Challenges of Optimizing Multiple Modulation Schemes in Transponder Design

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ABSTRACT

Increasing gate counts in FPGA's create an option of offering multiple waveform demodulation and modulation within a single transponder transceiver. Differing data rates, channel schemes, and network protocols can be addressed with the flexibility of software-based demodulation and modulation. Increased satellite longevity and reliability are benefits of software-based transceiver design. Newer packaging technology offers additional capability in reducing form factor and weight of a transponder. A review of the challenges in combining each of the above to produce the next generation of transponders is the subject of this paper.

KEYWORDS

Transponder, multi-mode, modulation, IC technology, IC packaging, FPGA, transceiver design.

INTRODUCTION

The processing of signals in space-based communication involves many clever schemes of data encoding, modulation, filtering, and amplification in order to transmit and receive information. Three key elements can be used to shape the discussion; namely, the radio band, modulation mode, and transmission format. In the case of telemetry, the interest lies in transmitting information from a vehicle about its status and determining its range. The same is true for control signals received at the vehicle. In the transponder communication scenario, marshalling effectively the improvements of advances in disparate but related disciplines; for example, semiconductors device physics, circuit design, packaging, and communication theory is the driving force for engineers, researchers, and marketers in improving transponder capability.

The challenges of optimizing multimode transponder design can be grouped into the following areas: RF transceiver design, baseband design, packaging, IC technology, form factor and weight reduction, antennae, and network. In this paper we shall deal with all but the last item of network concerns in the design of a transponder and assume that the network issues can be solved to make a working system between ground and space.

THE GENERALIZED TRANSPONDER

Different solutions have been developed since the beginning of space-based communication, starting with *Sputnik Zernli* in 1957. The most common telemetry, tracking, and control transponder systems today in the United States are SGLS, USB, and TDRSS. Each system has different capabilities for the space-based communication and has different ground link systems and customers. A progression is proposed here for discussion on the challenges of providing more capability in an ever smaller form factor, with an ever greater number of users of space-based communications. The first level is the most common solution available today which is a transponder with one format such as SGLS or USB. The second level is a transponder with two modes in at least one pathway such as SGLS and USB. The third level is a transponder with three modes such as SGLS, USB and TDRSS. The fourth level is a transponder using a more spectrally efficient modulation format, e.g. 8-PSK, with higher data rates with ground stations, equipped to command the vehicle and receive telemetry data in the newer format. Each of these levels can be further characterized by three categories of radio operation mentioned above; namely, the bandwidth of transmission, the modulation mode, and the format of information. The format of information is further categorized by whether the message is data, video, or voice. Most transponder performance today is data but the future may require compressed voice and video telemetry. Some of the characteristics are shown in Table 1 for comparison amongst the three waveforms: SGLS, USB, and TDRSS.

Table 1: Waveform Comparison [1, 2]

Characteristic	SGLS	USB	TDRSS
Frequency, GHz	1.76-1.84/2.2-2.3	2.025-2.11/2.2-2.29	2.1064/2.2875 2.0258-2.1179/2.2-2.3 13.4-15.4 22.55-23.55,25.25-27.5
Polarization	RHC	RHC	LHC, LHC or RHC
Access	FDM	FDM	SSA/KSA single, MA
Modulation	FSK/BPSK,PM,AM	PCM/PSK,PM	QPSK, SQPSK
Spread Spectrum	N/A	N/A	Data, command
Data Rate	1,2 kbps/7.8-128kps	1,2,4 kbps	0.1 kbps to 25 Mbps
Data Format	NRZ or BiΦ w/-L,M,S	NRZ	NRZ-L,M,S
FEC Coding	User defined	User defined	User defined
Data Interleaving	User defined	User defined	User defined
Data Encryption	User defined	User defined	User defined
Ranging Function	PN sequence	PN sequence/ tone	PN sequence w/BPSK
Data, Video, Voice	Yes, No, No	Yes, No, No	Yes, Yes, Yes

TRANSPONDER SIGNALS

One of the main problems in transponder signal processing for multimode operation is the dissimilarity in modulation formats; e.g. TDRSS and SGLS [1]. The goal is to determine an efficient and minimal transceiver structure which accommodates three of the pertinent waveforms used in transponder operation. For this purpose, a brief comparison of the following waveforms is made.

