History and Evolution of Millimetre-wave MMICs for Point-to-Point Radio

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Abstract — **Over the last two decades, the capability and implementation of mm-wave point-to-point radios has changed almost beyond recognition. A manually-tuned, waveguide-aficionado's delight has evolved into a highly manufacturable, field programmable terminal with lower cost, higher performance and much greater utility. These changes have depended largely on the availability and performance of GaAs Microwave Monolithic Integrated Circuits (MMICs). Waveguide mounted diodes of various types have been replaced by highly integrated receiver LNA-mixer, transmitter mixer-buffer and PA blocks manufactured in commercial foundries and packaged in SMT packages which can be machine assembled onto micro-strip radio boards. At these frequencies, "split" configurations are required to minimise RF losses, so the microwave components are exposed to a severe temperature range in an outdoor environment and power efficiency becomes very important.**

Keywords: Radio backhaul, point-to-point radio, mm-wave MMICs

I. INTRODUCTION

In the early 1990s, at frequencies above 10 GHz, transmission losses in coax and the cost and difficulty of using waveguide dictated that radios use a split configuration, with the RF components located outdoors directly behind the antenna to minimise RF losses. A single co-ax cable connects the ODU to the indoor unit (IDU) which provides the traffic interface to the user, and manages power supply and alarms.

All-outdoor radios have recently become more achievable with the advent of internet (IP) radios, with the reduction of the user interface to a single data stream which can carry IP based telemetry, with no need for separate service channels.

The general requirement of radios in the early 1990s was to carry a payload of multiple E1 (2048 kbps) or T1 (1544 kbps) continuous both-way traffic streams over a transmission range of 10 to 30 km. Each of these could carry 30 (E1) or 24 (T1) conventional PCM coded telephone conversations and associated signaling, multiplexed on a plesiochronous digital hierarchy (PDH) protocol as specified by the ITU. The advent of cellular telephony meant that the contents of E1 or T1 traffic streams changed to carry many more telephony channels each coded much more compactly; however, the multiple E1 PDH format remained as a preferred interface until recently. Interfaces of 34 and 45 Mbps are common in higher capacity radios and 155 Mbps SDH interfaces are now available.

Fig. 1 shows a typical split radio terminal. The RF parts of the terminal are located in an outdoor enclosure (ODU) coupled closely to the antenna, with a pair of waveguide filters and duplexer used to isolate the receiver from the local transmit signal, which may be as close to the receive frequency as <100 MHz at low frequencies, typically spaced more than 1 GHz away at higher frequencies.

Fig. 1: Typical split radio terminal with indoor and outdoor unit.

At this time, radios at 15, 18 and 23 GHz were generally based on Gunn diodes, with constant envelope modulation using 4-FSK, carrying payloads of 4 E1 or 8 E1 (8 or 16 Mbps) with a channel spacing of 7 or 14 MHz.

In some countries, 23 GHz radios could be free running in a 50 MHz allocated channel at 1 E1 to 8 E1 (2 to 16 Mbps). Later radios were locked to 7 or 14 MHz channels.

In synthesised radios, a varactor diode and a step recovery diode were mounted in the same waveguide resonator assembly as the Gunn diode oscillator – the varactor to tune the Gunn diode oscillator to a high (typically 80th) harmonic of a VHF synthesised oscillator, via a 70 MHz offset transfer frequency locked loop.

Receivers often used a 70 or 140 MHz first IF, and thus needed a narrowband (single channel) waveguide filter to provide protection against signals at the image frequency and to provide isolation for LO radiation from the antenna.

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Early receivers generally did not use an LNA, and used a diode mixer, thus receive noise figures of 10 dB were typical. Fig. 2 shows a typical 38 GHz receiver mixer in a “Cross Waveguide” configuration to isolate LO from RF.

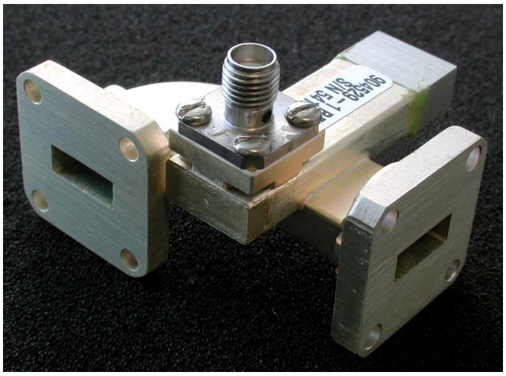

Fig. 2: A 38 GHz receiver mixer in a “Cross Waveguide” configuration.

