integration of different multimedia devices and services into a common system platform for automotive environments don't implies changes in the existent designs of cars, so it is expected to be a valuable option without significant additional costs. Moreover, given the physical way the different interfaces are connected between them, the following hardware requirements for in-car use are easily achieved. These requirements includes modular and extensible hardware concept, in order to be possible to add or remove single hardware components in an easy fashion; suitability for automotive applications, e.g. rigidity, temperature range. To all of this be possible, the wireless interface and the applications must give support for a networked environment. This makes easy the development of a universal system bus, in which can be possible to attach the different products of different suppliers. Another advantage is that modular software architecture for multimedia applications can be designed without strong efforts and cost penalties. This architecture can include features like the possibility to add or remove single software components, upgrade an existing version to a newer or give support to new multimedia services. This constitutes an obvious trend to integrate different new or existing standards in a single device, e.g. Personal Integrated Communicators, Consumer Electronics, in-car Infotainment. Form the part of manufacturers and suppliers, this trend can be seen as a starting point for the convergence of multimedia standards and applications. While the major of the previous specific applications are possibly tolerable in a home environment, for ergonomic, driving safety and limited space reasons, a single infotainment unit is strongly desirable in an automotive environment. Moreover, in the automotive environment additional car-specific applications, like travel information, navigation systems and climate control are expected by the user. The amount of common building blocks between these applications increases the potential for reducing the production costs and the development resources significantly. In addition it is desirable to offer the driver and his passengers a consistent interface to the different applications, using the same display and user interface which will be user adaptable in the future.

RF CMOS TRANSCEIVER DESIGN

Frequency Band Selection

The frequency selection took in account the need to obtain compact and miniaturized solutions. Moreover, the possibility to include chip-size antennas in the RF microsystem was a crucial (and a mandatory) requirement to comply with the former goal. In order to implement efficient power-consumption wireless sensor networks, it was also necessary the development of a low-

Wireless Interface at 5.7 GHz for Intra-Vehicle Communications

Figure 3. The system architecture of a wireless interface for vehicles

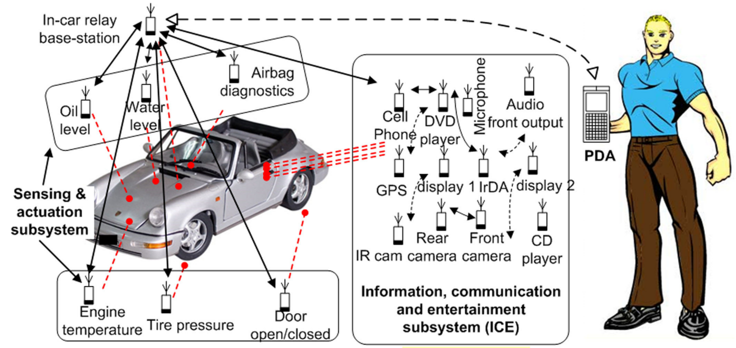
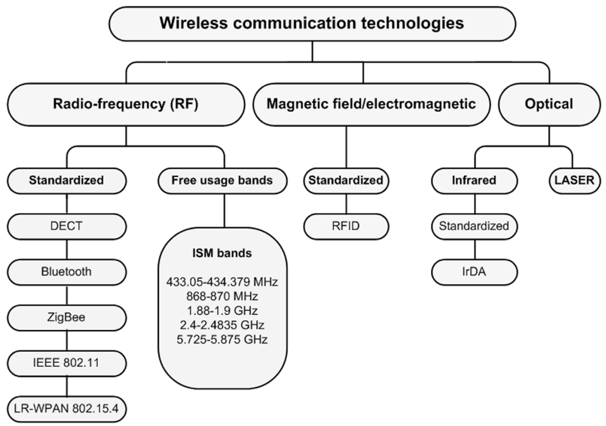