Starting with the SGLS uplink, the waveform can be described mathematically in (1) as a phase modulation with amplitude modulation of the subcarrier for command data. The ranging modulation has a pseudo-random number sequence which phase modulates the carrier causing a spread spectrum. The SGLS downlink is somewhat different, in that it is BPSK, which is phase modulated with two subcarriers for lower data rate on one channel, or no subcarriers on the other channel but with higher data rate. Ranging exists on the first channel with lower data rate. The USB waveform has two forms, which are similar to the SGLS with the following exceptions:

$$S(t) = \sqrt{2P}\cos\left(2\pi f_c t + \beta_1 x_1(t) + \beta_2 x_2(t)\right) \tag{1}$$

$$where\ P = total\ power,\ f_{sc} = carrier\ frequency$$

$$x_1(t) = A(t)\sum_{k=-\infty}^{\infty} \sin\left(2\pi f_{sc}^{k} t\right) \bullet P_c\left(t - kT_c\right), \beta_1 = \text{command modulation index}$$

$$x_2(t) = \sum_{k=-\infty}^{\infty} d_r^{(k)} \bullet P_r\left(t - kT_r\right), \beta_2 = \text{ranging modulation index}$$

$$x_1(t) = \sum_{k=-\infty}^{\infty} d_c^{(k)} B_c\left(t - k / R_c\right) \tag{2}$$

$$x_1(t) = \sum_{k=-\infty}^{\infty} d_c^{(k)} P_c\left(t - k / R_c\right) \bullet \sin\left(2\pi f_{sc} t\right) \tag{3}$$

where $x_1(t)$ is the command component and (2) is for bi-phase and (3) is for lower data rate command [3]. The ranging command for USB also takes two forms as follows:

$$x_2(t) = \sin\left(2\pi f_r t\right) \tag{4}$$

$$x_2(t) = \sum_{k=-\infty}^{\infty} d_r^{(k)} P_r\left(t - k \cdot T_r\right) \tag{5}$$

A sinusoidal function in (4) or pulse function in (5) provides ranging for USB. For the TDRSS waveform, a QPSK waveform, which is spread by a PN sequence, is transceived with three separate services. The first and last is limited to a single user (SSA) and single user at Ka band (KSA), while the middle service, multiple access (MA), can accommodate up to twenty users via a unique PN code for each user.

Comparing all three signals leads to these observations about similarities which are shared and not shared, shown in Table 1. SGLS and USB are similar waveform types in that they both have power spectral densities (PSD) which have phase modulated sinusoidal waveforms. In the case of USB, subcarrier modulation is used to transmit data, while SGLS does not. One of the significant differences between SGLS/USB together and TDRSS is the use of Spread Spectrum for transceiving data in the MA service. Given these differences, can an overall receiver architecture be devised that would function for both waveforms? What are the implications and issues for such architecture?

RF TRANSCEIVER DESIGN

Receiver

The design of the front-end transponder receiver and transmitter takes as many different instances as the number of frequency bands and modes that the transponder must transceive. So, for the receiver in Fig. 1, this means that a design would need to have as many front-end RF receivers, at least from the antenna to the Intermediate Frequency (IF) section, as frequency bands of interest or modes exist to demodulate. This situation increases the number of components and the size and weight of the receiver portion of the transponder for multimode operation.

