Highly Integrated RF–IC's for GSM and DECT Systems—A Status Review

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***Abstract*—TDMA based digital systems like GSM for cellular and DECT for cordless application have created an increasing market within Europe and gained widespread acceptance also outside Europe. This paper gives an overview of both systems. The system requirements and their influences on highly integrated RF IC's for GSM and DECT are discussed in detail. The various trends of progresses in integration of both systems will be shown, with the different advantages and the disadvantages of the concepts in use. The challenges of increasing the level of integration and an outlook to future will be presented.**

***Index Terms*—Digital mobile communication.**

I. GSM-RF Development Progresses

THE GSM system was established in the 900-MHz frequency band during 1992. Table I gives you an overview of the most important system parameters. First-generation RF products were available from various suppliers in mid-1990 (see Fig. 1). This designs were based on medium-level integration (partly building blocks) and used a 5-V supply voltage [1], [2]. The RF board design of a complete handheld at that time consists of about 400–500 components (Cs, Ls, R, IC's, etc.).

We find solutions on the market with a one-chip transceiver and additional external discrete components. Other solutions split in 2–3 integrated circuits (IC's) with a horizontal segmentation [receiver, transmitter, and phase-locked loop (PLL)]. Solutions with a vertical segmentation with a front-end RF part for up/down conversion, a backend IF part for modulation/demodulation purposes, and a PLL are also in use. Still, solutions with a high level of discrete transistors and passive components are produced.

Prealignement voltage controlled oscillator (VCO) modules replaces more and more discrete VCO designs, because the modules allows simpler final PC-board production without alignement.

At the beginning of GSM development, many different transceiver concepts were discussed [10], [11].

Fig. 2 shows a total view of all discussed and currently used transceiver architectures and their market share.

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In the 900-MHz GSM band, we find in the receive path:

1) single conversion to one IF of 40–130 MHz followed by a conversion to I/Q-Baseband [1], [2]; some years later IF frequencies between 250–450 MHz were introduced [3], [8];
2) dual conversion with two IF-frequencies, followed by a subsampling A/D conversion;
3) dual conversion with two IF-frequencies, follwed by a phase comparator and a RSSI evalution;
4) homodyn concept with direct conversion to I/Q Baseband [13], [15];
5) that direct A/D conversion or subsampling for low power application is still not in use and a dream of the future.

In the beginning, PCN (DCS 1800) and PCS (DCS1900) application used concepts 1)–3) with a further IF frequency and conversion. The newest IC developments with IF frequencies between 250–450 MHz can handle PCN/PCS with only one IF frequency.

The following transmit signal path solutions were discussed:

1) the upconversion modulation loop concept;
2) modulation at low IF frequencies with an additional upconversion mixing;
3) direct modulation with offset VCO signal;
4) direct modulation with direct VCO signal;
5) fractional N-synthesis combined with phase mudulation compensation (not in use);
6) direct digital synthesis (DDS) followed by upconversion mixing or upconversion loop (not in use);
7) direct digital synthesis (not in use and also a dream of the future).

But currently the first four receiver and transmitter concepts are mixed in up to eight combinations and are in volume production.

II. GSM-Receive Signal Path

In total, four receiver concepts are in use in the application of the GSM-system (see the block diagrams in Fig. 3). A receiver in GSM has to handle, according to the system specification, quite a lot of interfering signals (see Table I). Under these circumstances, it is clear that there is no solution possible for any of these concepts without a RF band filter (see filter 1 in Fig. 3) in front of the LNA in order to prevent overload of the input stage. The band filters before and after the low-noise preamplifier also reject image signals

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TABLE I
GSM AND DECT SYSTEM PARAMETERS