Figure 4. The available frequencies and their respective applications



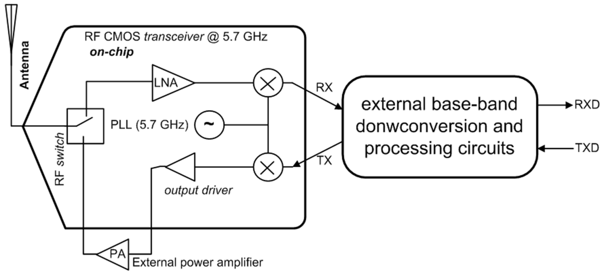
power/low-voltage RF CMOS transceiver, suitable for mounting in the antenna. In wireless communications, the antenna is one of the most critical subsystem, thus, in order to not compromise the desired miniaturization, the antenna must be small enough to comply with size constraints of the microsystems. The investigation of new frequency bands (Callaway Jr, 2004) and new geometries (Mackensen *et al.*, 2005) allow to get smaller antennas to integrate in wireless microsystems (Gutierrez *et al* 2001, Enz *et al* 2005). Also, the dimension of an antenna is proportional to the operating wavelength. Thus, the migration of wireless communication systems to higher frequency bands (as it is the case of the 5-6 GHz ISM band) facilitates on-chip implementation of antennas (Mendes *et al* 2005). This does the frequency selection to be one of the more decisive tasks, when RF transceivers are designed. Normally, the frequency must take in account some key-aspects: the desired range, the baud-rate and the power consumption. Unfortunately, these aspects trade between them, i.e., the optimization of one affects the others in an opposite way. The attenuation of RF signals in the free-space increases with the distance, thus for a simultaneously given transmitted power, P_t [dB], and receiver's sensitivity, S_r [dB], the frequency of operation is limited by the range, d_{max} [m], e.g., $f \le 10^{[(P_t - S_r) - 20\log_{10}(4\pi d_{max})]/20}$ [Hz] (Mendes *et al*, 2002). It must be noted that an increase in the power of RF signals, P_t [dB] compensates the additional losses in the radiowave channel. However, an increase in the transmitted power implies a higher power consumption, whose consequence is a decrease in the useful life of the battery. In conclusion, increasing the transmitted power is an unacceptable solution, especially when the goal is to keep or even increase the life of batteries. Applications that need high baud-rates also require high signal bandwidths. However, the frequency can't be arbitrarily increased, because this have implications in the power consumptions, e.g., at high frequencies, the transistors must switch faster, thus the energy dissipation will be higher. The main consequence from high power consumptions is the decrease in useful life of batteries, imposing the replacement.

The Figure 4 shows the available frequency bands for the different technologies used in wireless communications. The best free-usage frequencies for wireless devices are those belonged to the so called ISM band (Industrial, Scientific and Medical), due to its unregulated usage. This means that these frequencies are not subjected to standardization and can be freely used, since the emission powers are kept below the maximum levels imposed by national legislations. This usage-flexibility leaded to the rise and to the widespread of new and interesting applications. All of these and the former system-implementing aspects were decisive during the selection of the operating frequency, whose value was selected to be around the 5.7 GHz.

The Architecture of RF CMOS Transceiver at 5.7 GHz

The 0.18 µm RF CMOS process from UMC (United Microelectronics Corporation) was used for the fabrication of a 5.7 GHz RF CMOS transceiver. This process has a polysilicon layer and six metal layers, allowing integrated spiral inductors (with a reasonable quality factor, e.g., in the range 4-10), high resistor values (a special layer is available). Therefore, high on-chip integration is possible, in favor of better repeatability as well as less pin count (Choi *et al*, 2003). An important issue to take in account during the project of RF transceivers for use in any wireless network is that without proper design, the communication tasks may increase network power consumption significantly because listening and emitting are power-intensive activities (Enz *et al*, 2004). Thus, the power consumption of a RF transceiver can be optimized by predicting in the design the possibility to use control signals. The functions of such signals are to enable and disable all subsystems of the RF transceiver. These signals allow to switch-off the receiver when a RF signal is being transmitted, to switch-off the transmitter when a RF signal is being received, and allows the RF transceiver to enter to sleep when RF signals are neither being transmitted, nor being received. The Figure 5 shows the RF CMOS transceiver architecture, which is composed by a receiver, a transmitter, and a frequency synthesizer. The receiver adopts a direct demodulation, by means of envelope detection. The RF CMOS transceiver

Figure 5. The block schematic of the transceiver



is constituted by a Low-Noise Amplifier (LNA) that provides an input impedance of 50 Ω, the amplified RF signal is directly converted to the baseband with a single balanced active MOS mixer. The internal oscillator at 5.7 GHz is a Phase-Locked Loop (PLL).