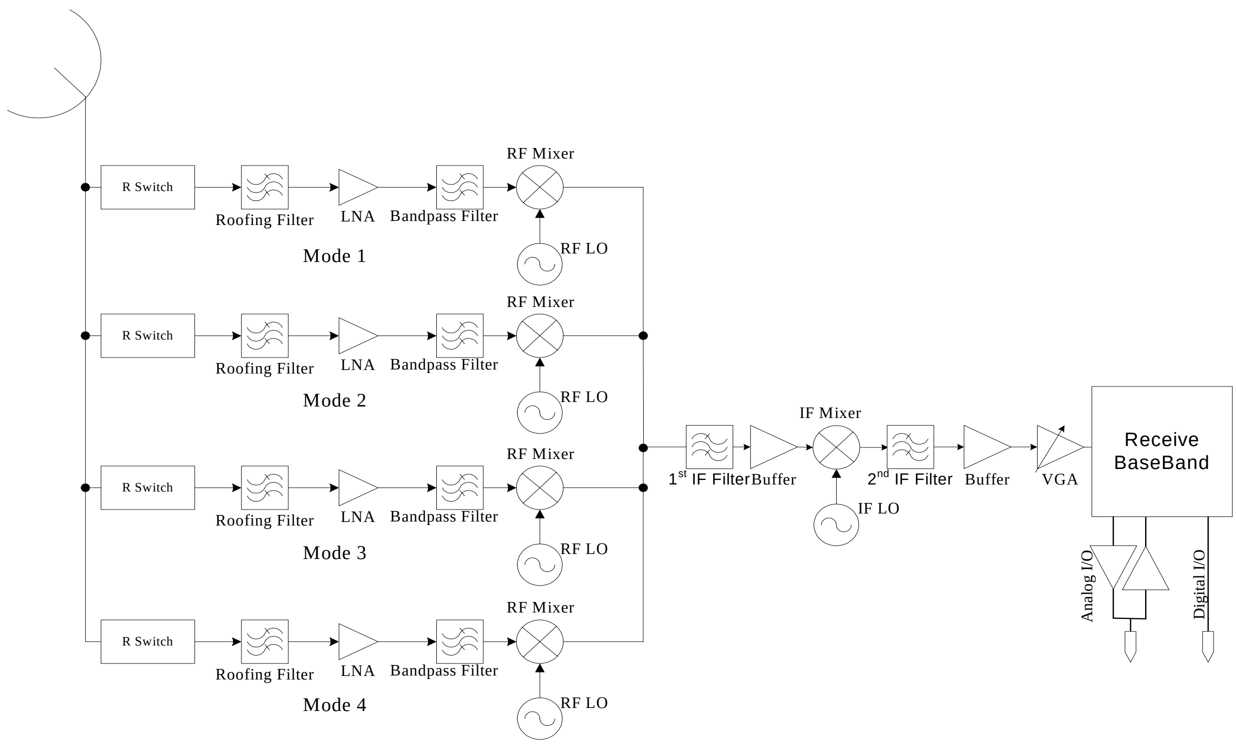


Fig. 1: Multiple RF Front-end Receiver

Reducing the number of RF receivers over a frequency spread of 2 GHz to 28 GHz used by SGLS, USB, and TDRSS is a challenge. What are some possibilities to accomplish a reduction without concern about cost? The roofing filter could be chosen easily enough to reject signals above 28 GHz. The problem then moves to making a frequency-selective LNA, by dynamically changing the resonant amplifying frequency and matching of the LNA. For the resonant frequency change, different cascode transistor widths could be switched in to resonate with a fixed inductor to effect amplification at different frequencies. Matching at the input should not change significantly thus the degenerative inductance could stay constant. This LNA design proposal would need to be based on an IC RF front-end as opposed to COTS and have an f_t of at least 40 GHz in order to have sufficient power gain at the required lower operating frequencies [4]. The higher operating frequencies, Ku and Ka, need a different technology, such as pHEMT. Thus, a current strategy of four separate receivers could be reduced to two. Different bandpass filters would need to be used to effect necessary attenuation outside of the passband for good image rejection on the first down conversion. Thus, a means of switching in different filters would be needed for the different frequency bandwidths over the wide range of reception posed above when combined into one versatile receiver front-end. The switching could be accomplished by using Micro-Electro-Mechanically (MEM) switched filters for the required performance at each frequency bandwidth of interest [5]. With the downconversion achieved, a common IF stage could be used to provide channel selectivity [6].