	GSM (E-GSM)	PCN (DCS1800)	PCS (DCS1900)	DECT
f_{uplink} (MHz) MS TX==>BS RX	890-915 (880-915)	1710-1785	1850-1910	1880-1900
$f_{downl.}$ (MHz) BS TX==>MS RX	935-960 (925-960)	1805-1880	1930-1990	1880-1900
Channel spacing (kHz)	200	200	200	1728
Duplex	FDD 45 MHz	FDD 75 MHz	FDD 75 MHz	TDD 10 ms
Number of freq. channels FDMA	124 (174)	374	298	10
Number of time slots per frame TDMA	8	8	8	RX: 12 followed by TX: 12
Max. number of users	992 (1392)	2992	2384	120
Modulation	GMSK B*T= 0.3	GMSK B*T= 0.3	GMSK B*T= 0.3	GFSK B*T= 0.5
TX and RX timing advance	3 time slots	3 time slots	3 time slots	0.5 frame
Modulation deviation (kHz)	67.7=logic+1	67.7=logic+1	67.7=logic+1	288
Channel data clock rate (kb/s)	270.833	270.833	270.833	1152
Speech codec	RPE-LTP	RPE-LTP	RPE-LTP	ADPCM
Speech rate [kbits]	FR: 13; (HR 6.5)	FR: 13; (HR 6.5)	FR: 13; (HR 6.5//EFR)	32
bit length (μs)	3.692	3.692	3.692	0.87
bits per time slot (with guard time)	156.25	156.25	156.25	480
bits per time slot (without guard time)	148	148	148	424
length of time slot (μs)	576.9	576.9	576.9	416.67
guard time (μs)	30.5	30.5	30.5	48.7
TDMA length of frame (ms)	4.615	4.615	4.615	10
frequency error (Hz)	< ± 90 (±0,1 ppm)	< ± 90	< ± 90	< ± 50000
phase error ΔΦpeak in TX burst	< 20°	< 20°	< 20°	
phase error ΔΦrms in TX burst	< 5°	< 5°	< 5°	
RX reference sensitivity (dBm) // S/(N+I) [dB]	-102 (today typical - 108) > 9		-102	-83 (today typical - 95), BER=10^{-3}
RX reference sensitivity (dBm)			-102	-73, BER=10^{-5}
RX-RSSI detecting- or agc range (dBm)	-102...-24			-93...-33
RX-adjacent channel rejection; due to in-band modulated interferer;				BER = 10^{-3};
Level of wanted receive carrier n (dBm)	-82		-82	-73 dBm
cochannel interferer level (dBm)	-93		-91	-83
n ± 1;adjacent channel (dBm) //	-73		-73 (coch.)	-58
S/(N+I) [dB]	-6		-6	
n ± 2; 2 channels adjacent (dBm) //	-41		-41	-39
S/(N+I) [dB]	-12		-12	
any other inband channel				-33
RX-minimum required 3rd order input point (dBm)	-18			-24
RX-intermodulation characteristics				
level of wanted carrier n (dBm)	-82			-80
requirement of S/(N+I) [dB] or BER [10^{-3}] in BB	(S/N+I) > 9			BER = 10^{-3}
level of unmodulated interferer 1 in offset to n	n ± 4: -49 (dBm)		-49 (± 400k)	n ± 4: -46 (dBm)
level of modulated interferer 2 in offset to n	n ± 8: -50 (dBm)		49 (± 800k)	n ± 2: -46 (dBm)
RX-Blocking characteristics level of wanted carrier (dBm)	-99	-97	-99	
with BB S/(N+I) [dB]	> 9	> 9	> 9	
level of unmod. block. sig. ± 0.6 to 1.6 kHz (dBm)	-43	-43	-43	
level of unmod. blocking sig. ±(1.6 to 3)MHz (dBm)	-33	-33	-33	
level of unmod. blocking sig. 915 to-3MHz (dBm)	-23	-26	-26	
level of unmod. blocking sig. +3 to 980 MHz (dBm)	-23	-23	0 //-12	
TX output power (W) //[dBm]	Power Cl.4; 2 W// 33±3; down in steps of 2 dB 0.02W// 13dBm	Power Cl. 1; 1 W // 30±3; down in steps of 2 dB 0.0025W// 0dBm	Power Cl. 1; 1W// 30±3; down in steps of 2 dB 0.0025W// 0dBm	0.25//+24±1
TX Spurious emission 0.1 - 1 GHz 1 - 12 GHz	<-36 dBm <-30 dBm	<-36 dBm <-30 dBm	<-36 dBm <-30 dBm	
Nominal temperature range (°C)				+15...+35
extreme temperature range (°C)	-10...+70			-10...+55

[concepts 1)–3)]. This filters consists, depending on the IF-circuit frequency, of a four- or six-pole filter (dielectric or SAW-filter type).

1) Heterodyn receiver with an IF of 45–82 MHz [1], [5] and in new design up to 250 and 450 MHz [3], [8] and down conversion from IF to I/Q baseband, recently the

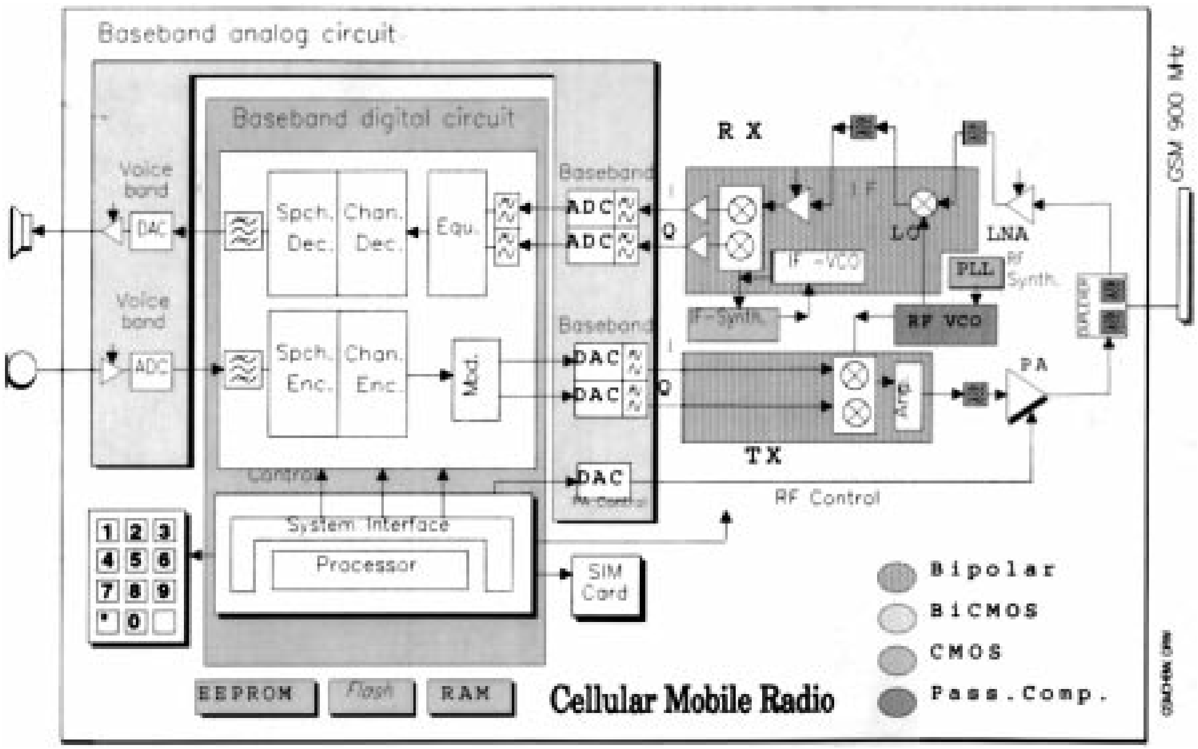

Fig. 1. Block diagram of a typical RF and baseband 5-V chipset for cellular GSM telephones.

