RF-Trends in Mobile Communication

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Abstract:

TDMA based 2/2.5G digital systems like GSM/EDGE and CDMA (spread spectrum) based digital systems like IS95 for wireless cellular communication have created an increasing market within Europe, the US and SEA since 1992 and have gained nearly world-wide acceptance. The total number of cellular subscribers has already reached the range of 1 billion and may grow to 2 billion by end of this decade. The 3G WCDMA based UMTS system started service in Japan in 2001 and in Europe in 2003.
Advanced Smart Cellular Phones are, already today, extended with Cordless, Navigation, Broadcasting and other services, e.g. DECT, WDCT, BT, Zigbee, RKE, GPS/Galileo, FM radio, DAB, TV, DVB, WLAN, RF TAGs. These multi-system phones will enable in the future nearly unlimited wireless connectivity and services.
This paper gives an overview on the trends and challenges for radio front ends in cellular and non cellular Systems-in Semiconductor integration, which will enable small, lightweight, powerful, low cost Smart Cellular Phones.

1. Introduction

Mobility and the wish for ubiquitous connectivity is an intrinsic factor in the past, in today's and in the future's society. Since the early 90-ties the driving factor for the incredible progress made in the new digital cellular and also non cellular systems were the advances in signal processing, and the ever higher integration levels and ever smaller feature sizes of the semiconductor CMOS VLSI, Bipolar, BiCMOS and GaAs technologies. Progress in these areas is still ongoing. The continuously increasing data traffic is a logical result of the rapidly increasing use of the Internet together with its new contents and new applications such as images via built in camera, streaming audio, image and even video.
The second Generation Mobile Network (2G/GSM) started services in 92 and is already reaching its limit in some megalopolis. Current cellular communication terminals are mainly dedicated to voice communication. The data rates supported by 2G systems are well below 100 kbps. Advanced applications, such as image and video transfer with their need for high-speed data transmission are either unattractive or simply not possible at such low data rates. The introduction of services like WAP (Wireless Application Protocol) suffers from the limitations dictated by the restricted system capabilities.
General Packet Radio Service (GPRS) will provide continuous and instant access to the Internet, which gives you – at least theoretically – "any information at any time at any place".
In order to meet the demand for higher data rates, a new generation (2.5G) e.g. Enhanced Data Rates for Global Evolution (EDGE) will bring the necessary data transmission bandwidth for voice and image services. With its new modulation scheme for high spectral efficiency, EDGE will enable operators to roll out additional services on the basis of today's GSM network.
Even higher data rates were forecasted and pushed the development and introduction of 3G. Data rates up to 2.048 Mbit are possible, with 3G services started already in Japan / 2001 and in Europe / 2003.
In the future co-integration of some of the non cellular systems like DECT, WDCT, BT, Zigbee, RKE, GPS/Galileo and even RF TAGs may be required to further increase wireless connectivity and service. Additional services such as WLAN Hot spots improve already today the internet connectivity, the available bandwidth and data throughput reasonably. Also long existing services as FM-radio and TV are now and will be in the future partly included into some terminal models.
The different services requested for future multi-media terminals require multi-band and multi-mode implementation both in RF and baseband signal processing. The data traffic will not only increase for the downlink from base station to terminal, it will also increase for the uplink from terminal to base station. Typical stand-by to talk time ratio of mobile phones today is about of 60 (300h/5h).
Using only the currently available architectures for multi-band and multi-mode terminals we may end up in bulky, heavy and expensive phones. Instead of the Software Defined Radio (SDR) approach we may see an intermediate step via Software Reconfigurable Radio (SRR) approach of RF and baseband parts.

2. Standards, Frequencies and Services

The migration path towards the next generation cellular system is rather different in the different regions of the industrialised world. Whereas Japan introduced the first digital cellular systems PDC in 91, the IS95/CDMA service in 97 and already started with UMTS/ W-CDMA in 2001, the legacy systems in America and in Europe require a more evolutionary approach which emphasis on backwards compatibility, cp. Figure 1.
The most important second generation system is European-based GSM, which has spread all over the globe and is now available in more than 197 countries,

with 555 operators and a total market share of 60% or 260 Millions out of a total of 435 Mill terminals produced in 2002 [13].