Transmitter

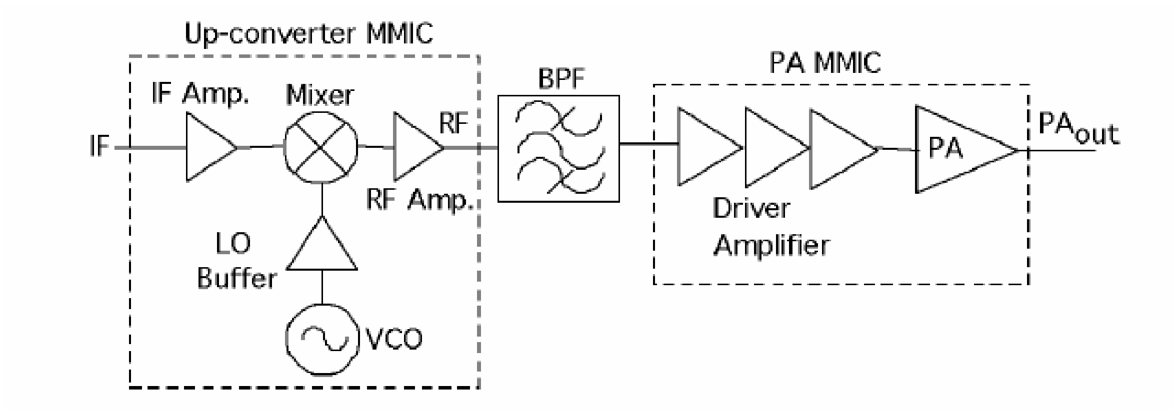


Fig. 2: Up Conversion at Ku and Ka Bands[7]

The transmitter, unlike the receiver, could be implemented in one path using GaAs technology over the frequency spread of 2 to 28 GHz. Again using a different BPF, switched in place by MEM, could allow for a unified path. Since multiple channels are required at the lower frequency range, a synthesizer would be required under the baseband control. At the higher frequencies, a VCO could provide the LO drive for the upconversion [8]. The last feature is the combining of transmit and receive functions in the same baseband.

GENERALIZED RADIO TRANSCEIVER

A simplified radio receiver was shown in Fig. 1., where detection of the RF signals is made over a frequency range of 1.76 to 28 GHz. The range and complexity of the analog receiver is wide band. Clearly, one challenge in the RF design of a generalized transponder is to receive and transmit at the 2 GHz, 14 GHz, and the 28 GHz bands, with the same analog components for a combined transceiver radio. Filtering represents another problem for a wide band receiver, at two widely disjoint frequency ranges in a Super Heterodyne Receiver (SHR) design, would be extremely challenging, based on filter bandwidth, quality, and shape factors. An obvious but unpopular solution here, to make progress, is to restrict the combined receiver to a combination of waveforms without the KSA service in TDRSS. The sacrifice would eliminate the highest data rates at 300 Mbps. This is an unlikely solution for the TDRSS user. Antennae polarization in TDRSS MA service is also a challenge for a combined service with SGLS/USB. One solution would be multiple antennae with a diplexer or triplexer to switch between the required polarizations.

Receiver Architectures

Three possible architectures for a generalized receiver will be discussed. The first choice is to maintain multiple PROM's with the software necessary for each demodulation desired, commanding the receiver into each mode by loading an FPGA, as shown in Fig. 3. The disadvantage of this receiver architecture is the number and size of PROM's needed to hold and load each waveform demodulation software code and an additional receiver to manage the waveform mode selection.