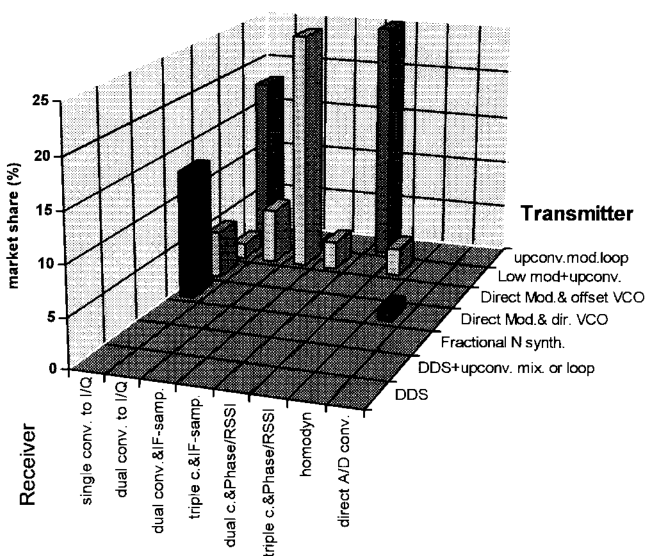

Fig. 2. Transceiver concepts discussed and partly used at the moment within the digital GSM handheld market.

IF gain control and conversion from 81.25 MHz is done with CMOS circuitry [5], [16], [19].

2) Heterodyn receiver with an IF of 72 MHz and a second down conversion with additional passive filtering at about 13 MHz and followed by IF sub-sampling A/D conversion.
3) Heterodyn receiver with an IF of 72 MHz and a second down conversion with additional filtering at about 6.5 MHz and followed by a phase-comparater and a slow A/D converter for radio signal strength measurement; this concept is similar used in all PDC 0.8 and 1.5 GHz applications in Japan.
4) Zero IF concept with additional baseband filtering and variabel gain baseband amplifier in front of the A/D converters.

The first concept has a complete linear signal handling up to baseband and requires only a IF roofing filter. This allows to increase the IF filter frequency from 70 to 80 MHz to values between 200–450 MHz. The system designer can reduce the number of poles of the band/image filters, which reduces costs too. This also makes the local oscillator for downconversion less sensitive to pulling effects caused by input signals within the system band and reduces the LO leakage to the input.

Increasing the IF frequency results also in reduced SAW filter chip and package size with a potential for further cost reduction in the near future.

The dual conversion to IF sampling concept 2 is also a very interesting concept. Due to the limited dynamic range of A/D converter at this IF-frequency, it still needs a second IF filter before subsampling to baseband.

The phase and RSSI sampling concept 3 has the highest requirement on the second IF filter because it uses a IF limiter amplifier.

The advantage of the zero-IF concept 4 is that it does not require the first IF filter and the second filter. To reduce pulling of the local oscillator caused by input signal and LO injection to mixer input the VCO needs a very good shielding and isolation. This increases cost in production.