The RF CMOS transceiver can operate in the frequency range of 5.42-5.83 GHz. This is done by changing the frequency division ratio in the feedback path of the PLL. The PLL has four digital inputs to select one in sixteen possible division ratios. The output frequency is given by $f_{out}=f_{ref}\times 2\times(200+D)$, where D is the equivalent decimal of digital inputs for a reference frequency of f_{ref}=13.56 MHz.

The lowest noise-figure (NF) of LNA is achieved with an inductively degenerated common source amplifier with tuned load. In these conditions, the input impedance at 5.7 GHz for matching with the antenna is easily adjusted to 50 Ω. As it is depicted in the Figure 6, the LNA has a single transistor in the amplifier, thus, the reduction of active devices sacrifices the gain, but achieves lowest NFs. It must be noted that the latter Figure doesn't shows the circuits to provide bias to the LNA.

The upconversion and the downconversion operations are done with two mixers that are ac-coupled to the LNA and are modified versions of the Gilbert cell (see the Figure 7) (Gramegna *et al*, 2004). Also, both mixers are directly driven by the differential outputs of the on-chip frequency synthesizer.

The Frequency Synthesizer (the PLL)

An on-chip frequency synthesizer provides local versions of the carrier frequencies to both the downconversion and the upconversion mixer. This frequency synthesizer is a Phase-Locked Loop (PLL) with a integer divider in the feedback loop, whose dividing ratio can be digitally programmed to generate local carrier frequencies in the 5.42-5.83 GHz frequency range. The Figure 8 illustrates a block diagram showing the structure of PLL. This the PLL has a reference generator circuit with a crystal based oscillator at 13.56 MHz, followed by a Phase-Frequency Difference Circuit (PFD), a current steering charge pump (CP), a third order passive filter. The passive section output is connected to the VCO, that generates the desired frequency range of 5.42-5.83 GHz. Finally, in order to get the desired frequency in the previous range, this one must be divided by 400+2S, where S is integer and belongs to {0,1,…15}. Then the output of the divider connects to the PFD, closing the loop. The output frequency produced by the PLL depends from the divider ratio, N, and is $f_{out}=f_{ref}.N$

Figure 6. The schematic of low-noise-amplifier (LNA) – the biasing circuit is not shown