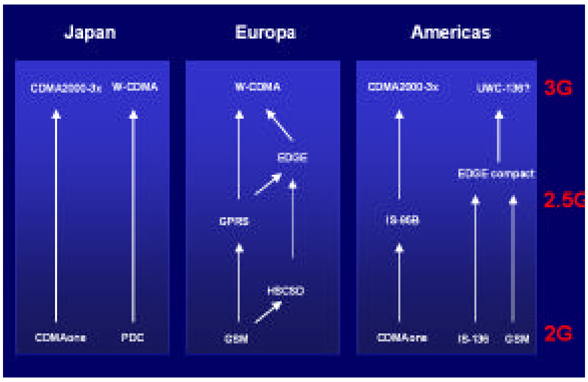

Figure 1. Evolution of Networks

Other important 2G standards include the US-based IS136 and CDMAone, and Japan based PDC. The penetration rate of mobile services exceeds 60% in some Asian and European countries. The total number of mobile subscribers to 2G services today is 847 million, corresponding to 72% of all digital subscriber services and is still growing [11].
Considered as “2.5G” systems are the GSM based GPRS, the packet enhanced PDC-P, and extensions of CDMAone which are already in service. Japan is the country that requires the earliest deployment of 3G type services due to the spectrum bottlenecks and also to extend the success of the 2G data services in operation now, such as i-mode.
3G systems, as they are currently driven by two 3G partnership projects, 3GPP and 3GPP2, are based on CDMA technologies and are evolutions from CDMAone (leading to multi-carrier CDMA, driven by 3GPP2) and GSM (leading to UMTS with its two modes, driven by 3GPP). EDGE (whose evolution is now within 3GPP) is sometimes also included in 3G, as well as the cordless DECT standard (to ease the integration of private branch exchanges). 3G systems mobiles will have peak rates of 384 Kbps in the first phase and will be extended in the second phase up to 2Mbps.
Some terminal suppliers today produce more than 60 different mobile phone types, to address the different systems, bands, market requirements and trends. GSM triple band phones are already standard and 4 band solutions are to come. Voice centric phones still are the largest market, but already now mobils with Bluetooth connectivity and / or embedded FM radio are in production. Some 3G mobils in Japan have implemented location service and tracking via GPS, a service, which may become a standard in 2008 for all terminals. Also other applications such as MPEG players and colour cameras are already embedded in some phones.
The Pocket PC, PDA and cellular phone worlds merge into combined devices. Additional to Bluetooth also 2.4GHz WLAN service may be included for data downstream and even digital TV broadcast receivers for movies. This makes new applications now possible such as on-line video, video conferencing, on-line banking etc. This requires additional computational power and security measures.
Table 1 (page 7) shows a matrix of standards and frequency bands. Terminals with various combinations out of this matrix of different wireless services, different frequency bands and different standards are produced already today and even more choices will be available in the future. This variety will be implemented in many mobile products, addressing high volume mass but also lower volume life-style niche markets.

3. Mobile Transceiver

Cellular systems

The GSM system was established in the 900 MHz frequency band during 1992. First generation RF products were available from various suppliers in mid 1990. These designs were based on low level integration and used a 5 V supply voltage [1, 2]. The RF board design of a complete handheld at that time consisted of more than 500 components (Cs, Ls, R, ICs etc.).

