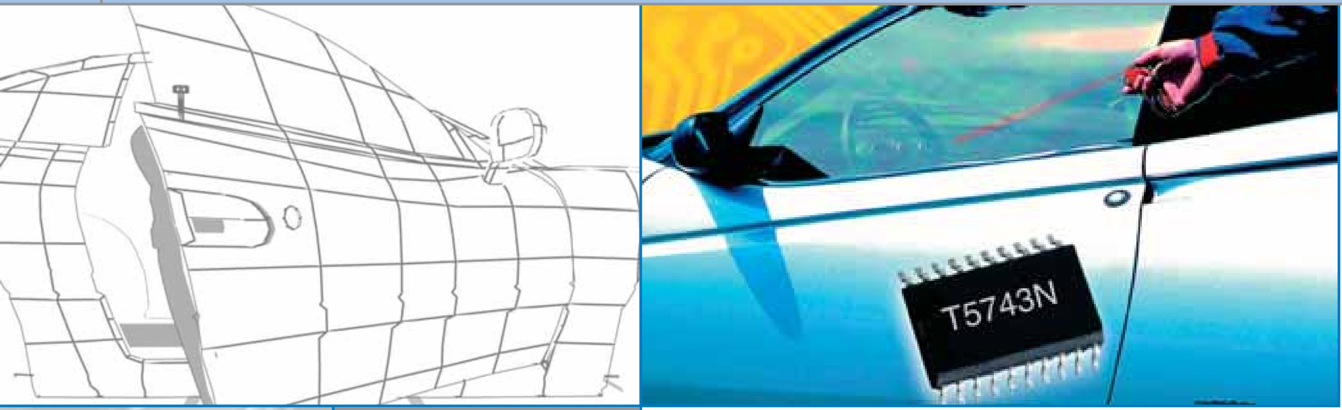


A COMPARISON OF A PLL-BASED TRANSMITTER DESIGN AND A SAW-RESONATOR-BASED DESIGN

Performance versus Cost

Johannes Baur

Abstract

The technological progress and cost reduction of integrated RF circuits allow the full integration of frequency synthesis circuits such as PLLs even for the use in RF remote control applications. Well-accepted and still technically competing are cost-reduced SAW-resonator-based applications.

Introduction

Buying a television set without a remote control? Unbelievable, these applications are 100% equipped with InfraRed (IR) remote controls – and it's convenient. In many applications, the use of an optical link is sufficient. But what about garage door openers, or weather stations? These applications are supposed to bring comfort to the user, and this is only possible in case of a successful data link through the surrounding, such as garage doors, walls and even furniture. RF technology was for a long time too expensive to approach this cost-sensitive market. First RF transmitters for remote controls covering the nowadays well-accepted Industrial Scientific Medical (ISM) bands used discrete circuits. The core of an RF transmitter design is the frequency synthesis, those discrete solutions used a ceramic or a SAW resonator. The cost of the bill of material was acceptable for these convenience applications; however, the RF performance was just at a low technical level.

The widely accepted RKE (Remote Keyless Entry) applications based on IR systems in the automotive market paved the way for developments using integrated RF circuits with the advantage of applying PLL-based frequency synthesis systems. Currently, brand-new cars do have RF remote controls, most of them use PLL-based systems. Atmel has been one of the very first manufacturers supplying fully integrated RF transmitters and receivers.

The so-called SRDs (Short Range Devices) feature

- Short transmitting range up to 100 m
- Low data rates (1 kBd to 10 kBd)
- Low current consumption (< 10 mA)
- Mostly battery driven (transmitters), e.g. 3-V cells
- Suitable for hand-held operation (transmitters), small application size, dedicated antennas