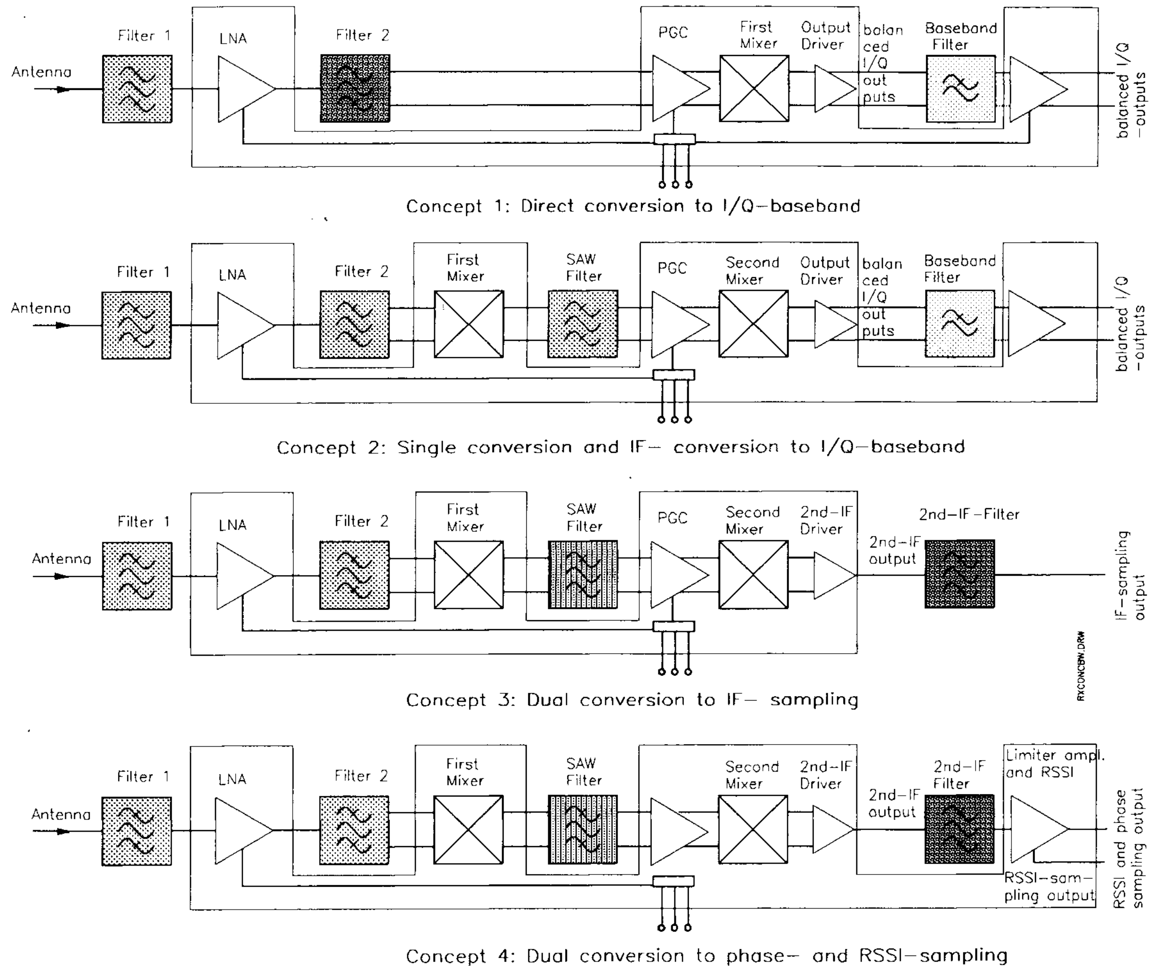

Fig. 3. Receiver architectures used at moment within the digital GSM market.

III. GSM-Transmit Signal Path

The transmitter part of the GSM related system concepts is also dominated by four concepts (see the block diagram in Fig. 4):

1) low IF I/Q-modulation (100–300 MHz) followed by a upconversion modulation loop;
2) direct I/Q modulation with transmit LO signal generated by mixing via an IF LO and RF local oscillators. Using a frequency offset of both LO's results in less feedback leakage sensitivity if power amplifier (PA) is switched on. This is also very popular at PDC 0.8 and 1.5 GHz applications;
3) direct I/Q modulation with local oscillator running on transmit frequency;
4) low IF frequency I/Q-modulation (100–300 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.

Concept 1, when using a low-noise TX-VCO with an output level of about +10 dBm offers lower broad-band noise, so that the duplexer can be replaced by antenna switches and the band filter after PA by low-pass filters. Careful frequency plans and filtering after downconversion mixer and modulator is necessary, to prevent spurious emission during TX burst.

With concept 2, you can prevent the feedback problem from the PA output signal by frequency offset of both local oscillators. It needs a careful selection of both LO's in terms of frequency plan and LO phase noise for low spurious emission and broad-band noise.

Concept 3 is very straightforward and has no spurious problem, because only one LO signal is present during transmit mode. But it requires very good shielding of the unmodulated VCO, to prevent remodulation if PA is switched on. It requires additional band filtering after the modulator to reduce the broad-band noise of modulator in the receive band, similar to concept 2. Unfortunately, most PA's have a very nonlinear transfer characteristic and TX broad-band noise is mixed up to the receive band. Special in power class 1 and 2 (20 and 8 W) the shielding has to be improved. A further disadvantage is the required IF frequency of 45 MHz for receive mode.

Concept 4 has the advantage that the interstage filter between modulator output and upconversion mixer input reduces the broad-band noise at the RX band generated by the modulator. However it requires a very good image filter, to suppress the unwanted images. For both LO's we have the same condition as in concept 2.

Because of the two active local oscillators during TX mode, concepts 1, 2, and 4 are very sensitive to spurious emission and need good filtering and optimized frequency plans.