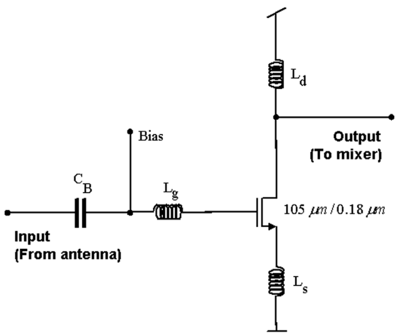


Figure 7. The electronic schematic showing the mixer structure

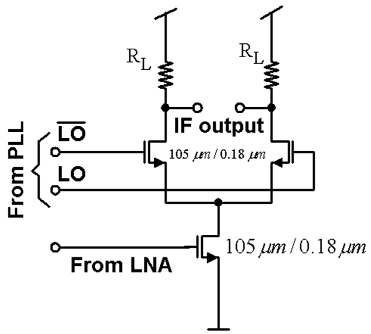
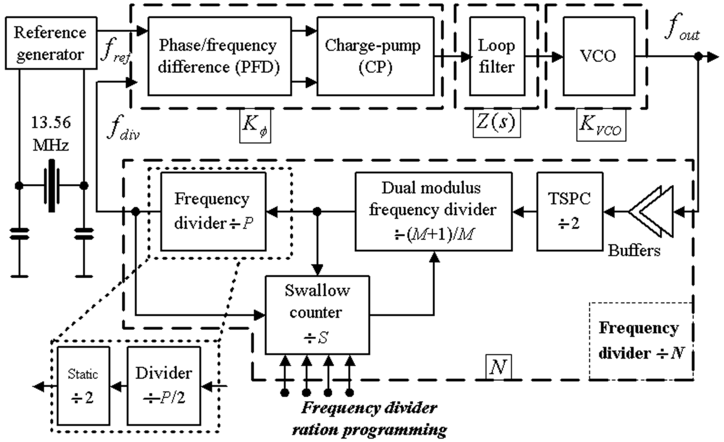


Figure 8. The block diagram of the PLL



[Hs]. The PLL acts a frequency multiplier of the reference frequency, f_{ref} [Hz].

The Frequency Divider

The PLL is one of the most challenging blocks of RF transceivers because it operates with the highest speed and the stringent trade-off between the speed and the power consumption. To have an ideia, typically, the blocks with higher power consumptions are the Voltage Controlled Oscillator (VCO), the frequency divider and the buffers. Thus, the efforts to reduce the power consumption and increase the speed, must always take place in the design. Also, the most complex and challenging stage of a PLL is the frequency divider, which must be designed with very care in order to keep the power at a low acceptable level, at the same time it meets the speed specifications. In high frequency PLLs, the high power consumption is mainly due to the first stages of the frequency divider that often dissipates half of the total power. The use of conventional static CMOS logic in the first stage is not possible. This is due to the high input frequency (Pellerano *et al*., 2003). The overall divider has two true-single-phase-clock (TSPC) frequency dividers, that halves the following dividers, which use static logic.

For this PLL, the desired divider ratio, N, in the feedback path is equal to $2(M.P+S)$, where $(M+1)/M$ (with M=10) are the variable frequency divider ratios of the prescaler, S=20 is the divider ratio of the main counter, and S is the divider ratio of the swallow counter. The main counter has a divider by $P/2$=10 followed by a toggle flip-flop, which makes the feedback signal at the divided input, f_{div}, of the PFD to have a duty-cycle of 50% (as it happens with the reference signal at the main input, f_{ref}, of the PFD). Compared with other situations, where the PFD's inputs have different duty-cycles, this minimises possible delays that can arise, during the locking process of the PLL. This is of special concern in situations when the PLL is turned on or after an order to switch the frequency at its output.

The Figure 9(a) shows the structure of the TSPC frequency divider by two and prescaler. The Figure 9(b) is the schematic of the TSPC divider by two, and the Figure 9(c) is the schematic of the prescaler. The buffers are not shown in the schematics. The frequency at the input of the prescaler is in the range 2712-2915 MHz, and previous measurements for this technology showed that for frequencies above 2 GHz, it is impossible divide higher frequencies with static logic. The TSPC logic must be used to allow the further static logic circuits to work. The TSPC logic was used again to overcome the impossibility to implement the first stage of the prescaler (the frequency divider by 2/3 with modulus control) with static logic in this technology. However, in order to the TSPC dividers work properly, the inputs must be rail-to-rail.

In the global structure of the frequency divider, the swallow counter plays an important role, e.g., the fixed division by 10 or 11 is extremely easy to achieve. The difficulty is to establish the precise intervals in which the division must be made and why. The Figure 10 shows three situations of divisions give by $200=(15\times10)+5\times10$, $203=(3\times11+12\times10)+5\times10$ and $215=(15\times11)+5\times10$ (for the global divisions of 400, 406 and 430), as well as the behaviour of the $(M+1)/M$ control signal to the prescaler. The clock (CLK) signal is the signal at the output of the VCO, VCOout, after to be divided by two in the TSPC frequency divider, thus, this is why half of the counting are refereed and not the exact value. Basically, the idea behind the frequency division is the definition of a general rule to simultaneously make the division of the minimum to the maximum in steps of one (in this case, from 200 to 215), and further in steps of two. In this case, the difference between the two limits is 30 and the swallow counting is from 0 to 15, so the values $11\times S+10\times[\max(S)-S]+50$, with $S\in\{0,1,\ldots,15\}$ and $\max(S)$=15 will be a useful solution to the

Figure 9. The block diagram of (a) the buffers, the TSPC divider by two, followed by the prescaler; (b) the schematic of TSPC divider by two; and (c) the schematic of the prescaler. The buffers are not shown in the schematics.