FSK demodulators were a frequency discriminator, often delay line based at 70 MHz, followed by a slicer and simple threshold detector – requiring a 23 dB SNR for 1E-6 BER with 4-FSK – about 10 dB more than coherent 4-PSK would allow. System margin could be improved by 20 dB by introduction of coherent QAM and LNAs with image reject mixers – but non-constant envelope and LNAs required low cost MMICs.

The introduction of cellular telephone systems, especially GSM in 1991, and the de-regulation of the telecommunication market worldwide triggered a vast increase in demand for low-capacity point-to-point digital radios and the demand for, and value of, spectrum increased pressure on spectral efficiency. Cost and bandwidth efficiency became paramount. As cell sites were often within 4 km range of each other and of exchange locations, and spectrum at 38 GHz was available at a lower cost than at 15, 18 and 23 GHz, there was a growing demand for radios at 38 GHz. Most manufacturers already had a family of radios at lower frequency, so the architecture of the first “true” mm-wave radios at 38 GHz followed the architecture of their siblings at 15, 18 and 23 GHz.

II. THE DEMANDS OF MARKETING AND MANUFACTURING

Marketing demands and manufacturing realities put pressure on engineering to deliver the following features:

- Tunability in the field over each of many 2 GHz radio bands from 15 to 42 GHz
- Flexibility over band dependent transmit – receive spacing of less than 100 MHz to more than 1 GHz
- Common architecture and parts for 2 to 155 Mbps and on to 1 Gbps to ease manufacturing inventory
- Common architecture and parts for many bands from 15 to 42 GHz to ease manufacturing inventory
- Transmit power control, ATPC, and adaptive modulation, to accommodate frequency re-use and rain fades
- Transition from 15 to 38/42 to 60 GHz and on to 80 GHz
- Transition from 4-FSK to QPSK to 16 QAM to 256 QAM and on to 1024 QAM
- PDH/SDH to internet radio transition (FDD to TDD)
- Cost – cost – cost – and if a 38 GHz radio doesn’t transmit as far as a 15 GHz radio, it should cost less!
- Lower DC consumption, higher data rates, more system margin, greater power control, lower noise figure, etc.

III. THE ENGINEERING RESPONSE

The key to cost was the replacement of discrete “diode in waveguide” assemblies by microstrip mounted MMIC devices, initially “chip-and-wire” such as the 38 GHz receiver shown in Fig. 3, but eventually housed in overmoulded and cavity SMT compatible packages [1] – for example, see Fig. 4.

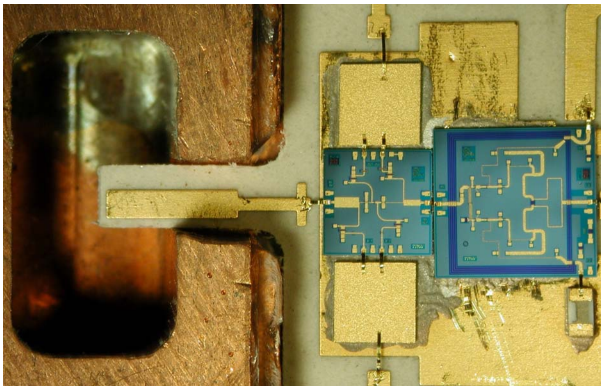

Fig. 3: Prototype chip-and-wire 38 GHz receiver, *circa* 1995, showing waveguide antenna, two-stage pHEMT LNA MMIC and adjacent sub-harmonic image-reject mixer MMIC with on on-chip IF quadrature hybrid.

The widespread introduction of GaAs MMICs required the defence-based cost model of 1990’s foundries to give way to a commercial, high-volume model, and required a major effort from engineering to reduce the area of GaAs needed to achieve the required functionality, to improve manufacturing yield and decrease testing cost. A joint effort between the foundry, design engineering, device modelling, test engineering and packaging processing was needed to do this, and it is ongoing.

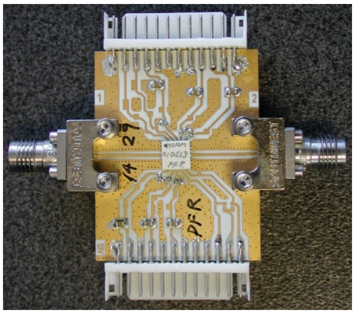

Fig. 4: Packaged 42 GHz driver amplifier on connectorised test board.