National Regulations

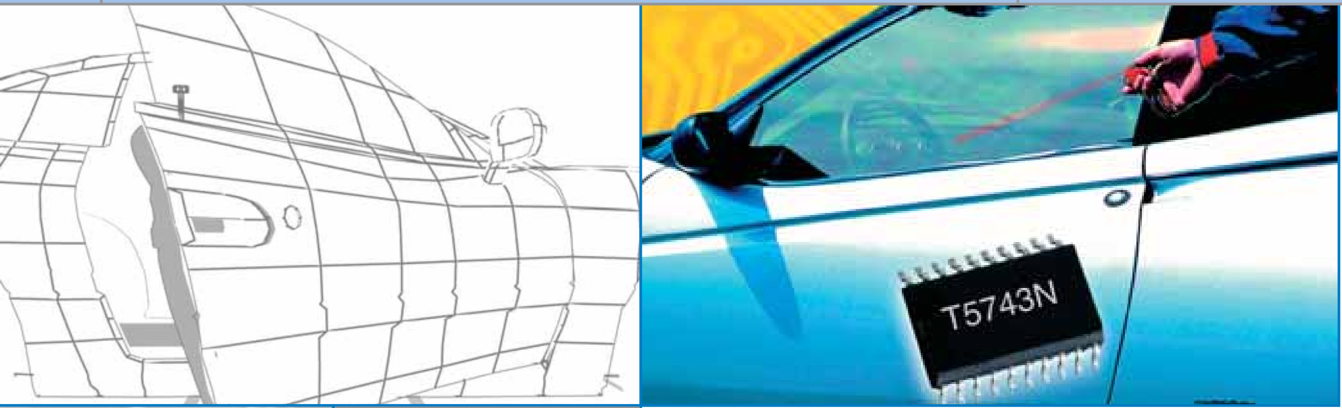
The national approval organizations (ETSI - European Telecommunications Standards Institute and FCC – Federal Communications Commission, US) take care about regulations dedicated to all RF applications. The availability of channels, prescribed radiation characteristics and licensing is given by EN 300 220 (EU) and FCC part 15 (US).

Available ISM bands around 315 MHz, 433.92 MHz (see Figure 1) and 868.3 MHz were assigned for the operation of SRD applications. They are restricted to +10 dBm equivalent radiated power (ERP) and a bandwidth of (870 kHz, where the usage is not application specific (all valid for 433-MHz band) and license-free. Spurious emissions are restricted as well, thus, adjacent channel users are protected up to a certain power level.

Due to growing density of RF radiators, product compliance and concept suitability to those standards became more important – the spectral performance dominates over system cost.

402-405 MHz	433.050-434.790 MHz	470-862 MHz	860.00-865.00 MHz	868.000-868.600 MHz	868.600-868.700 MHz	868.700-869.200 MHz	869.200-869.250 MHz	869.250-869.300 MHz	869.400-869.650 MHz	869.650-869.700 MHz	869.700-870.000 MHz	1785-1800 MHz	Maximum Power Level	Integral	Dedicated	External	Permitted Channel
													See Annex	Y	Y	No	All
													10 mW	Y	Y	No	All
													10 mW	Y	Y	No	All
	Y												10 mW	Y	Y	No	All
													25 mW	Y	Y	No	All
				Y									25 mW	Y	Y	No	All
						Y							25 mW	Y	Y	No	All
									Y				500 mW	Y	Y	No	25 kHz
											Y		5 mW	Y	Y	No	All

Figure 1. Extract of EN 300 220 Concerning Power, Bandwidth and Antenna



SECURITY
ALARM
CAR ACCESS

Example of a PLL-based Transmitter Solution

Major blocks of a transmitter and the functional demands:

- Frequency synthesis
  - Accuracy
  - Stability
  - VCC and temperature dependency
  - Phase noise and spurious generation
- Power amplification
  - High efficiency
  - Less VCC and temperature dependency
  - High isolation
- Modulation capability of the RF carrier
  - ASK: fast on-off keying without cross-talk
  - FSK: flexible pulling of frequency reference

The frequency reference is a quartz crystal driven by an oscillator circuit (XTO). To achieve fast settling-times (less current consumption and short response time), a phase comparator frequency at 13.56 MHz was chosen. Settling time is ts ~ $1/f_{XTAL}^2$.

Since the form factors of hand-held devices is crucial, a further advantage is the possibility to design a crystal blank in a smaller and lighter packages. Applied quartz crystals are available in different blank cuts, this determines the drift vs. temperature: BT cut-quadrature dependency and AT cut-cubical dependency. The design is centered to 25°C with the consequence that a cubical cut results in less overall dependency.

Ordering parameters:

- Frequency tolerance: initial/temperature/aging (e.g. ±30, ±30, ±10)
- Maximum series resistance R_S (< 110 Ω)
- Load capacitance Cl (e.g. 12 pF)

A quality factor is the suitability for low drive levels (100-200 nW). Contamination during fabrication results in DLD (drive level dependency) and may cause an increase of RS – the start-up process fails.