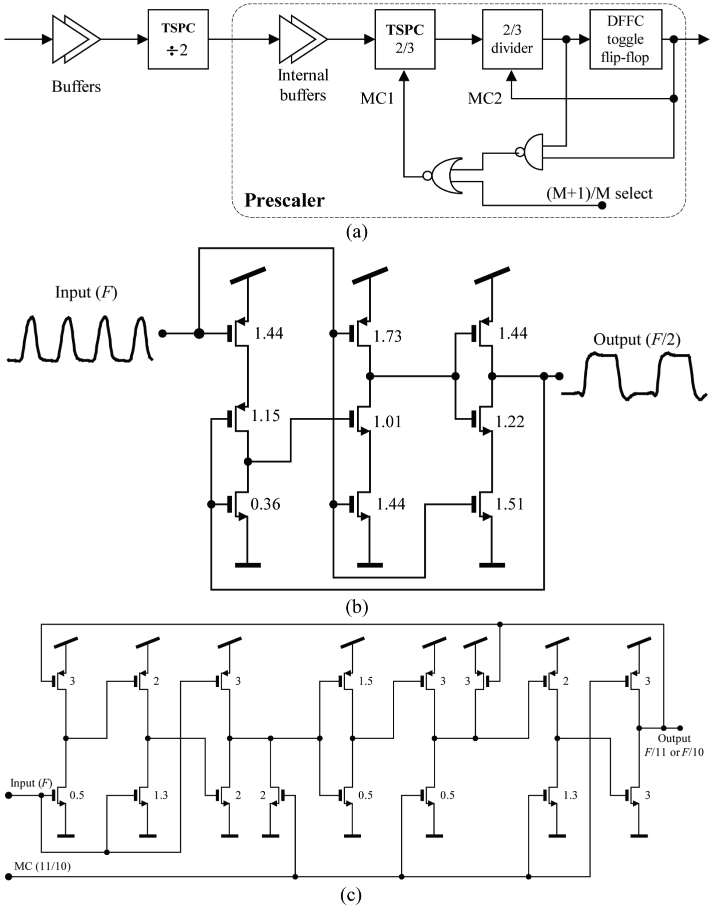
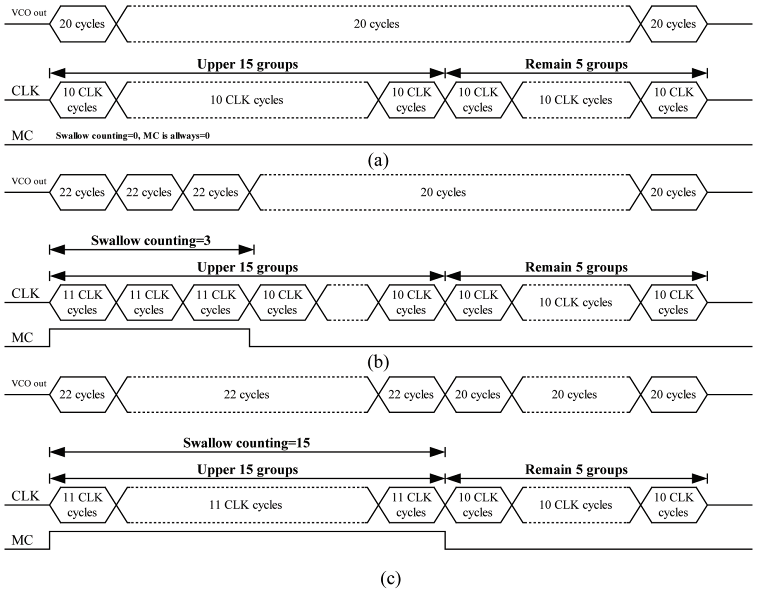