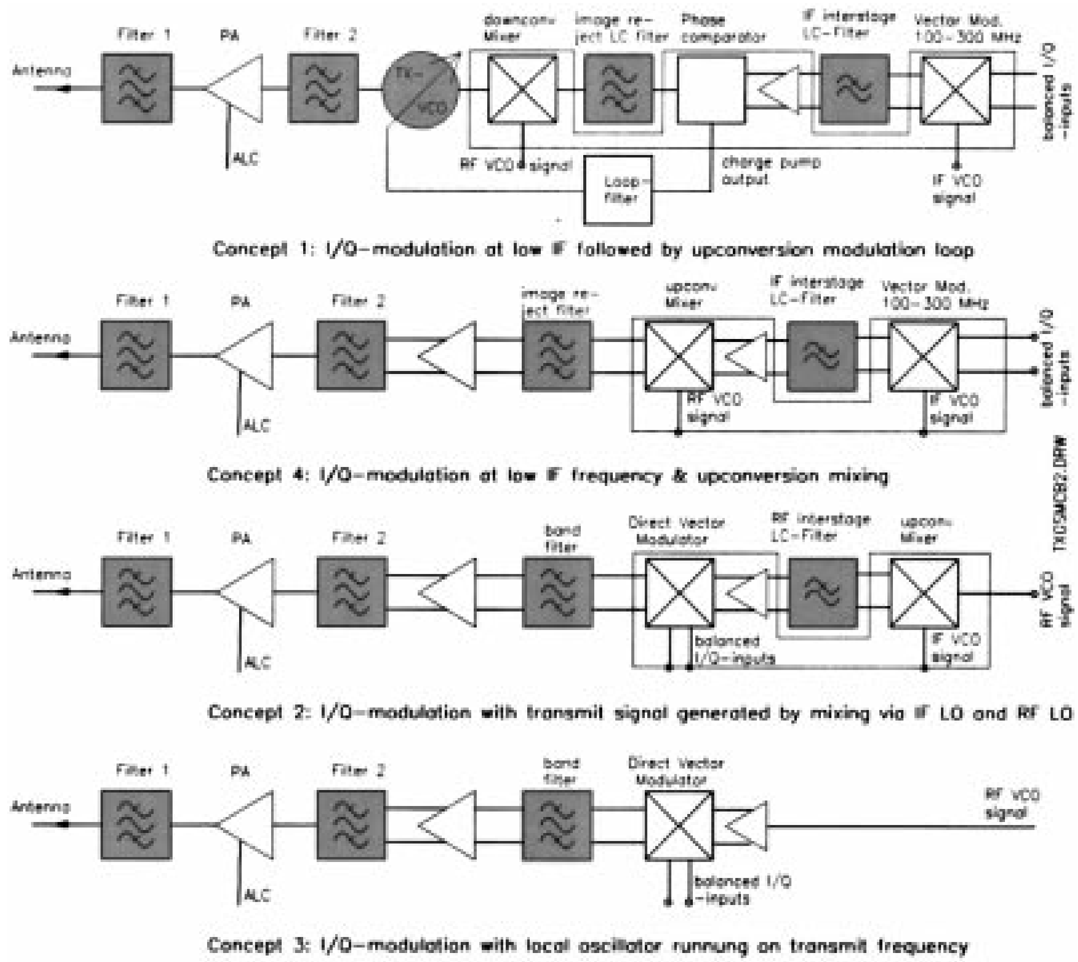

Fig. 4. Transmitter topologies used at moment within the digital GSM market.

For the future dual-band (GSM &PCN or PCS) application, concepts 1 and 4 may have some advantage. But in the end the market decides what concept is used.

In the GSM-related systems, we find more and more tendency to dual-band handheld solutions and further increase the first IF frequency to the range up to 400–500 MHz. Also, the total component count for the RF front end moved from 400–500 down to 200–300, with further potential to around 100 components or less. Also, since 1995, complete handhelds using 2.7 V for the complete RF function without the PA have been available [3], [7], [8], [17].

IV. DECT-RF Development Progresses

The first cordless sets according to the DECT system were introduced in the market in mid-1994 (see Fig. 5). They were already with a high level of integration in baseband, whereas the RF had a high content of discretes, resulting in nearly 400 components on the RF part of the board. Also, at the beginning of DECT development, many different transceiver concepts were discussed [12].

Fig. 6 shows a total view of all discussed and currently used transceiver architectures and their market share.

In the 1900 MHz DECT band, we find in the receive path:

1) single conversion to one IF of 110 MHz followed by conincidence demodulation;
2) dual conversion with two IF-frequencies;
3) homodyn concept with direct conversion to I/Q baseband.

The transmit signal path solutions under evaluation were:

1) the open-loop modulation concept;
2) modulation at low IF frequencies with an additional upconversion mixing;
3) direct modulation with direct VCO signal or offset VCO (not in use);
4) direct digital synthesis (DDS) followed by upconversion mixing or upconversion loop (not in use);
5) direct digital synthesis (not in use).

The integration stepped forward here. Three receiver and two transmitter concepts are mixed up to three combinations and are now in volume production (see Fig. 6). We find solutions on the market with a one-chip transceiver [6] and additional external discrete components. Also, two IC's splitted horizontally into a receiver and transmitter [9] or splitted vertically into a front-end RF part for up/down conversion and back-end IF part for modulation/ demodulation were published. Still, solutions with a high level of discrete transistors and passive components were produced. Here RF-VCO modules do not have such a high market share than in the cellular application. The DECT system bandwith is only

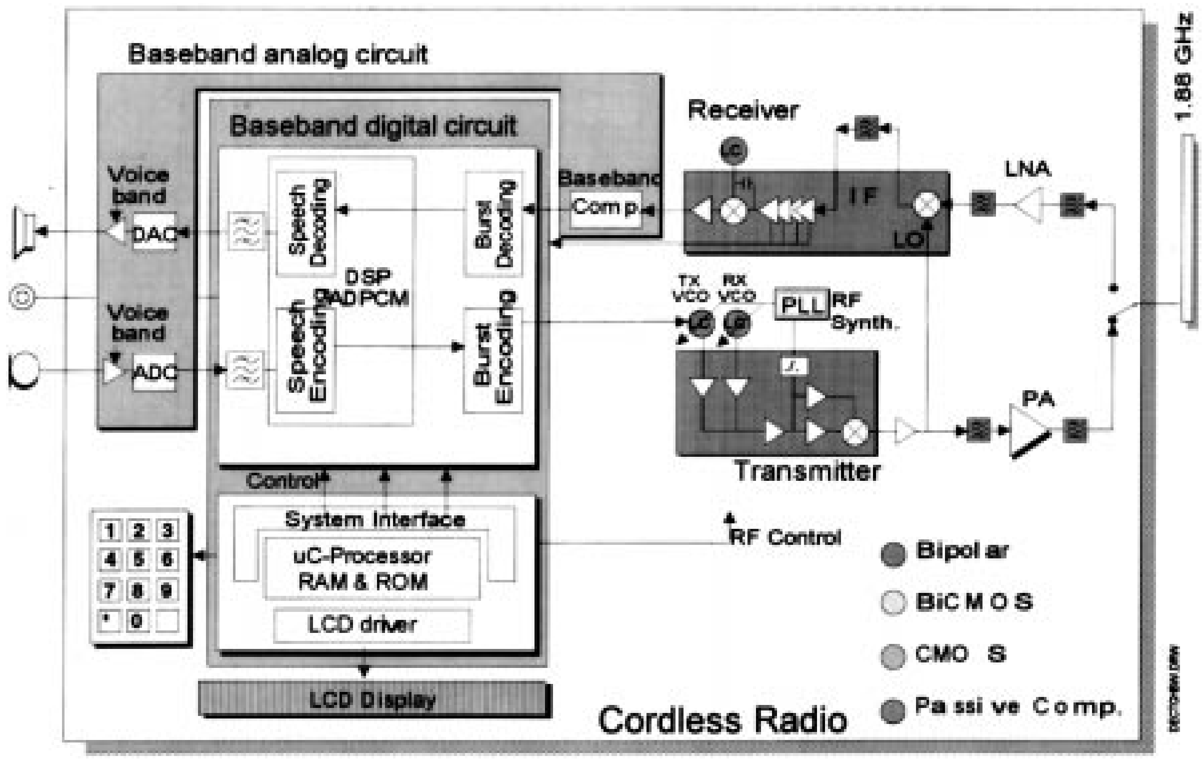

Fig. 5. Block diagram of a typical RF and baseband 3-V chipset for cordless DECT telephones.