The next part of the frequency synthesis is the fully integrated PLL, charge pump, loop filter, VCO and integer divider for an accurate and stable generation of the RF frequency, see Figure 2.

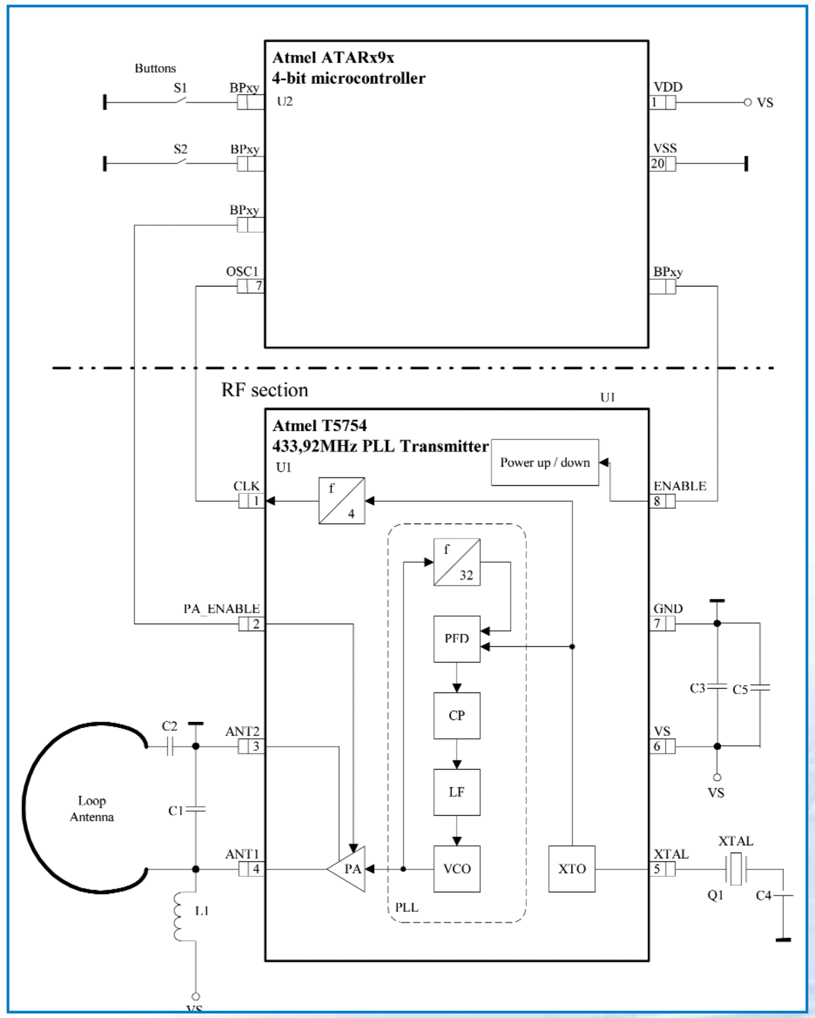


Figure 2. ASK PLL Transmitter Solution T5754 and Peripherals

Actual design uses an RC VCO, alternatively an LC structure could be used. The difference is the amount of generated phase noise besides the carrier, which is important since the signal is likely to be received by adjacent channels. This is subject of the ETSI/FCC regulations, too. The allowed bandwidth according to ETSI is ±870 kHz, centered at 433.92 MHz, and ±0.25% of the carrier frequency at 315 MHz (±787 kHz) according to the FCC regulations.

Regarding the demands of SRD applications in terms of radiated output power and product cost sensitivity, it is sufficient to integrate just an RC VCO. A screen shot is shown in Figure 3. The T5754 datasheet specifies the in-loop phase noise PLL at 20 kHz, i.e., the amount of noise generated by the VCO, which is reduced by the function of the PLL and loop filtering.

Due to the wide operating range of some VCO designs, a robust power supply rejection is required to guarantee a spectral clean ASK switching.

Regarding the integer division VCO down to the PLL or a possible division between XTO and PLL, a microcontroller-controlled multi-channel transmitter (Tx) is possible.

A spin-off of an integrated PLL-Tx is a quartz crystal accurate clock which clocks a microcontroller. Figure 2 proves that this reduces the application cost and the overall tolerance of the RF telegram timing.

