Practical Cryogenic Receiver Front Ends for Commercial Wireless Applications

Balam A. Willemsen

Superconductor Technologies Inc., Santa Barbara, California 93111, USA

Abstract — **Long-life, high-reliability cryocoolers, developed in the past decade, have allowed for the limited deployment of cryogenic microwave electronics in commercial wireless networks. We survey some of the background leading to current CRFEs and experience learned from early deployments. System reliability is a key issue for wireless providers, and must be an inherent consideration for CRFE design. CRFEs can be designed for lower cost by consolidating, eliminating and simplifying parts and assemblies. Here we focus on a new approach for computer aided filter trimming of complex filters in complex RF paths. Finally, we look ahead to other potential advances in CRFEs.**

Index Terms — **Cryogenic electronics, Land mobile radio equipment, Land mobile radio spectrum management, Circuit tuning.**

I. INTRODUCTION

Since the discovery of superconductivity in 1911, there has been interest in making use of the unique electronic properties of materials as they are cooled to extremely low temperatures for practical applications. By the mid 1960s several applications were on the verge of practicality. Yet, for all this time one thing remains true, "cryogenic electronics will only be as useful as the cost and reliability of the refrigeration permits." [1] In the radio frequency and microwave arena, cryogenics was thus relegated for many decades to high value applications in radio astronomy and satellite communication where the costs of reliable refrigeration were acceptable.

In the late 1980s, two important changes occurred that led to the work described in this manuscript: The discovery of High Temperature Superconductors (HTS) in 1987, and the evolution and rapid deployment of large terrestrial wireless communications networks. By 1997, the field had matured to the point that limited quantities of Cryogenic Receiver Front Ends (CRFEs) had already been deployed with the wireless providers and had been subjected to life tests by the basestation manufacturers.

Today, over 6,000 CRFEs are in use in North American wireless networks. While several companies, large and small, have pursued this market and developed and tested prototypes, only Superconductor Technologies Inc. (STI) has achieved any measurable level of deployment. The goal of this paper is to summarize some of the key technical design considerations of the most recent generation of STI CRFE, which are all aimed at reducing recurring cost, and thus increasing the practicality of the end product. Much background information can be found in a variety of other sources such as [2] or [3].

II. BENEFITS OF CRFEs TO WIRELESS NETWORKS

CRFEs that incorporate HTS, such as the Superlink Rx® offer a unique combination of sensitivity, selectivity and size when compared with other technologies. The sensitivity is mainly provided by cryogenically cooled LNA, which does not add as much noise to the signal as it would if it were not cryogenically cooled. Selectivity is primarily improved by means of the thin-film HTS "brick-wall" filter which is typically not much larger than a postage stamp, while providing the selectivity and loss characteristics of a much larger filter. Of course, the overall system size is not determined by the filters alone, but the overhead of the cryopackaging, cryocooler and controller can be offset by sharing these among some large number of RF paths. A typical CRFE contains 6 filter/LNA paths. The system performance benefits provided by using a CRFE can be particularly significant in today's CDMA networks which can be particularly sensitive to noise and interference. [4]

STI has performed numerous uplink enhancement trials over a period of 4 years to help quantify these benefits with multiple customers, infrastructure types, regions. In particular, 10 of these trials have been in CDMA networks at 850 MHz. One useful and simple to measure metric that can be looked at is the reduction in handset transmit power, which is an indirect measurement of the base station sensitivity. Over these 10 CDMA 850 trials, the average reduction in handset transmit power was 4.1 dB. More details on how these trials break down in terms of region or infrastructure type are shown in Table I.

TABLE I
SUMMARY OF TRIAL RESULTS FOR STI CRFEs IN CDMA 850 MHZ NETWORKS.

Category	Handset transmit power change (dB)	#
Average	**-4.1**	**10**
Urban	-5.5	3
Suburban	-3.5	3
Rural	-3.5	4
OEM A	-4.3	7
OEM B	-4.1	2
OEM C	-2.5	1

III. CRYOCOOLERS AND SYSTEM RELIABILITY

One of the key reasons STI has succeeded where others have not, was the early emphasis on developing our own, compact, low-cost, efficient, high-reliability free-piston Stirling cycle cryocooler[5]. The breakdown of costs of the key subsystems in a typical CRFE is shown in Figure 1. It can clearly be seen that far from an "invisible cryocooler" the cryocooler and its DSP based controller circuit board are a significant, but tolerable 24% of the total system cost. Production volume remains the only way to reduce the cryocooler cost, while various ways to reduce costs in the other areas will be discussed in sections IV-VI.
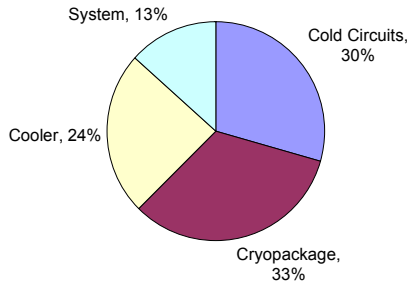

Figure 1. Breakdown of loaded costs of CRFE subsystems as of 2008. The dominant sources of cost are the cold circuits, cryopackaging and cryocooler/controller.