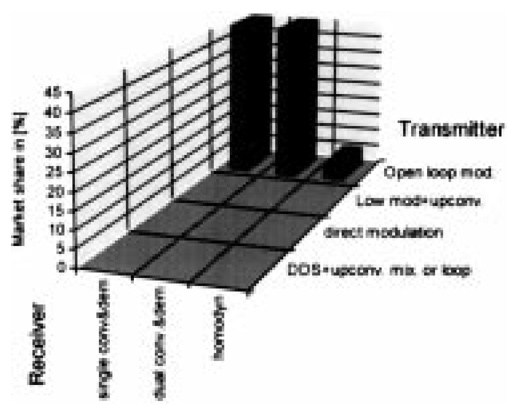

Fig. 6. Transceiver concepts used at the moment within the digital DECT handheld market.

20 MHz. This allows the building of VCO's on the PC-board without alignment. With a high enough tuning range, it is possible to handle all tolerances of the components in the VCO tank circuit.

V. DECT-Receive Signal Path

Fig. 7 shows the block diagrams of the receiver concepts which are in volume now:

1) zero IF /or very low IF concept with additional baseband filtering and variable gain baseband amplifier in front of the A/D converters: one company has now started production with this concept;
2) dual conversion receiver with an IF 110 MHz and a second IF of 5–6 MHz, with additional passive filtering followed by IF limiter amplifier and demodulator: the receiver part of the first generation was dominated by dual conversion receiver design, and now production is more and more being replaced by a single conversion concept;
3) heterodyn receiver with an IF of 110 MHz and a limiter amplifier and demodulator at this frequency: this concept gets more and more market share, because of its high sensitivity and simple and low-cost application [9], [14].

If the zero-IF or very low concept is used, additional analog baseband gain control, filtering, and processing is required or two additional baseband A/D converters are needed. This increases die size. The advantage is that it allows one to replace the IF filter. Reduced filter costs contribute in higher die cost for the baseband analog processing. Today's solutions have reasonable lower minimum input sensitivity.

The DECT GFSK modulation allows one to use a simple FM demodulator and a low-cost first IF filter. Also, the FM demodulation is not sensitive to local oscillator frequency offsets and still has potential for further integration.

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

The single-conversion concept has brought down the component count in the application to a reasonable level and has the same sensitivity of −95 dBm.

VI. DECT-Transmit Signal Path

The transmitter part of the DECT system concepts is dominated also by two concepts (Fig. 8):