The design of integrated amplification stages is less VCC- and temperature-dependent and uses highly efficient operation modes. This might result in an increase of the harmonics and thus requires a low-pass characteristic of the antenna matching circuit.

Note: Generated spurious emissions at ±n xf_{clk} have to meet the regulations.

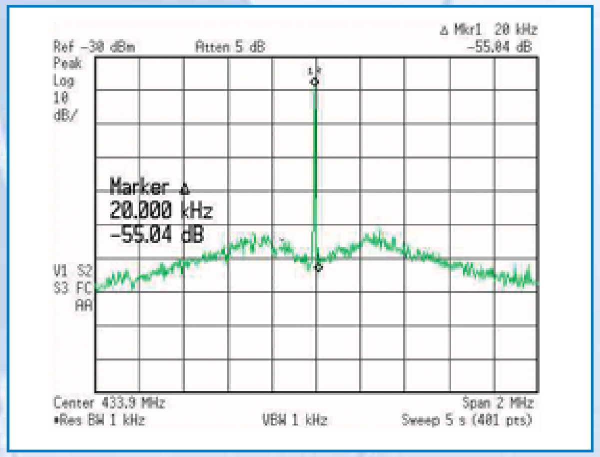
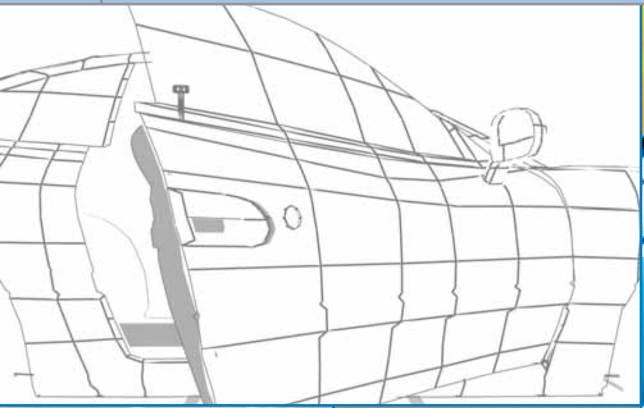


Figure 3. Radiated Carrier: In-loop Phase Noise PLL at +20 kHz : -85 dBc/Hz



SECURITY
ALARM
CAR ACCESS

Example of a PLL-based Transmitter Solution (cont´d)

ASK modulation (1 kHz to 32 kHz) is done through a TTL input signal, FSK modulation is achieved by pulling the quartz crystal with an additional serial or parallel cap, using a present microcontroller port as switch. Typically, a pulling of up to ±150 ppm is possible (see Table 3).

Table 1 provides a representative overview about the cost of such a design. Only the RF section is considered.

Table 1. BOM PLL Transmitter

Bill of material RF circuit section: Atmel ASK PLL Transmitter						
Components	Value	Tol.	Material	Housing	Manufacturer/ Distributor	Price/Pcs (100k)
U1	T5754			TSSOP 8L	Atmel	0.53 €
Q1	13.56 MHz	+-30/+-30/12pF	quartz crystal	U2G	ACAL	0.51 €
C1	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C2	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C4	12pF	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C5	47pF	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C3	1nF	10%	X7R	Size 0603	e.g. muRata	0.0014 €
L1	12nH	5%	LL1608-FS	Size 0603	Toko	0.04 €
					for RF circuit section	
					Total cost	1.09 €
					Component count	8 pcs

For further application and product details, see Table 3.

Example of a SAW-based Transmitter Solution

The frequency reference is a SAW resonator as the core of either a Colpitts oscillator or a Pierce oscillator circuit. Oscillation stability, VCC and temperature dependency as well as the modulation capability depend on the chosen basis circuit topology.

General assumption:

- ASK operation using a 1-port resonator in a Colpitts oscillator
- FSK operation using a 2-port resonator in a Pierce oscillator

Compared to a PLL design, the necessary building blocks are the same, but all blocks are included in a single transistor stage. This is possible since the SAW resonator already oscillates at the actual RF frequency. Nevertheless, for a competitive output power and a stable application, a second stage acting as amplifier is necessary, see Figure 4.