Figure 10. Swallow counting process to generate the appropriate MC signal for the prescaler, for three global division ratios: a) 400, b) 406 and 430



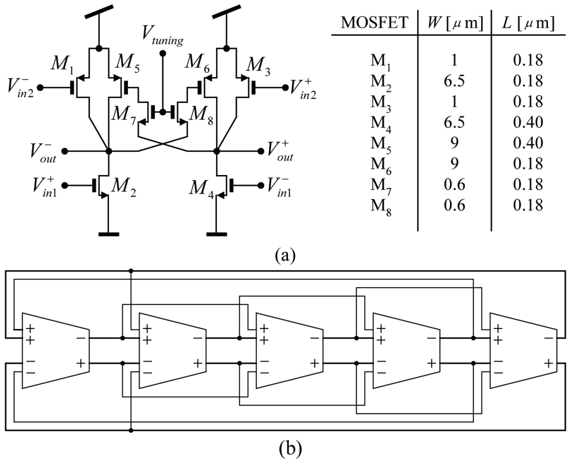
problem. Then the final division ratios in steps of two, are ensured by the first TSPC toggle flip-flop, at the same time the last static toggle flip-flop in the main counter, *P*, ensures that the divided signal has a duty-cycle of 50%. The swallow counter is essentially a descendent programmable counter and it operates as follows: the counter is initiated to the desired value *S*, and then it starts to counting in the descending order until zero. Meanwhile, the MC signal is activated then, it falls down, except when *S* is already initialized at zero.

The Voltage Controlled Oscillator

The VCO is based on a ring-oscillator topology instead of a tuned LC VCO because it is desired to save the on-chip area. Ring oscillators have more phase noise than LC oscillators (Abidi, 2006, Hajimiri, 2000). For overcoming this limitation, the bandwidth of the PLL must be high enough to “clean-up” the output spectrum around the 5.7 GHz interval (Gardener, 1980).

The ring oscillators are classified according theirs switching characteristics, e.g., non-saturated and saturated types (Park *et al*., 1999). For the non-saturated VCOs, the phase-noise is:

Figure 11. Voltage-control oscillator: a) saturated unity cell, with the MOSFET's dimensions and b) the complete VCO with five inverter cells



MOSFET	W [μm]	L [μm]
M_1	1	0.18
M_2	6.5	0.18
M_3	1	0.18
M_4	6.5	0.40
M_5	9	0.40
M_6	9	0.18
M_7	0.6	0.18
M_8	0.6	0.18

$$N = \frac{4kR\Delta T}{1 + (2\pi f_m RC)^2}, \tag{1}$$

where ΔT [s] is the on-time of the transistors inside a delay cell, f_m [Hz] is the offset frequency from the carrier, and RC [s] is the equivalent time-constant which is taken from the first-order model of the delay cell. An analysis to the equation (1), reveals that a short on-time is desired to have a low noise power. In order to such a goal be achieved, a simple inverter-based ring oscillator is not suitable, because a full switching never happens, thus a certain kind of anticipation in order to force a full switching must be done. The Figure 11(a) shows an unitary cell of a ring oscillator, which is of differential type and have two cross-connections (M_5/M_7 and M_6/M_8) between its inverter cells (M_1/M_4 and M_2/M_3) in order to make a latch to force the inverters to fully saturate (Park *et al*., 1999). The complete VCO uses a set of five inverter cells, which were connected as shown in Figure 11(b).