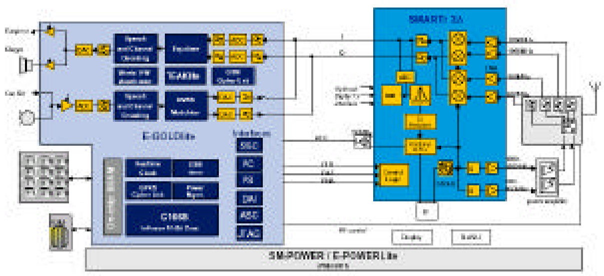

Figure 2. 2G/GSM System Solution

Now in market introduction are single chip RF transceivers in CMOS with only about 60 additional external discrete components, see Figure 2. The Zero-IF receiver has become state of the art in 2003, whereas in the transmit path direct modulation, modulation loop concepts and ΣΔ-Modulation-loop concepts are competing. VCO-modules are to be increasingly replaced by On-chip VCO’s. Figure 3 shows an overview of all the concepts discussed, which are partly being used at present.
For power amplifiers the discrete components approach is nearly completely replaced by modules. The technologies in use are Si-LDMOS, GaAsHBT and SiGe-Bipolar PA’s, which may gain a bigger market share in future.
The development of integrated circuits for UMTS is now on the same integration level as in 2G. Since 2001 the 1-st generation mobiles have used a single conversion concept with one IF in the RX-signal path.
The required transmit path is similar to the solution described under GSM. Compared to GSM it additionally requires an IF-TX variable gain amplifier and an additional RF-TX variable gain amplifier.
Already at the end of 2003 also Zero-IF-RX and Direct Modulator TX Single-Chip Solutions similar to GSM

will be introduced into the market to allow the terminals designer to shrink further size, form factor and cost of the future terminals.

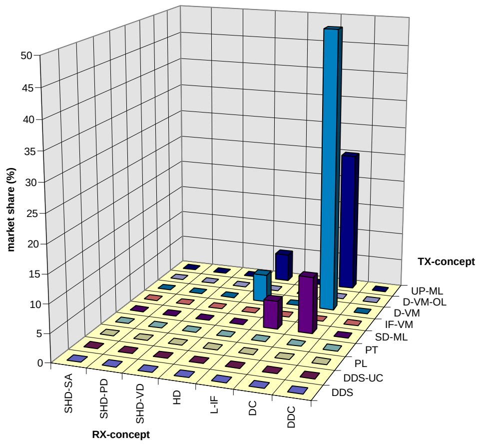

Figure 3. Status of GSM RF RX/TX concepts in 2003

For the IS95/ N-CDMA systems the RF integration hasn't reached the same level of integration as in 2G/GSM. The integration path is about 4-5 years behind GSM. In GSM already in 1999 single chip transceiver were introduced to the market. IS95 solutions in 2004 are still being implemented out of 2 chips, e.g. a receive and transmitte chip.

Non cellular systems DECT and BT

The first cordless sets according to the DECT system were introduced into the market in mid 1994. They employed already a highly integrated baseband chip, whereas the RF had a high content of discrete components resulting in more than 400 parts on the RF section of the board.

Bluetooth development was strongly influenced by DECT technology.

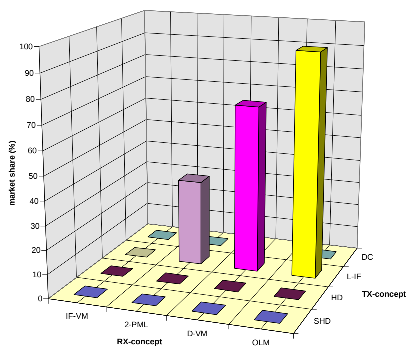

Figure 4. DECT & BT RF RX/TX concept status 2003

Four different receiver and transmitter concepts are mixed up to several combinations and are now in volume production (Figure 4). Single chip transceiver [6] with On-Chip-VCO's is now state of the art with a few external discrete components. All other solutions are no longer in production.

Non cellular systems WLAN

2nd generation WLAN integration is very similar to 3G integration. It was based on a single chip IF transceiver with IF-receiver and I/Q vector modulator and either a second chip for RF front-end up-/down-conversion or a discrete approach. Now similar to 3G single chip Zero-IF demodulator and modulator solutions are introduced into market.

3.1. Receive signal path

Cellular systems

At the beginning of GSM development many different transceiver concepts had been discussed [10; 11]. Figure 3 gives a total overview of all discussed and currently used transceiver architectures and their market share. Receiver and transmitter concepts currently most frequently in use are mixed up to 6 different combinations.