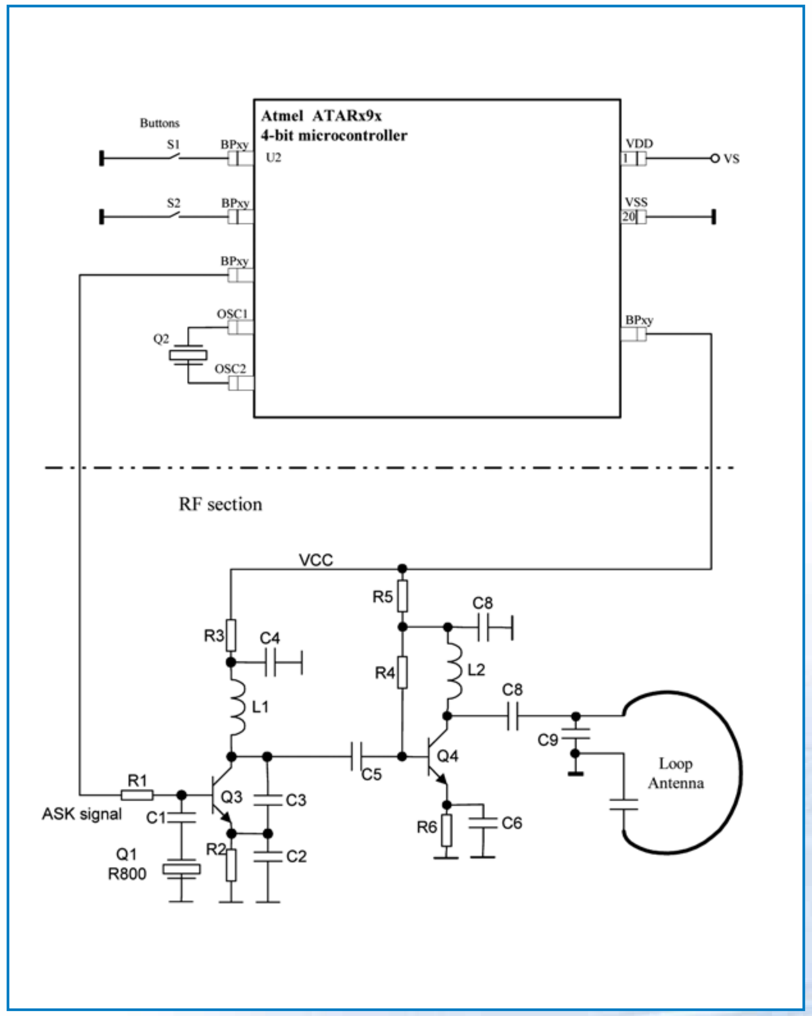


Figure 4. Discrete ASK SAW Transmitter Solution

The function of SAW devices is based on the piezo-electrical effect. Figure 5 shows a schematical view: The two interweaved comb structures of IN and OUT in a distance of the wavelength λ result in a **S**urface **A**coustic **W**ave (SAW). Due to the very high permittivity of the substrate ($\varepsilon r \sim 10.000$), a small component size is possible.

The chosen substrate determines the temperature dependency and operation bandwidth. The deviation df/f_0 depends on $-1/K^2$ and is typically centered at 25°C. Bear in mind that automotive demands regarding the operating temperature ranges of transmitters (-40°C to +85°C) and receivers (-40°C to +105°C) are really tough to meet. Using $LiTaO_3$ or $LiNbO_3$ substrates, it is not possible to design a state-of-the-art SRD system.