The Loop-Filter

As previously stated, the ring oscillators have more phase noise than LC oscillators (Abidi, 2006, Hajimiri, 2000) thus, a third order passive filter, composed by a second order section (C_1, C_2 and R_2) and a first order section (C_3 and R_3), providing an additional pole it is used. The first order filter reduces spurs caused by the multiples of reference frequency, whose consequence is the increasing of the phase noise at the output. The stability is guaranteed by putting this last pole five times above the PLL bandwidth and below the reference. The stability in the loop is obtained with a phase margin of $\pi/4$ rad or higher. The choice of passive components must obey to the following: given the bandwidth, f_p [Hz], the phase margin ϕ_p [rad], the minimum attenuation, A_{min} [dB], measured at

multiples of the spurious reference frequency, f_{ref} [Hz], which is imposed by the low-pass filter R_3C_3, it will result in the five passive components of the loop-filter (Banerje, 2006):

$$C_1 = \frac{\tau_1}{\tau_2} \times \frac{K_\varphi K_{VCO}}{(2\pi f_p)^2 N} \times \sqrt{\frac{1 + (2\pi f_p)^2 \tau_2^2}{[1 + (2\pi f_p)^2 \tau_1^2] \times [1 + (2\pi f_p)^2 \tau_3^2]}} \tag{2}$$

$$C_2 = C_1\left(\frac{\tau_2}{\tau_1} - 1\right) \tag{3}$$

$$R_2 = \frac{\tau_2}{C_2} \tag{4}$$

with τ_1, τ_3 and τ_2 being respectively

$$\tau_2 = \frac{(2\pi f_c)^{-2}}{\tau_1 + \tau_3}, \tag{5}$$

$$\tau_3 = \frac{\sqrt{10^{\frac{A_{min}}{10}} - 1}}{2\pi f_{ref}} = R_3 C_3, \tag{6}$$

and

$$\tau_2 = \frac{(2\pi f_c)^{-2}}{\tau_1 + \tau_3}. \tag{7}$$

Finally, the capacitance C_3 and the resistance R_3 are given by:

$$C_3 \leq \frac{C_1}{10} \text{ and to } R_3 = \frac{\tau_3}{C_3} \tag{8}$$

Table 1 shows some specifications, LF components and the significant results

RESULTS

At frequencies in the range 5.42-5.83 GHz, the LNA has a gain in the range 9.60-9.81 dB (see the Figure 12a), an IP3 of 9.1 dBm (see the Figure 12b), a stabilization factor K of 1.21, making the LNA unconditionally stable (K>1). The VCO has a constant K_{VCO}≈2.8 [GHz/V], obtained from the linear range. The charge-pump has *up* and *down* currents of 269 μA and 201 μA, respectively, and a detector gain constant K_ϕ=75 μA/2π rad. The *up* and *down* currents of 269 μA and 201 μA, respectively, and a detector gain constant K_ϕ=75 μA/2π rad. The LNA showed a power consumption of 9.65 mW. The voltage-to frequency (VF) characteristic is showed in the Figure 13.

The passive components were selected using a custom template spreadsheet. The Table 2 shows some specifications, LF components as well as the significant results, and it can be seen that the PLL has an almost fixed time to lock and independent from the division ratio, e.g., respectively about 10 μs and 7 μs for the first and second filters.

CONCLUSION

The Figure 14 shows the photograph of an encapsulated RF transceiver die, which was fabricated in the 0.18 μm RF CMOS process from UMC and occupies an area of 1.5×1.5 mm². This RF transceiver presents a total power consumption of 23 mW, supplied from a coin-sized battery with 1.5 V. These characteristics fulfill the requirements for short-range communications for using the 5.7 GHz ISM band. This RF transceiver can be integrated as a port of a wireless interface to provide intra-vehicular communications wirelessly of acquired data from sensors, to control actuators and to exchange multimedia data in