As of late 2007, the population of 6,000 deployed cryocoolers in CRFEs had surpassed 200 million cumulative runtime hours. Thus, on average, each cryocooler had been running continuously for over 4 years!
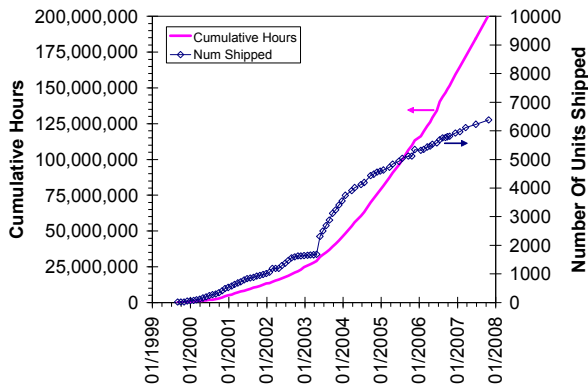

Figure 2: STI production coolers have accumulated over 200 million hours of operation in the field

The overall system MTBF > 500,000 hours is not limited by the cryocooler or the HTS, or even the cryopackaging. Instead, most of the system failures in the field have occurred because of the more conventional components such as the printed circuit boards and the cooling fans.

Of course the relative low-cost and high-reliability of the STI Sapphire crycooler make it attractive for other cryogenic electronic applications. As such, it was selected for use in the Allen Telescope Array, a radio astronomy project which went online in late 2007.

IV. DESIGN FOR LOW COST

Design for low-cost and high reliability implies eliminating parts and simplifying processes where possible. As initially conceived [10] and deployed in 1997, the STI CRFE was a very complicated assembly requiring many custom machined parts with features from multiple sides. While this is acceptable for satellites or other applications where these costs are dwarfed by other costs, it is not for widespread commercial applications.

Thus, in 2004 we undertook a major effort to redesign the CRFE for lower cost. Since much of the cost of the CRFE is in the cryopackaging, much of the effort was expended there. Much of this simplification can bee seen in Figures 3 and 4, showing pictures of the insides of a 2004 vintage dewar and one from 2008. As can be seen, the assembly has been greatly simplified, with many parts being consolidated and/or eliminated altogether. In particular, many threaded parts, mainly screws and connectors have been eliminated or replaced with spring clips.

Figure 3: Inside views of the cryogenic rf housings (microenclosures) inside 2004 dewar (left) and 2008 dewar (right). The 2008 dewar has been optimized to eliminate parts as compared to the 2004 design.
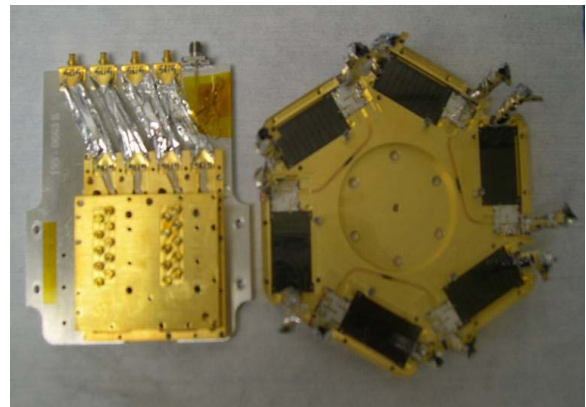

Figure 4: Expanded views of one of the three microenclosures in a 2004 dewar (left) and a 2008 microenclosure.

V. Filter Trimming

Another area where this is apparent is in the fine-tuning of the filter. It is very common for high performance filters to make use of mechanical tuning elements to correct for manufacturing tolerances which can affect the center frequency of the filter, as well as its return loss. At STI we initially incorporated dielectric tuners using sapphire cylinders above our filters [11]. These work very well, providing sufficient tuning range to adjust center frequency and return loss. However they still require precise, fine-detail machining to incorporate the fine threads required for fine positioning of the dielectric rod, and since these actuators form an integral part of the RF enclosure, their cost is shipped with the final product.

Another approach was developed at Conductus, where the tuning elements are small pieces of HTS attached to a spring clip[12]. The actuator for the spring clips was designed as a separate piece which could be removed from the part once the filter was tuned. In this way, some of the cost is shifted from the product to the tool required to make the part, which can then be amortized over a large number of products.

In ref. 6 we described an approach for computer aided filter trimming, which allows the filter to be trimmed for center-frequency and return-loss without any additional mechanical tuners. The additional features required for trimming are fabricated along with the filter and thus do not add any cost. This approach leads to well tuned filters in their test housing, but by the time the filters are integrated with the rest of the rf chain required for the system that includes bond-wires, LNAs, cryocables, switches and connectors the return loss of the chain is degraded.