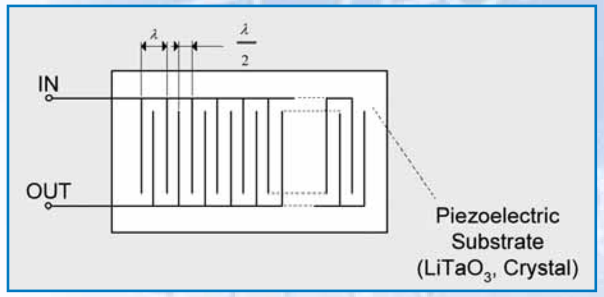
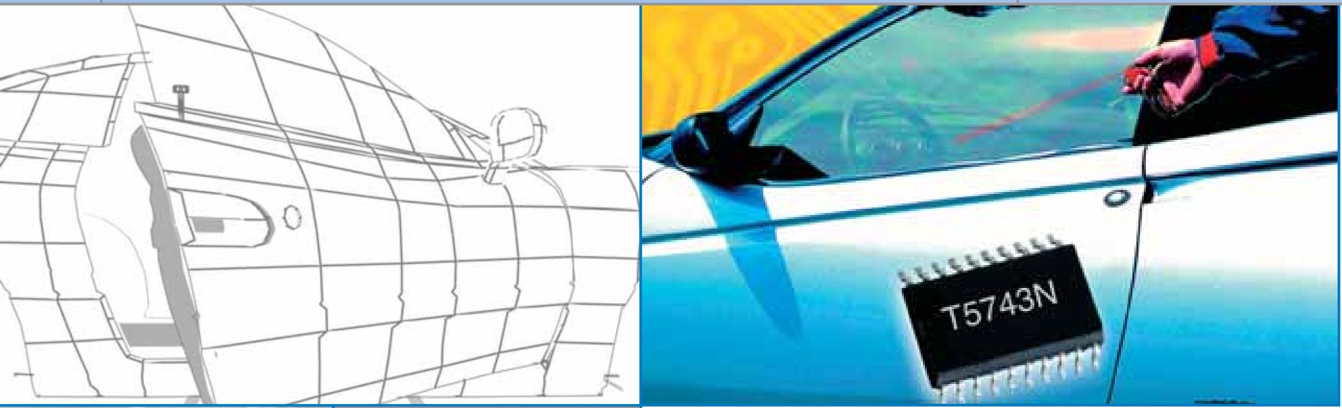


Figure 5: Structure of a 1-port SAW resonator

Ordering parameters of a SAW resonator:

- Frequency tolerance: initial/aging (e.g. ±75 kHz, -10/+ 50 ppm)
- Frequency tolerance: temperature coefficient (e.g. $-0.032\ ppm/K^2$)
- Motional resistance R_S
- Piezo-electrical substrate (quartz crystal, $LiTaO_3$, $LiNbO_3$)

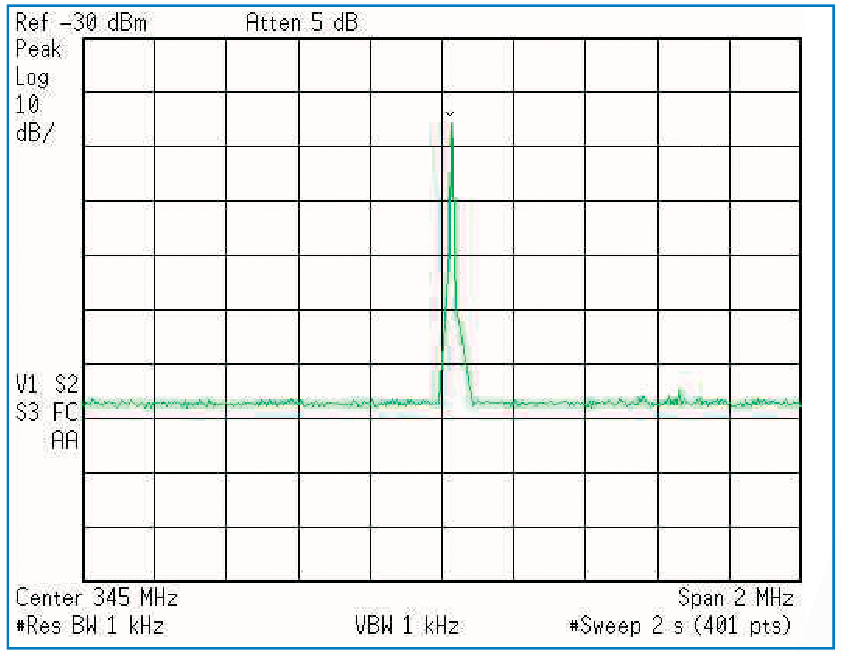
The maximum data rates of ASK systems are limited to roughly 4 kBd due to settling times of 15 to 20 µs.