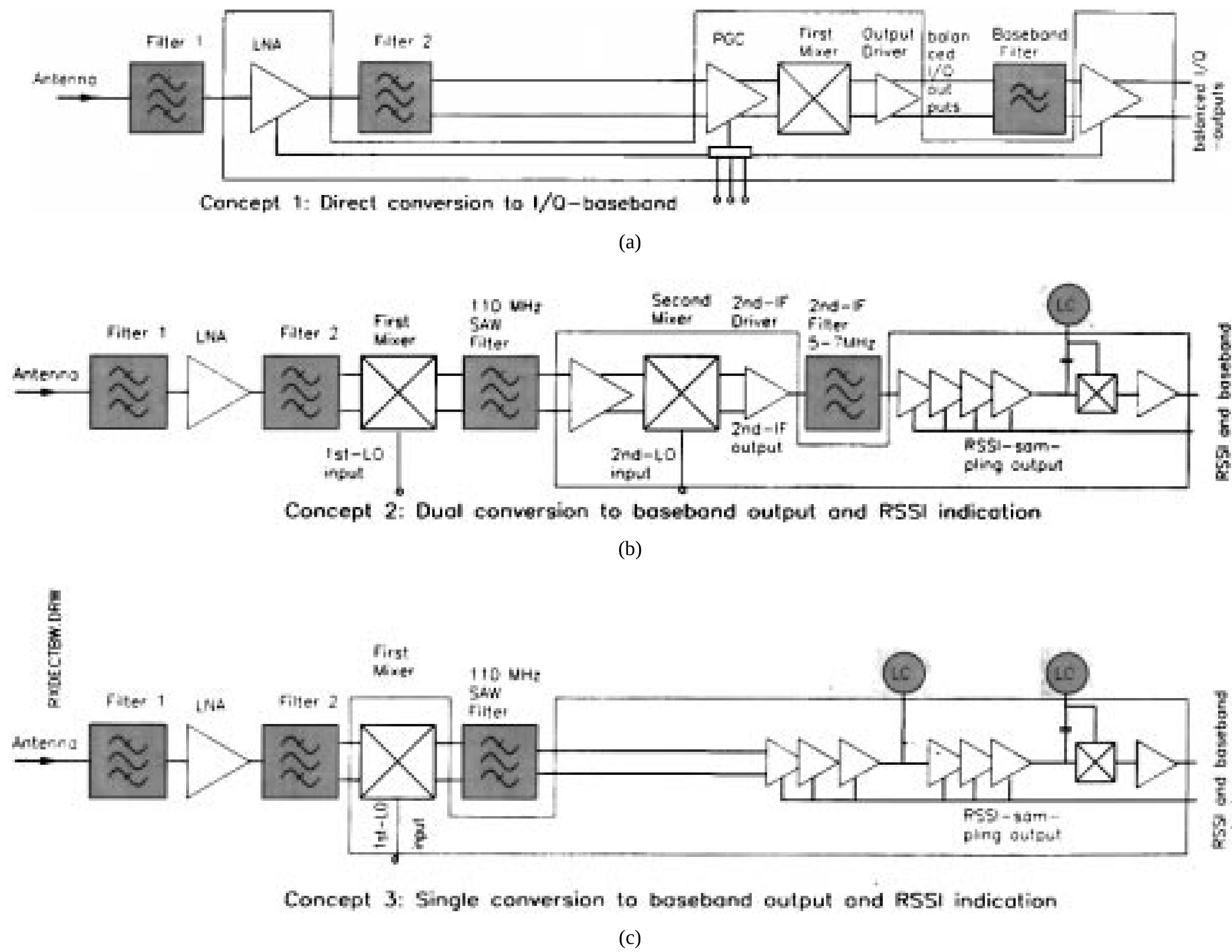

Fig. 7. Receiver architectures used at the moment within the digital DECT market.

1) low IF frequency-modulation (100–300 MHz) followed by upconversion mixing and passive image filters; this was published only in the very beginning, but is not in volume production now;
2) open-loop modulation with a local oscillator running on half the transmit frequency; this concept has highest market share [9], [18].

The low IF modulation and upconversion mixing according to concept 1 has the advantage that there are no frequency drift problems during TX time slot. If the loop filter frequency of the IF PLL is aligned to less than 1 kHz, then 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, to have a low enough spurious emission.

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

For the future, Dual-mode (GSM & DECT or PCN & DECT) applications may become available on the market. It depends on the cellular system providers and their monthly charges where the market finally will progress.

The ongoing RF integration reduced the component count from about 400 parts to 150 in the meantime, with further potential to less than 100 components. Since 1996, handhelds also with 3-V supply voltage for the complete RF function without the PA are available.

The future trend is to further reduce the supply voltage down to 2.7 V or less and decrease the current consumption and the peripheral component count. Bipolar PA's may replace discrete transistor PA's and GaAs PA's.

VII. Conclusion

The GSM and the DECT system have both created a strong new market within Europe and other areas of the world, and along the way RF integration has become a very important factor in reducing component count and production cost. The new RF–IC solutions use advanced bipolar technology with a transit frequency of 25–30 GHz. This enables the handset manufacturer to reduce voltage and power contributing in lower size and weight and to develop one standard PC-board platform for GSM, PCN, and PCS.

Extensive simulations and measurements are required and need an experienced device designer who also considers the

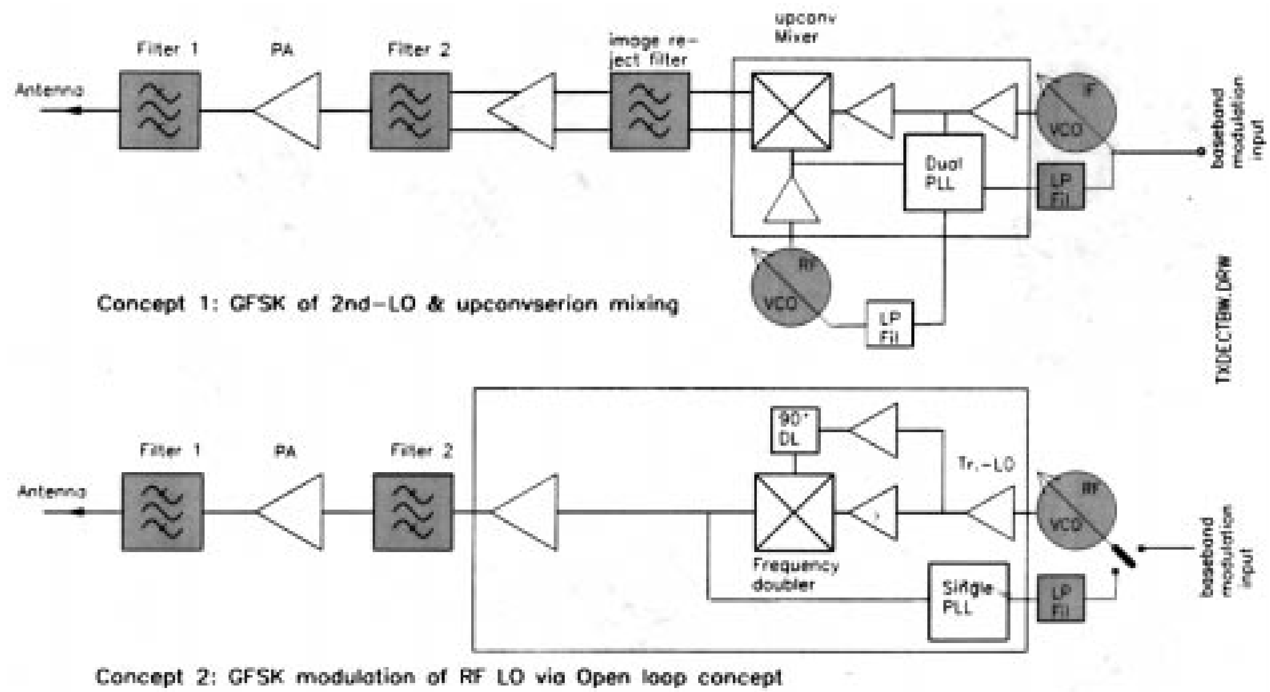

Fig. 8. Transmitter topologies used at the moment within the digital DECT market.

impacts of package and board. A high level of customer support is required to introduce such RF devices. Customers need to know the device-specific limitations of the test results and want recommendations for a specific board layout.