In this respect, the mechanical tuner approach can lead to better system performance, as it allows the filter to be tuned so as to compensate for any mismatches in the other components in the rf chain. As a first approach, the pre-tuned filters were integrated with the rest of the components in the standard mechanically tuned filter housing, removing 8 or 9 of the 10 tuners required for each filter for a substantial reduction in labor and materials cost for trimming each filter.
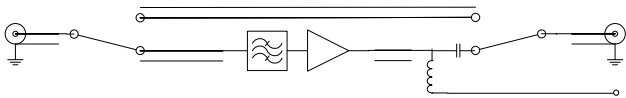

Figure 5: Model rf chain for one CRFE path, including filter, cryogenic LNA, bias tee, connectors, bond wires etc.
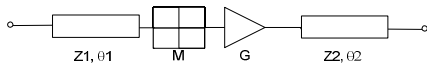

Figure 6: Simplified model of the rf chain used in parameter extraction, the filter is replaced with an equivalent coupling matrix and the amplifier with an idealized gain block. All of the other components are replaced with a physical transmission line defined by an impedance and phase.

In parallel, we developed approaches for computer-aided trimming of the whole rf chain. We know that the resonator frequencies alone are sufficient to optimize the rf chain from our mechanical tuning experience, so we should not have to add any additional trimming features to the filters. We add complexity to the objective function used in the curve fitting and consider only S11 and S21 when fitting, as our simplified model of the RF chain does not model S12 or S22 well. As before, we optimize only the resonator frequencies to trim the rf chain, leaving the extracted coupling values, gain and transmission-line parameters constant during the optimization. In practice, this approach leads to as good ot better system return-loss than the mechanical tuner approach with very high yields (>95%). The most significant source of failure in the process is human error, where the wrong recipe is applied to the wrong filter and/or other damage is done to the filter during trimming. Ultimately, in high enough volume, the scribing process itself could be automated to improve yield further.

As such, the filter trimming process which used to take a technician 20-30 minutes per rf path can largely be automated with a technician only required to move the dewar from one station to another.

1) Cool down and collect filter S-parameter data
2) Bin filters for similar turn-on characteristics
3) Assemble microenclosure/dewar (filters, LNAs, cryocables, switches, …)
4) Cool down and collect dewar S-parameters
5) Perform parameter extraction on dewar S-paramters
6) Determine filter trimming recipe
7) Apply filter trimming recipe to set of filters in dewar (manual)
8) Cool down and collect final dewar data
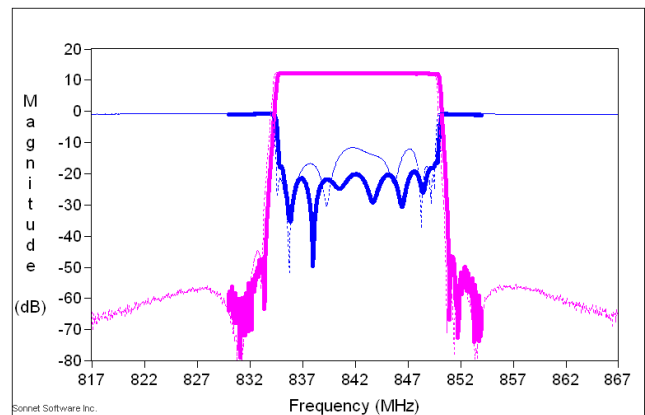9) Weld dewar for final system integration

Fig 7: Typical performance of one CRFE rf path including HTS filter, LNA, cryocables, switches and connectors. Average return loss is better than -16 dB for the entire path. In this case, the filter was shifted by 300 kHz and optimized for return loss.

Generally, the filter analysis and trimming processes described here also work well with dynamically tunable filters such as those described in [9] or [10] where the only knobs available for optimizing the filter response are the resonator frequencies.

VI. Future Directions

As was seen in Figure 1, the cold circuits themselves make up a substantial portion of the cost of a CRFE, so efforts to reduce their cost can be beneficial. The cost of the HTS filters is dominated by the cost of the substrate, so that the circuit cost can be affected in three ways. The simplest of these is to reduce the cost of the substrate material itself, i.e. switching from Magnesium Dioxide (MgO) to a more commonly used substrate such as Sapphire. Substrate cost can also be tied to the size of the circuit, which can be reduced either by growing higher performance HTS materials[7] and/or miniaturizing the circuits. We expect that in the coming years, one or more of these approaches will be used to reduce filter cost.

There are also many applications where the transmit side of the link would also benefit from lower losses and sharper filtering, but so far the power levels required have remained out of reach of cryogenic circuits. This may change over the next few years as base station transmit powers drop and by making use of novel circuit approaches[8].

VII. Conclusion

Long-life, high-reliability cryocoolers enable the use of cryogenic microwave circuits in commercial wireless networks. For six channel HTS CRFEs like today's Superlink Rx, the cryocooler does not dominate either system cost or reliability. Other components must also be designed for lower cost by simplification, in particular the cryopackaging. The introduction of computer-aided filter trimming has been an area of substantial improvement for both cost and overall system performance.

Acknowledgement

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