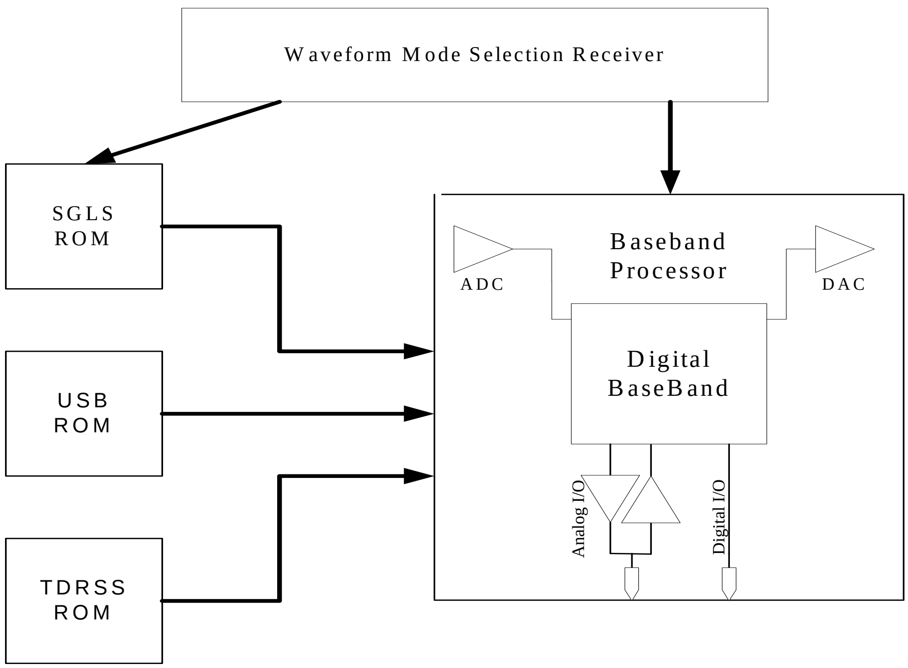


Fig. 3: PROM-Based FPGA Receiver Design

Conversely, all three digital demodulations could be loaded into one *large* FPGA, to be simultaneously resident, as in Fig. 4. A mode determination is then made as to which single demodulation scheme is in use at a time. The advantage of this scheme is that all demodulation modes are available without reloading. The major disadvantage is that some redundancy exists between the three different demodulation modes, all simultaneously present. The other disadvantage is the size of the FPGA necessary to hold all three demodulation modes simultaneously may well exceed current capacity for logic in the largest FPGA available today. This would certainly be the case if radiation tolerance design redundancy is required, where a 3 to 4 times increase in logic is necessary to produce the radiation tolerance. Additionally, up to a 10% penalty in speed is taken for the redundant logic necessary to increase the radiation tolerance of the circuit design.
The last receiver scheme is to combine different waveform demodulation functions into a common architecture, as shown in Fig. 5. To evaluate what is needed to achieve this goal, the elements necessary for the generalized digital demodulation are next discussed.