Today there are still some external components required in addition to the silicon transceiver solutions. Therefore, the challenge is:

- to reduce further the external component count and reduce overall cost;
- to use on-chip VCO's;
- to implement on-chip matching of front-end and on-chip filtering;
- to make on-chip alignement, and tuning, etc., by three wire control bus;
- to develop on-chip PLL's and on-chip baseband analog filtering.

Also, more and more low-frequency and IF functions could be solved by CMOS- or BiCMOS technology.

Further challenges are:

- optimal frequency planning, to prevent in-/or nearband spurs, which requires deep discussion with system partners and other component suppliers and simulation of the whole system;
- to more strongly influencing passive component suppliers, for example, SAW filter suppliers, to develop IC friendly in-/output ports, e.g., balanced (differential or symmetrical) ports, to improve interfacing to balanced IC circuit ports.

It is fascinating to see how system specifications and progresses in SAW filter technology had an influence on the RF concepts and the forward integration. This led to the RF-product families available on the market. The common development in the last years are the power of RF-analog design and implementation technique, as well as further evolution in silicon processing technology.

The development path to system-on-chip is still ongoing; the race is far from over.

References

[1] J. Fenk, W. Birth, R. G. Irvine, P. Sehrig, K. R. Schön, "An RF front-end for digital mobile radio," in *IEEE 1990 Bipolar Circuits and Technology Meet. 11.2*, pp. 244–247.

[2] I. A. Koullias, S. L. Forgues, and P. C. Davies, "A 100 MHz IF amplifier/quadrature demodulator for GSM cellular radio mobile terminals," in *IEEE 1990 Bipolar Circuits and Technology Meet. 11.3*, pp. 248–251.

[3] J. Fenk, W. Veit, S. Ganser, K. Hadjizada, S. Heinen, H. Herrmann, and P. Sehrig, "A 2.7 V 800 MHz-2.1 GHz transceiver chipset for mobile radio applications in 25 GHz fT Si-bipolar," in *IEEE Bipolar Circuits and Technology Meet.*," Minneapolis, MN, 1994, pp. 175–178.

[4] L. Longo, R. Halim, B.-R. Horng, K. Hsu, and D. Shamlou, "A cellular analog front end with a 98 dB IF receiver," in *Int. Solid State Circuits Conf.*, San Francisco, CA, 1994, pp. 36–37.

[5] B. Madson and D. E. Fague, "Radios for the future: Designing for DECT," *RF Design*, vol. 16, no. 4, pp. 48–53, Apr. 1993.

[6] T. Stetzler, I. Post, J. Havens, and M. Koyama, "A 2.7–4.5 V single-chip GSM transceiver RF integrated circuit," in *Int. Solid State Circuits Conf.*, San Francisco, CA, 1995, pp. 148–149.

[7] C. Marshall, F. Behbahani, W. Birth, A. Fotowat, T. Fuchs, R. Gaethke, E. Heimerl, S. Lee, P. Moore, S. Navid, and E. Saur, "A 2.7 V GSM transceiver IC's with on-chip filtering," in *Int. Solid State Circuits Conf.*, San Francisco, CA, 1995, pp. 148–149.

[8] S. Heinen *et al.*, "A 2.7 V 2.5 GHz bipolar chipset for digital wireless communication," in *Int. Solid State Circuits Conf.*, San Francisco, CA, Feb. 1997, pp. 306–307.

[9] A. Bateman, D. H. Haines, and R. J. Wilkinson, "Linear transceiver architecture," in *Vehicular Technology Conf.*, Philadelphia, PA, 1988, pp. 478–484.

[10] A. Bateman and D. H. Haines, "Direct conversion transceiver design for compact low-cost portable mobile radio terminals," in *Vehicular Technology Conf.*, San Francisco, CA, 1990, pp. 668–674.

[11] G. Schultes, A. L. Scholtz, E. Bonek, and P. Veith, "A new incoherent direct conversion receiver," *Vehicular Technology Conf.*, Orlando, FL, 1990, pp. 668–674.

[12] J. Sevenhans, A. Vanwelsenaers, J. Wenin, and J. Baro, "An integrated Si bipolar RF transceiver for a zero IF 900 MHz GSM digital radio

frontend of a hand portable phone," in *Custom IC Conf.*, San Diego, CA, 1991, pp. 7.7/1–4.
[13] V. Thomas, J. Fenk, and S. Beyer, "A one-chip 2 GHz single superhet receiver for 2 Mb/s FSK radio communication," in *Int. Solid State Circuits Conf.*, San Francisco, CA, 1994, pp. 42–43.
[14] J. Sevenhans, D. Haspeslagh, A. Delarbre, L. Kiss, Z. Chang, and J. F. Kukielka, "An analog radio front-end chip set for a 1.9 GHz mobile radio telephone application," in *Int. Solid State Circuits Conf.*, 1994, pp. 44–45.
[15] J. R. Longo, M. A. Copeland, P. Schvan, and R. H. Hadaway, "A low voltage silicon bipolar RF front-end for PCN receiver applications," in *Int. Solid State Circuits Conf.*, San Francisco, CA, 1995, pp. 140–141.
[16] J. Fenk and P. Sehrig, "Low-noise, low voltage, low power IF gain controlled amplifiers for digital wireless communication," in *Advances in Analog Circuit Design*, Villach, Austria, Apr. 1995.
[17] S. Heinen, S. Beyer, and J. Fenk, "3.0 V 2 GHz transmitter for digital radio communication with integrated VCO's," in *Int. Solid State Circuits Conf.*, San Francisco, CA, Feb. 1995, pp. 146–147.
[18] A. Hairapetian, "An 81 MHz IF receiver in CMOS," in *Int. Solid State Circuits Conf.*, San Francisco, CA, 1996, pp. 56–57.

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