In the 900 MHz GSM Band we find in the receive path:

1. Single conversion (HD) to 1st IF of 40-130 MHz with a conversion to I/Q-BB [1; 2]; some years later IF frequencies between 250 to 450 MHz were introduced [3; 8], now replaced by Zero-IF.
2. Dual conversion with two IF-frequencies (SHD-SA), followed by a subsampling A/D conversion, also replaced by Zero-IF.
3. Dual conversion with two IF-frequencies (SHD-PD) followed by a phase comparator and a RSSI evaluation as Polar demodulator (PD), also replaced by Zero-IF.
4. Zero-IF with direct conversion (DC) to I/Q Baseband [13,15]. This concept has today the highest market share.
5. The Digital Down Conversion (DDC) with A/D conversion or subsampling is too power consuming for a terminal and therefore not in use yet. It would be the basis for a software radio; today it is the topic of research work and may develop similar to Zero-IF the next few years.

Non cellular systems DECT and BT

The DECT and Bluetooth GFSK modulation allows using simple FM demodulators. Also the FM demodulation is very insensitive to local oscillator frequency offsets and supports further integration. In the receive path three different concepts were in use, shown here in chronological order.

1. Dual conversion receiver with an IF 110 MHz and a second IF of 5-6 MHz (SHD), with additional passive filtering, followed by an IF limiter amplifier and a demodulator. The receiver part of first generation was dominated by dual conversion receiver design, but since 1997 is no longer in production.
2. Heterodyne receiver with an IF of 110 MHz (HD) and a limiter amplifier and demodulator at this frequency. This concept was produced from 1994 up to 2000, because of its high sensitivity of down to –97 dBm [9].

3. Low IF concept with an IF-frequency range (L-IF) of 1-3 MHz has been produced since 2002, because it allows to replace an IF-filter and to further reduce board area and component cost. This solution had less sensitivity in the range of -90...-93 dBm.

The dual conversion concept was easy to develop at the beginning, because all FM demodulator components were available from standard TACS, Amps and CT1 systems. But the second down conversion increased the component count.

The single conversion concept has reasonably brought down the component while achieving the same sensitivity of up to -97 dBm.

The low-IF concept now in use has additional low IF amplification. This can be done at low frequencies with lower power consumption and with reduced external component count. In spite of having 3-4 dB less sensitivity as the single conversion concept, low-IF gained thanks lower cost, nearly the whole market share.

Non cellular systems WLAN

Most of current WLAN solutions are based still on a heterodyne concept with one IF filter. The next generation products now in market introduction will migrate to Zero-IF topology.

3.2. Transmit signal path

Cellular systems

The transmitter part of the GSM related system concepts are also dominated by 5 concepts.

1. Low IF I/Q-vector modulation IF-VM at frequencies of 100-500 MHz followed by a upconversion mixing and passive image filters. This concept is also in use at PDC 0.8 and 1.5 GHz and in CDMA applications.
2. Direct I/Q vector modulation D-VM with a local oscillator frequency of 1, 2 or 4 times the transmit frequency.
3. Direct I/Q modulation (D-VM-OL) with transmit LO signal generated by mixing via an IF LO and RF local oscillators. Using frequency offset in both LOs results in less LO feedback leakage sensitivity. Now no market share any longer.
4. Low IF I/Q-modulation (UP-ML) (100-300 MHz) followed by an upconversion modulation loop. Now this concept has the highest terminal market share.
5. ΣΔ-Modulation Loop Concept (ΣΔ-ML) was introduced in 2001 and gain more and more market share.

New modulation techniques e.g. the Polar Modulator (PM) or Polar Transmitter (PT) topologies may be implemented within the next future, because these techniques offer potential improvements in the efficiency of the whole transmit path including the PA and will extend talk time reasonable.

Non cellular systems DECT and BT

For the transmitter part of the DECT system also different concepts were discussed.

1. Low IF vector modulation (IF-VM) at frequencies of 100-300 MHz followed by an upconversion mixing and passive image filters. This was only published in the very beginning, but is not in volume production any more.
2. Open Loop Modulation (OLM) with local oscillator at half or double transmit frequency. This concept has highest market share.
3. Fractional PLL based 2 point modulation loop concept (2-PML) with local oscillator oscillating on two times of the transmit frequency or at half the transmit frequency, this concept is gaining more interest, because it can be also used for multi-slot application.
4. I/Q based Direct Vector Modulator (D-VM) is also in use.