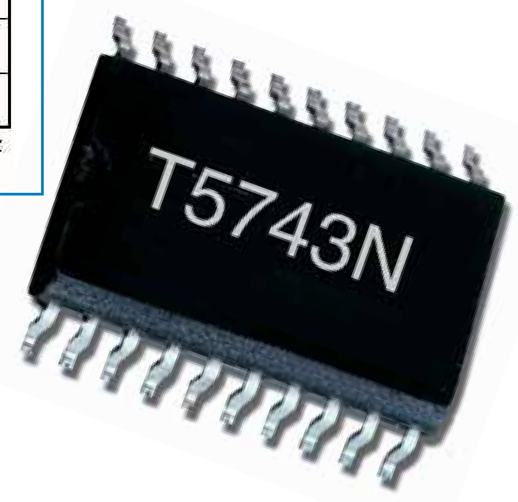


EXAMPLE OF A SAW-BASED TRANSMITTER SOLUTION (cont´d)

One major advantage of SAW resonator designs is the reduced phase noise. The comparison between Figure 3 and Figure 6 shows the narrow-band spectral view (measurement ResBW = 1 kHz). Note the noise floor of the spectrum analyzer besides the carrier.

Figure 6. Radiated Carrier of SAW Tx: Reduced Phase Noise





EXAMPLE OF A SAW-BASED TRANSMITTER SOLUTION (cont´d)

Designing such a discrete application is difficult since it requires experienced oscillator and analog design skills. Nevertheless, this solution is more flexible than a fully integrated one, and it enables quick and easy modifications, e.g., of the harmonic level generation.

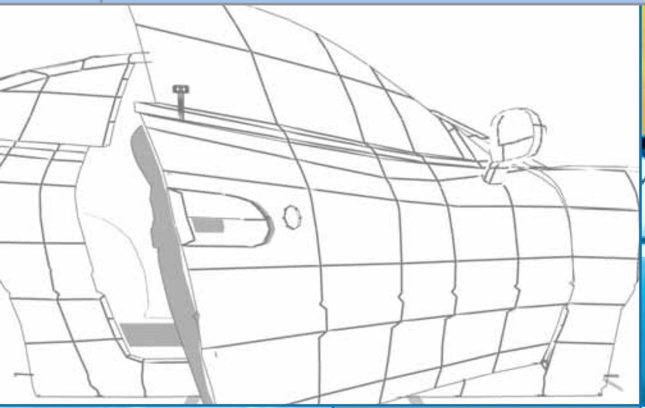
When using FSK modulation, designers must spend some effort in achieving a sufficient frequency deviation. A 2-port resonator, designed in a Pierce oscillator circuit, is needed. Pulling the frequency reference is done by a serial varactor or a PIN diode.

Table 2 provides a representative overview on the cost of such a design.

Table 2. BOM - SAW Transmitter

Bill of material RF circuit section: SAW resonator ASK Transmitter						
Components	Value	Tol.	Material	Housing	Manufacturer/ Distributor	Price/Pcs (100k)
Q1	R800	75kHz/ -0.032ppm/K²	quartz crystal	QCC4A	Epcos AG	0.40 €
Q3	BFR193T		npn RF transistor	SOT 23	Vishay	0.074 €
Q4	BFR193T		npn RF transistor	SOT 23	Vishay	0.074 €
C1	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C2	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C3	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C4	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C5	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C6	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C7	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
C8	t.b.d.	2%	C0G	Size 0603	e.g. muRata	0.0015 €
R1	t.b.d.	5%	D11 CRCW	Size 0603	Vishay	0.0010 €
R1	t.b.d.	5%	D11 CRCW	Size 0603	Vishay	0.0010 €
R2	t.b.d.	5%	D11 CRCW	Size 0603	Vishay	0.0010 €
R3	t.b.d.	5%	D11 CRCW	Size 0603	Vishay	0.0010 €
R4	t.b.d.	5%	D11 CRCW	Size 0603	Vishay	0.0010 €
R5	t.b.d.	5%	D11 CRCW	Size 0603	Vishay	0.0010 €
R6	t.b.d.	5%	D11 CRCW	Size 0603	Vishay	0.0010 €
L1	t.b.d.	5%	LL1608-FS	Size 0603	Toko	0.04 €
L2	t.b.d.	5%	LL1608-FS	Size 0603	Toko	0.04 €
additonally needed for same signal accuracy						
Q2	4 MHz	t.b.d	quartz crystal	any	any	0.30 €
					for RF circuit section	
					Total cost	0.95 €
					Component count	21 pcs

For further application and product details, see Table 3



Comparison of Both Solutions - Conclusion

The advantages of the PLL-based design are related to performance: the quality in terms of **frequency synthesis**. Current and future applications move to narrow-band RF systems, the RF bands are more and more overcrowded. Therefore, excellent selectivity and sensitivity on the receiver side is necessary, which is only possible with narrow-band PLL solutions.