Fundamental Gunn oscillators for receiver and transmitter LOs gave way to transistor VCOs at 1 to 3 GHz driving MMIC based multipliers and amplifiers. These had much worse phase and amplitude noise than Gunn oscillators. They also had much lower cost and wider tuning range. Higher frequency monolithic VCOs followed, with freedom from “creaking” a benefit resulting from integrated resonators.

The need for high level QAM dictated a move to heterodyne approaches with intermediate frequencies (IFs) increased from 70-140 MHz to 1-4 GHz to ease selectivity of waveguide filters and spurious performance of mixers. This allowed designs with a single mm-wave oscillator while these were still expensive, and provides more flexibility now that reduced high frequency VCO costs allow independent transmit and receive paths. Direct QAM modulation at RF is the next challenge and will further reduce power consumption and cost.

Better LNAs provide lower noise figure, higher linearity receive mixers allow higher LNA gain thus improving overall noise figure, and balanced mixers accommodate poorer LO AM noise performance.

Higher linearity transmit mixers allow higher level operation to improve transmit noise figure and allow higher order QAM, better balance reduces the need for "roofing filters" to suppress LO breakthrough [2]. Higher linearity power amplifiers allow higher order QAM thus higher capacity for a given bandwidth [3].

The need for advanced simulation tools (e.g. harmonic balance analysis and EM algorithms) and device models and for the successful design of these receiver, transmitter and power amplifier MMICs cannot be over emphasised.

Not all of the innovation has come through the RF side, as digital signal processing has made similar major advances over the past two decades. Better error correction and more efficient modem technologies have allowed implementation losses to be lowered to a fraction of a decibel over theory, and the use of DSP to adaptively pre-distort signals to obtain higher effective transmit power levels is changing the design criteria for PAs, as "well behaved" saturated power becomes more critical than third order intermodulation at backed off power levels, and higher order odd intermodulation becomes more important. Measures such as envelope tracking to improve the effective PAE of power amplifiers also contribute to overall DC power reduction in radios [4] and may benefit from changed design criteria in PA design.

IV. CHALLENGES TO MMIC DESIGNERS

High linear power over a wide bandwidth presents a major challenge for physically smaller LNAs, power amplifiers and mixers. Better linear and non-linear models are needed, with ability to scale parameters so that the geometry of active devices is part of the optimisation process and coupling between more compact structures is taken into account [5]. Cycle times demand first-time success at higher frequencies, putting pressure on modelling and simulation tools. Other specific challenges include the following:

- Wide tuning range and low phase noise for high level QAM presents a major challenge for VCOs
- Higher IFs dramatically increase the LO range required of mixers, particularly if high- and low-side injection frequency plans are needed to satisfy different radio frequency plans, and when it is desired to cover two or three microwave bands with a single chip-set
- Variable transmit power requirement at low cost increases the pressure on PA and driver amplifier performance, particularly if gain control through varied bias is used to reduce DC power consumption and remove the need for separate passive attenuator stages with their undesired insertion loss (and hence noise)
- Freedom from susceptibility from interference in a more crowded spectrum and physical space, with smaller antennas further increases receiver linearity requirements for both even and odd intermodulation products
- Thermal performance at high power levels in a low cost SMT packaged environment affects die thickness and transistor layout and interacts with package design
- SMT packaged parts places an additional emphasis on the need for high level ESD protection for GaAs devices which themselves are highly susceptible to ESD damage
- The advent of flip-chip at higher frequencies requires better EM and thermal analysis and new package design.

V. FUTURE TRENDS IN RADIO SYSTEM DESIGN

Current frequency plans and channelisation are designed for a PDH/SDH environment which assumes full duplex transmission at a constant rate in both directions over a fixed radio path. Frequency re-use and antenna performance are reliant on this assumption. As a consequence, the bandwidth of a radio cannot usefully be changed "on the fly", although many modern radios do have the capability to change the QAM index and hence the data rate within a fixed spectral mask. This allows the threshold of the radio to be changed to accommodate slow fading or traffic capacity reallocation if the terminal equipment can accept a lower data rate during propagation fades.

One way of increasing the utility of the mm-wave spectrum is to move to a full TDD frequency plan, where a single radio channel is used to alternately send bursts of data in both directions. This fits well with the internet protocol, and represents a major departure in radio design which offers significant savings in radio cost and weight, and challenges to MMIC design. A full IP radio will have short "T to R" transition switching times and will substitute a high-linearity low-loss switch for the current waveguide based FDM duplexer. While a waveguide filter will still be required between the MMIC T/R and the antenna, it will have greatly relaxed specifications compared to the current filters which are required to suppress the local transmit signal by 60 dB or so, and will consequently be smaller, lighter and cheaper. It will also potentially have much wider bandwidth, restricted in FDD radios to less than 50% of the transmit-to-receive frequency spacing. This may allow full band tuning.