The low IF-modulation & upconversion mixing according to concept 1 avoids drift problems during TX time slot. If the loop filter frequency of the IF PLL is aligned to less than 1 kHz, the modulation signal can be superimposed on the tuning voltage. But it requires a very good image filter to suppress the unwanted image. A careful selection of both LO signals is needed in order to achieve a spurious free emission.

Concept 2 is very straightforward and has no spurious problem, because only one LO signal is present in transmit mode. But it requires very good shielding of the VCO to avoid remodulation with the power amplifier output signal. When the local oscillator runs at half or twice the transmit frequency the LO feedback pulling sensitivity is reduced. Also the PLL charge pump output must have a very low leakage current.

The closed loop modulation concept allows transmission during more time slots, without the frequency drift problems often caused by the leakage current of the varactor.

The ongoing RF-integration reduced the component count from more than 400 parts to ca. 50 in the meantime and there is even further potential to achieve less than 20 components. Since 1997 also handhelds with 3 V supply voltage also for all RF blocks except the PA have been used. The future trend is to further reduce the supply voltage down to 1.5 V, which will further decrease the power consumption and the peripheral component count.

Non cellular systems WLAN

2nd generation WLAN solutions were based on a single chip IF transmitter using an I/Q vector modulators. All new solutions are based on I/Q direct vector modulation. The vector modulator offers the best approach for the transmit signal path of the Direct Sequence Spread Spectrum modulation scheme of 802.11b and the OFDM based modulation scheme of 802.11g and 802.11a.

3.3. Technologies for Transceiver and Power amplifiers

In GSM applications the technologies used in 1990, due to lower level of integration (up to 5 RF chips) were bipolar receiver, transmitter and presacler and CMOS for PLLs, see Figure 5. Later BiCMOS gained reasonable market share. With the advances in CMOS Technologies, we did find in 2002 solutions with lower levels of integration of 3 chips in 0.35µ, 0.25µ and 0.18µ technologies. With today's 0.13µ even single chip

CMOS transceiver are introduced. In next future advanced dedicated 0.13µ BiCMOS technologies still will coexist with CMOS for the cellular applications, because BiCMOS will offer better RF in-/out performance, lower component count and lower cost compared to pure CMOS. This improved performance is required with the up-coming multi-band and multi-mode transceivers. Between antenna and transceiver there will be more signal loss, therfore only with the better performance of BiCMOS over today's CMOS the system and customer requirements can be met.

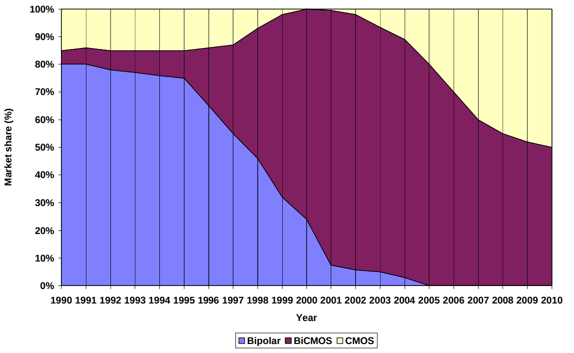

Figure 5. Technologies in use for GSM transceivers

The technologies used for cellular power amplifiers show a very different picture compared to transceivers, see Figure 6. Today LDMOS and GaAsHBT Technologies dominate the market.

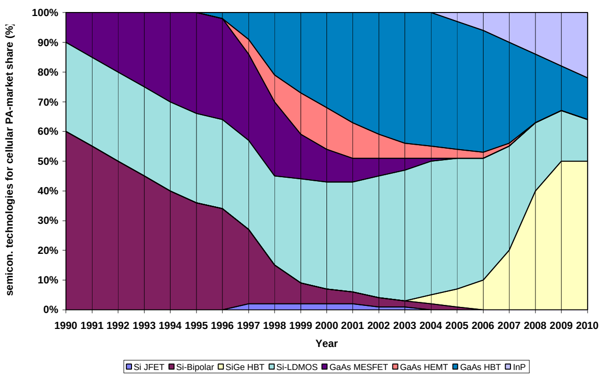

Figure 6. Technologies in use for cellular power amplifiers

Due to the very critical output matching of power amplifiers, production tolerances impacts the overall yield of the assembled terminal boards, therefore the discrete PA solutions in the terminal boards were step by step replaced by module solutions with 50 Ω In-/Output impedance and pre-tested guaranteed RF performance. One bottleneck for talk time of terminals is still the low level of efficiency at typical output power of 0.6W