Furthermore, a **flexible channel selection** can only be achieved with quartz-crystal-based solutions. These devices are more likely to get ordered in a customized way than SAW devices. Some bands are not even available to operate with SAW apps.

High temperature applications (even up to +125°C) and **modulation rates up to 32 kHz**, an important current-saving feature, can be achieved.

It is obvious that **applications** with an integrated PLL-Tx with a minimum amount of external components and reduced need for analog design skills such as theory of oscillators and PLL are much more easy than SAW-based designs.

Finally, the **reliability** regarding mass production, EMI and RFI is increased, which reduces **time-to-market**.

The advantage of SAW-based designs is the lower total **component cost**. SAW applications are about 13% cheaper than PLL-based designs. (see Table 1, Table 2). When considering the **power consumption efficiency**, the SAW TX side provides better results (33% vs. 22%) thanks to the missing current consumption of the PLL circuit.

It seems that even some automotive suppliers have switched to discrete solutions since cost considerations have currently a priority over performance issues, which will certainly not be the trend in long-term.

Table 3. Comparison PLL-based Tx vs. SAW-based Tx

Comparison PLL based transmitter - vs - SAW based transmitter

based on average priced components

Parameter	PLL Tx	SAW Tx
Frequency synthesis	*e.g. Atmel UHF Transmitter T5754 (433 MHz)*	
tolerance - initial	+-30 ppm	+-170 ppm
tolerance - temperature -40..-+85	+-40 ppm	-150 / +70 ppm (incl Vcc depend.)
tolerance - aging	+-10 ppm	-10/+50 ppm
tolerance - XTO	+-30 ppm	--
total tolerances	**+-110 ppm**	**-330 / +290 ppm**
covering all ISM bands	YES; different product versions available; XTAL determines RFcarrier in ISM band	NO; just widely used RF carriers possible. New 868 MHz(EU) bands too tight.
supply voltage range	fixed range; 2.0V .. 4.0 V	flexible design; often 3V Li cell / 9V block used; frequency synthesis is d VCC dependent
output power	7.5 dBm @50 Ohm	flexible design; see efficiency
power efficiency = Pout/ VCC*ICC	=7.5dBm/ (3V*8.5mA) = 22 % (incl. Is_{PLL}=3.6mA)	=10dBm/ (3V*10.1mA) = 33 %
temperature range	-40 .. + 85 (125°C) suitable for high-T apps	typ. -40 .. + 60 (+85°C) high tolerance for high-T apps
modulation		
ASK	to 32 kHz	<< 32 kHz, limited due to settling-time, (mostly direct switching of SAW and 1..4 kBd used)
FSK data rate frequency deviation	to 32 kHz frequency deviation to +-100 .. 150ppm possible neglectable dependancies	< 32 kHz, limited data rate < +-100 ppm, limited frequency deviation (VCC / temperature dependant to +-50ppm; strongly dependant on oscillator analogue design)
Other		
BOM component count	8	21
BOM cost	1.09 €	0.95 €
PCB size	comparable	comparable
easy design-in	no analogue & RF design skills needed (except antenna)	experienced analogue & RF design skills needed for secure apps
type approval (ETSI /FCC/ etc.)	comparable; PFD spurious possible, but not critical higher phase noise, but not critical	comparable
EMI / RFI	robust design, due to high integration level	discrete design is likely to be subject of EMI/RFI

Outlook

Current automotive developments are based on bi-directional RF links to improve the feature set and convenience. Since the amount of RF users has been steadily increasing, and the usage of the available bands needs to be more efficient, channel-spacing and multi-channel devices are the next evolution step. The most recent extension of the PLL-based synthesizer is the fractional-N device. These new devices allow the generation of pure high-frequency sources with flexible channel spacing from a few hundred Hz to several hundreds of kHz.

CONTACT

Atmel Germany GmbH, Theresienstr. 2, 74072 Heilbronn, Tel. 07131 67-2081, Fax: 07131 67-2423