The logical extension to this capability would be to allow instantaneous bandwidth variation combined with frequency agility to allow dynamic allocation of bandwidth resource amongst a group of radios sharing the same allocated microwave band – much as lower frequency radios do today. In the short term, this will be possible only in bands where there is no existing population of conventional FDD fixed channel and bandwidth radios, and would presumably require national administrations to change their interference management procedures. The 58 GHz bands offer this possibility [6]. However, the major challenge for MMIC design is to accommodate the move from FDD to TDD operation,

TABLE I

SOME MILESTONES IN POINT-TO-POINT RADIO

Year	**1980**	**1985**	**1990**	**2000**	**2010**	**2015(?)**
Modulation	2FSK/ASK	QPSK	4FSK/MSK	16 QAM	256/512 QAM	Direct Mod
Bits/Hertz	0.5	1	1	2	4+	4+
Transmitter	Gunn	Linear PA	Gunn or saturated PA	Better linearity	Integrated upconverter	LO suppression
Receiver	No LNA		MMIC LNA	Integrated Rx	Better linearity	
Bands	15,18, 23 GHz		38 GHz		42 GHz	E-band
Comments		Costly first coherent radios improve threshold by 3 dB	LNA improves Rx threshold by 7 dB			Removes IF stage. 250 MHz channels with Gbit capacity at E Band.

involving the design of high linearity low loss T/R switches and fast switching bias control for PAs to manage noise injection into the receiver from a biased transmitter chain, if T/R switch isolation is insufficient.

Another innovation which will become more attractive with "all outdoor" radios is the use of direct modulation in the transmitter. Split radios generally send the transmit signal up the cable from IDU to ODU at several hundred MHz, with the receive signal at a lower frequency. It makes sense to generate the QAM transmit signal in the IDU and up-convert in the ODU. As the last IF in the transmit chain needs to be several GHz to allow realisable microwave filters to be used to achieve the required rejection of spurious signals such as leaked LO and image signals, an additional up-conversion process is required in the ODU, in addition to frequency equalisation and adaptive level control to compensate for the "root F" transmission characteristic of a varied length of coax cable. In an "all outdoor" radio, the digital signal is available at the ODU, hence single conversion is practicable, with the I/Q modulator operating at an IF of 1 to 4 GHz. Alternatively the I/Q signals can be directly modulated onto the mm-wave carrier. The constraints to this are the spectral mask rules which limit the level of LO radiated. Mixers at these frequencies have difficulty in achieving the balance required to meet the specified rejection, and to maintain this over temperature and frequency. External compensating circuitry is currently used to feed DC adjustment signals in parallel with the I and Q baseband modulating signals [2]. Improved balance in mixers is desirable to allow further simplification in radios. This requires more comprehensive EM analysis and better production control in MMIC manufacturing facilities.

Table 1 summarises some of the milestones in point-to-point radio development over the past 30 years.

CONCLUSION

Great progress has been made over the last two decades in introducing MMIC based components to replace discrete diode in waveguide structures, with major improvements in radio functionality, reliability and cost. Ongoing cost pressures require further cost reduction in MMICs themselves, and improvements in performance to reduce the number and complexity of supporting circuits. Examples include higher levels of integration, combining image reject mixers and their LO buffers and multipliers with LNAs and RF buffers, and multi-stage buffer amplifiers able to be used as VGAs without the need for external attenuators. Improvements in linearity and mixer balance are also needed to further simplify radio support circuitry. There is an ongoing need for better modelling and simulation tools to facilitate these developments, in addition to more comprehensive analysis of the processes available to the designer, requiring a tradeoff of cost and yield against linearity, breakdown characteristics, and reproducibility and stability of device parameters.

In summary, the high frequency point-to-point radios of the 80's and early 90's were at a fixed frequency and used non-coherent modulation of a single type and bandwidth that was relatively inefficient in bandwidth and threshold. Today's radios are tunable over a band and utilise extremely efficient (up to 512 QAM) adaptive coherent modulation that can scale back during fading. The key enabling technology for this change in the RF units is the advent of the highly integrated, surface-mount, packaged MMICs at all of the point-to-point frequency bands.

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