Non cellular systems DECT, BT and WLAN

First generation BT RF-chips were in BiCMOS. Now nearly all BT include RF and BB in a single chip CMOS, partly in 0.25µ or 0.18µ and will further migrate to 0.13µ. About 95% of all WLAN 802.11b/g solutions are still using BiCMOS technologies. Within the next years CMOS will gain also more market share. Bipolar power amplifiers have replaced discrete transistor power amplifiers and GaAs power amplifiers. Power amplifiers for DECT, BT class2 (100mW) and WLAN are silicon based MMICs, in most cases 2 stages, with an integrated driver and end amplifier.

4. Challenges

In the GSM related systems the trend goes increasingly towards RF single-chip 4-band handheld solutions, all using the Zero-IF receive concept. The total component count for the RF front end has been reduced from 500-600 components down to 60, with potential to go further to around 40 components or less. Supply voltage started in 1990 with 5V, changed during 1995 to 2.7V and may change in 2004 to 1.5V [3, 7, 8]. The front-end antenna switch is dominated now by RF front-end modules, which include also the SAW or FBAR receive filters.

Further integration of complete transceivers, all filters, antenna switches, duplexers, isolators and power amplifiers into one extremely small sized RF module with chip-on-board technology is the challenge for the next future. First solutions now offered for GSM quad band might become standard within 3-4 years. In additional to chip-on-board technologies also RF-solutions with System-in-Package using multi-chips or stacked chips will be developed.

For voice centric terminals several companies announced Single-Chip RF and BB solution for 2004.

In a legacy GSM infrastructure it is necessary to offer 4-band GSM and dual mode GSM/ UMTS terminals. This is the next challenge to develop and fabricate a highly integrated single-chip in order to reduce cost and external component count.

The power amplifiers in use today are mainly based on GaAsHBT or Si-LDMOS Fets, assembled in LTCC or in laminate based modules. The PAs in most applications are connected directly to the battery. High efficiency switch mode converter for regulated supplies are not in use any more. The limited efficiency of the power amplifiers in the average traffic mode corresponding to 0.6 Watt at 900 MHz is one major bottleneck today in the transmit path. The highest efficiency of 40 - 50% is only reached at 2Watt (peak) output power at 900 MHz. There is enough potential for improvement, that a doubling of the talk time at average power levels should become possible.

Future terminals will have much higher data traffic (up to 1Gbit) also for the up-stream from terminal to base station, this will require further optimisation of the transmit signal path towards higher efficiency compared with today's solutions. Polar modulation and polar transmitter topologies offer a way out for this improvement.

For future terminals offering multi-band (e.g. 4 bands 2G + 3 bands 3G + 2 bands WLAN) and multi-modes (e.g. GSM+UMTS+BT+WLAN+GPS+FM-radio) as indicated in Table 1 even the advances in integration by module assembly are not sufficient. New Software Reconfigurable Radio (SRR) integration in transceivers, power amplifiers and filter alignment and/or tuning technologies combined with all new success in MEMS technologies may allow further miniaturisation of the radio front end.

5. Conclusion

The cellular systems like 2/2.5G GSM, IS95 etc. and the non-cellular systems like DECT, BT, WLAN etc. together have created a strong new market within Europe and other areas of the world. RF integration has become a very important factor to reduce component count and production cost in the according mobile terminals.

The development towards system-on-chip implementations is still ongoing; limitations that we still have today can be solved step by step i.e. with on-chip VCOs, on-chip filters, on-chip tuning, on-chip demodulation, on-chip alignment by 3 wire control lines, on-chip ADC/DAC, digital interface etc. Also more and more low frequency analog, IF and RF functions can be integrated together in CMOS- or BiCMOS technology. Within this decade, the terminal market will have reached a market volume of nearly one billion handsets for 2&3G per year. This market will push the system-on silicon-development of highly integrated single chip RF&BB chipsets in advanced CMOS technologies.