Figure 12. The plot of (a) S_{21} [dB] and (b) IP3 parameters

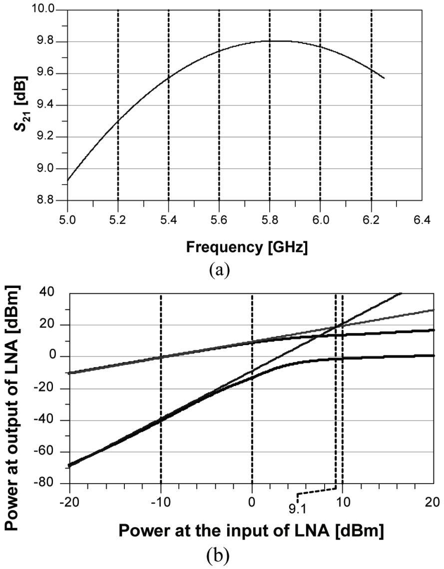


Figure 13. The V/F characteristic of the VCO

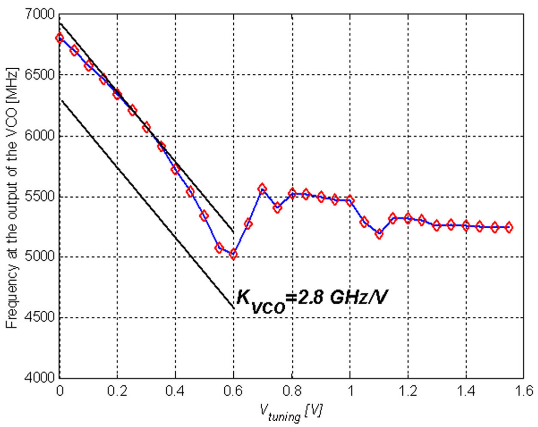
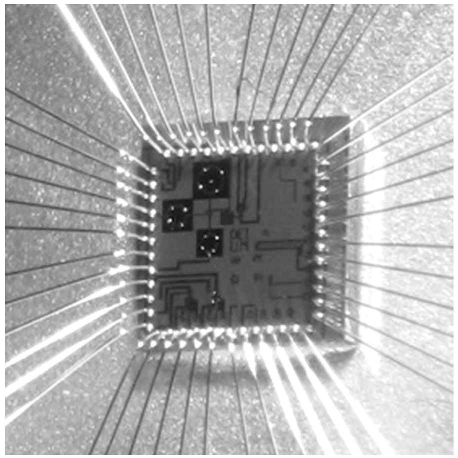


Table 2. Specifications, LF components and most significant results

	Filter	1		Filter	2	
Phase margin - ϕ_p [º]		45			55	
Bandwidth f_p [kHz]		900			900	
Frequency f_c [kHz]		589			540	
Attenuation *attn* [dB]		10			10	
C_1 [pF]		25			21	
C_2 [pF]		200			330	
R_2 [$k\Omega$]		3			3	
C_3 [pF]		2.5			0.7	
R_3 [$k\Omega$]		14			17	
N	400	414	430	400	414	430
Time to converge [µs]	10.6	10.8	11	7.3	7.6	7.7
Actual phase margin [º]	29.34	36.22	35.77	52.28	51.78	51.23
Actual freq. f_c [kHz]	594	286	279	271	264	256
Natural freq. f_n [kHz]	241	237	233	194	191	187
Dumping - ξ	1.823	0.448	0.444	0.605	0.594	0.583

Figure 14. A die photograph of the encapsulated RF CMOS transceiver



information, communication and entertainment systems in (ICEs) cars.

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KEY TERMS AND DEFINITIONS

Frequency Divider: An electronic system that picks an input signal with a given frequency and produces an output signal with a smaller (thus, divided) frequency.

Wireless Interface at 5.7 GHz for Intra-Vehicle Communications

Frequency Synthesizer: The same as PLL.

LNA: Low-Noise Amplifier.

Loop Filter: Filter used on a given PLL.

Mixer: A non-linear system that mixes two frequencies.

PLL: Phase-Locked Loop.

Radio-Frequency (RF): Frequencies used to transmit data across the air.

RF Transceiver: Wireless interface sub-system responsible for transmitting/receiving signals.

VCO: Electronic system that generates a periodic signal, whose frequency depends from the input (or the control) voltage.

Wireless Interface: An electronic system for connecting a variety of devices (sensors, multimedia players, computers) to support wireless communications.