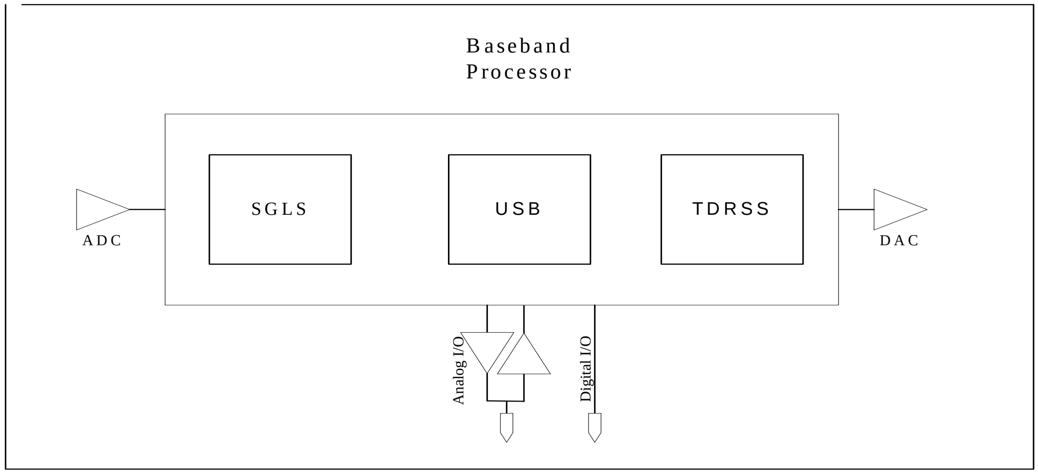


Fig. 4: Parallel Resident Waveform Baseband Architecture

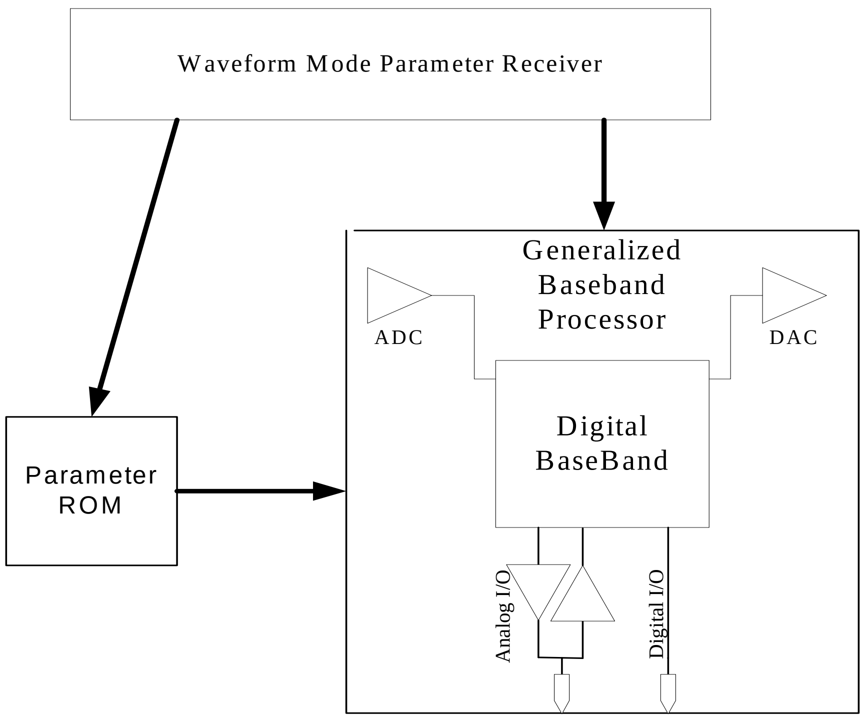


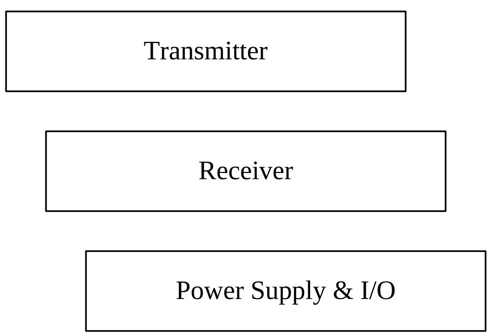
Fig. 5: Parameter Based Baseband

The generalized receiver, as shown in Fig. 5, could be created by linearizing the FSK modulation of SGLS with the QPSK type modulation of USB and TDRSS [9]. The mathematics for this method is left to the research literature. However a summary is discussed relative to transponder design. If the digital receiver demodulation is broken down into five main elements; then, a parameter based receiver could be designed based on generalized receiver architecture. Instead of a modulation code load from PROM into a FPGA, a parameter load of much less size to a resident generalized receiver could be designed. The demodulation mode would be determined by the parameter load or update of the parameters loaded or commanded to the FPGA, in a transponder design. The parameters relative to a generalized digital receiver could include the code length, NRZ type, modulation mode, spectrum spread, and filter type, for example. NRZ mode in a transponder is NRZ with –L, M, or S or Bi-ϕ with –L, M, or S, parameterized for Table 2 as 0 to 7. Modulation format is parameterized by waveform. Spreading factor is parameterized by the presence of a unique pseudo-random sequence or not. Filter parameterization at baseband is parameterized sequentially for Butterworth, Bessel, or Square-Root Raised Cosine.

Table 2: Generalized Receiver Parameters [10]

	SGLS	USB	TDRSS
Word Length		16-64 Barker	1023x256
NRZ	1,2,3, or 4,5,6,7	0	2,3,4
Modulation Format	1	2	3
Spread	0	0	1
Filter	1	2	3

PACKAGING



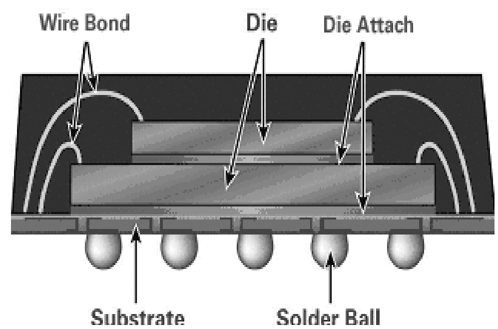


Fig. 6: Board Based Design

Fig. 7: Multichip Stack

Progress in packaging technology offers many new opportunities to reduce weight and size of previous assemblies. In Fig. 6 is shown the common stacked board design of transponders. In Fig. 7 is shown a progression to condensing the form factor by placing the major circuit components on top of each other in a much closer proximity via a multi-chip stack. Alternatively, multiple packages could be placed in a stacked manner with separate power bussing. For larger chips, the newest package, constructed at the wafer level on the order of die-sized components, offers the possibility of a vertically-stacked System-on-a-Chip (SOC) design at the DSP or FPGA level in the near future. All of the progress in packaging technology offers a means of significantly reducing form factor and weight in transponder design. Stacked dies are more expensive than stacked packages [11].

TRENDS

Improvement in packaging capabilities, shown in Fig. 8, offer increased density of design in increasingly smaller form factor. The trend of greater performance in smaller volume means a lower weight transponder design with mixed mode operation is a near term realizable goal.