Semiconductor companies offering a complete system solution comprising hardware and software will need also in future the expertise in conception, design, application and production of the key components of a terminal. These will enable them to optimise the receive and transmit signal path integration and the baseband signal processing for best of class performance, lowest power, minimum component count and cost.

It is fascinating to see how new system specifications, progresses in silicon; especially CMOS technologies and SAW or FBAR filter technologies have influenced the RF-concepts, architecture and integration. This led to the advanced RF-product families available on the market. The driving developments in the last years have been the cleverness of RF-analogue, mixed signal and digital design and implementation technique, the ongoing evolution in silicon processing technology, as well as new assembly and packing trends.

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7. Glossary

	Receiver topologies
SHD-S	Super heterodyne followed by IF sampling; also called dual conversion
SHD-PD	Super heterodyne -polar demodulator
SHD-VD	Super heterodyne - Vector demodulator
HD	heterodyne or single conversion
L-IF	low IF
DC	direct conversion, homodyn or Zero-IF
DDC	Digital down converter
	Transmitter topologies
DDS	Direct digital synthesis
DDS-UC	Direct digital synthesis followed by upconverter
IF-VM	IF based vector modulator followed by upconverter
D-VM	I/Q based Direct Vector Modulator
D-VM-OL	I/Q based Direct Vector Modulator with Offset LO
UP-ML	upconversion modulation Loop
SD-ML	Sigma-delta Modulation Loop
PL	Polar Modulator
PT	Polar Transmitter
2-PML	Fractional PLL based 2 point modulation loop concept
OLM	Open Loop Modulation

Band		Market					Standard																
MHz	Systems Notes	Region					DAMPS IS136 TDMA	GSM GPRS EDGE	3GPP2 IS95/CDMA/2000_3G1X EV	CDMA2000/3X	3GPP UMTS W-CDMA	PDC Jpn	FM-Radio	TV / DVB	DAB L-Band	DECT	WDCT	BT/2.4GHz	WLAN/2.4GHz/802.11b	WLAN/2.4GHz/802.11g	WLAN/5GHz/802.11a	GPS/GALILEO/1.575GHz	RKE
	Channel spacing	(kHz)					30	200			5000	25/50	300	7000/8000		1728	1728	1000	11000	20000	20000	2000	300
	Channel Bandwidth /Chip rate	(kHz)							1228	3684	3840				1536	1728	1728	1000	11000	11000 - 16500	11000 - 16500		
	Datarate	(kbit/s)					<9.6	<9.6 <53.6 <245.6	<14.4		<2000	<9.6				1152	1152	1000	... 11000	... 54000	... 54000		<10
		EMEA	NAR	CALA	AP	Jpn																	
48 - (860)	EU: 860; US: <800	x	x	x	x	x																	
88 -108	FM Radio	x	x	x	x	x							optional					optional					
410	PMR/PAMR	x		x					x														
450	PMR/PAMR (old C-net)	x		x	x			x	x														
480	PMR/PAMR	x		x				x	x														
700	alpha; former TV		x					x	x	x													
750	new US		x					x		x													
800	Cellular; PDC800					x						x											
850	cellular		x				US	EU/US	x	x													
869	RKE: 868 - 870	x																					
900	GSM	x						EU/US															
915	ISM US		x																				
1500	Cellular; PDC1500											x											
1575	GPS/GALILEO																					Jpn	
1472	DAB: 1452 - 1492	x																					
1700	Korea - PCS				x					x													
1800	DCS	x						EU/US	x														
1890	DECT: 1880 -1900	x																					
1900	PCS		x				US	EU/US	x	x													
2100	IMT-2000 FDD//ARIB	x				x			x	x	Jpn												
2100	IMT-2000 TDD	x																					
2400	ISM Band: 2400 - 2483	x	x	x	x	x																	
2500	new IMT2000 to be def.																						
2600	new IMT2000 to be def.	x	x	x																			
5250	USA, EU: 5150 - 5350	x	x	x	x	x																	

Table 1. Matrix of possible frequencies and services with current available combinations