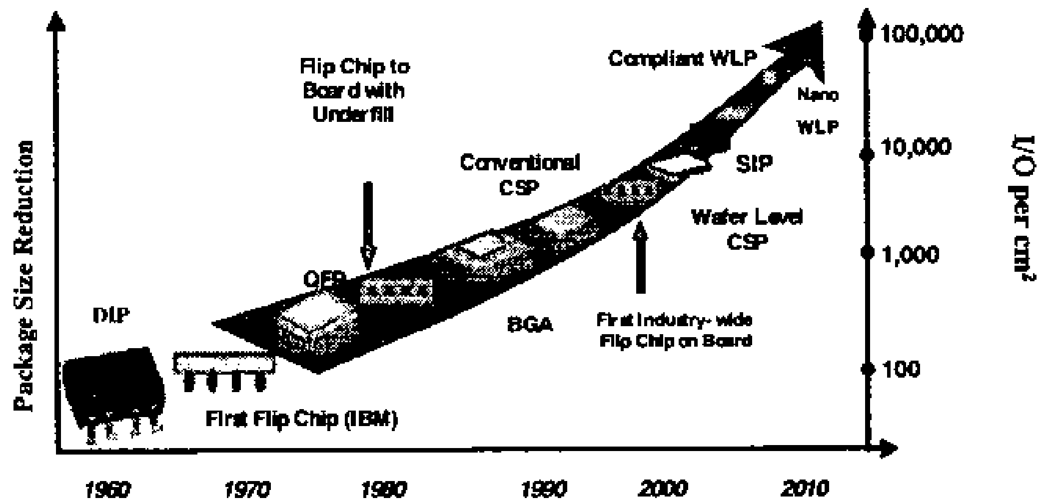


Fig. 8: Trend of Increasing System Density in Packaging [12]

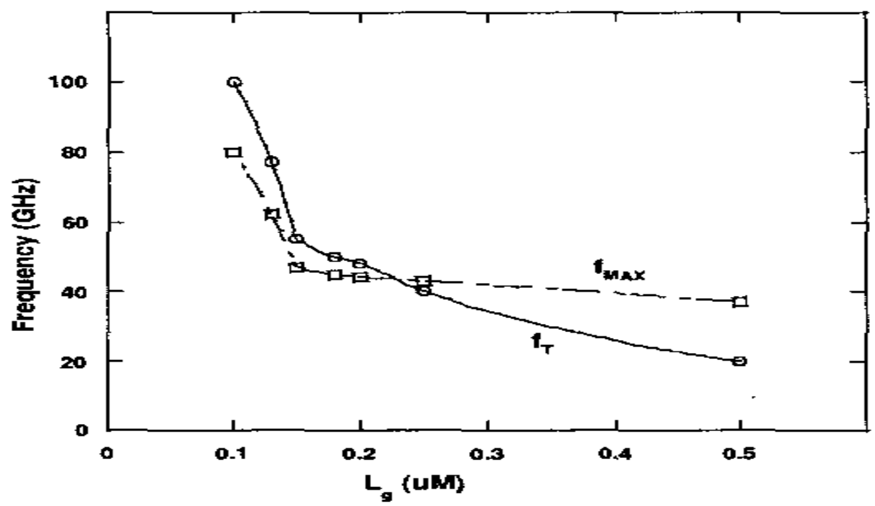


Fig. 9: Trend of Increasing Device Performance by feature size reduction [13]

Simultaneously, the trend of increasing device performance, shown in Fig. 9, scaled as minimum feature size continues to shrink, predicts higher levels of circuit and system integration at the wafer level. The limiting factors are the development of system and circuit design techniques suitable for integration of all design disciplines on a single substrate [14].

CONCLUSIONS

A review of the challenges of multimode transponder design has been discussed with the goal of progressively increasing the performance of telemetry while reducing weight and form factor. The increased transponder performance gained could be accomplished by incorporating the latest advances in circuit design techniques in semiconductor processes capable of simultaneous integration of RF/Analog, mixed-signal, and digital design disciplines. Additionally, the form factor of transponder design could be reduced by the use of multi-chip stacked and MEM's technology advances. Finally, employing the concept of linearization of phase modulated wave forms could provide the means of making a generalized digital baseband signal processor for multimode, multiformat, multiband software transponder radio.

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