Assessment of Superconducting Technology for Urban Wireless Communications

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Abstract-**Superconducting cryogenic receiver front ends have shown that they can increase the coverage of cellular base stations by several times. However the improvements due to HTS filter and the LNA have not been clearly differentiated. This paper investigates the influence of the two components on performance of base stations in urban environment. Obtained results suggest that less costly filter alternatives are more suited to current cellular systems while the HTS technology could be an important factor for future wireless systems.**

I. INTRODUCTION

The first field trials of HTS materials to wireless communication systems came in the form of HTS filters employed in receivers front end for cellular phone base stations as early as 1996. Today over 1.5 billion people around the world (1/4 of the world's population) [1] own a mobile phone, and in the foreseeable future service providers will once again be presented with network capacity shortages, like the AMPS system experienced in the late 1980s. With this looming threat and the huge number of base stations, the claim from CRFE producers that each base station can yield an additional income of US$280,000 to US$350,000 [2] through the use of CRFE technology created a promise of a big market in waiting. However the number of CRFEs employed is so far very small, only about 5,000 and mostly in USA.

High Temperature Superconducting (HTS) planar filters exhibit very high selectivity and very low insertion loss. When installed together with cooled Low Noise Amplifiers (LNA) between the antenna and receiver electronics into a conventional cellular base station, these so called cryogenic receiver front ends (CRFE) were reported to fill coverage gaps, reduce adjacent band interference, improve channel capacity utilisation, extend high speed data services to more users and reduce the number of dropped calls and access failures experienced by users.

Field trials and continuing operation of installed CRFEs have shown that coverage improvements of up to seven times may be possible as illustrated in Figure 1 and Figure **2** [3-5]. Dropped calls were also reported to be reduced by over 40%. However no in depth information to what extent the individual components of the cryogenic receiver front end are responsible for the improvement in base station performance has been published.

In this paper an investigation has been carried out to evaluate whether it is the very low insertion loss or high selectivity of the superconducting filter which increases the coverage of the base station (or alternatively the number of users) or an improved LNA is responsible. Understanding which component of the front end is the most significant in a given environment will allow for the optimisation of the design of Front Ends to maximise the performance and minimise costs.

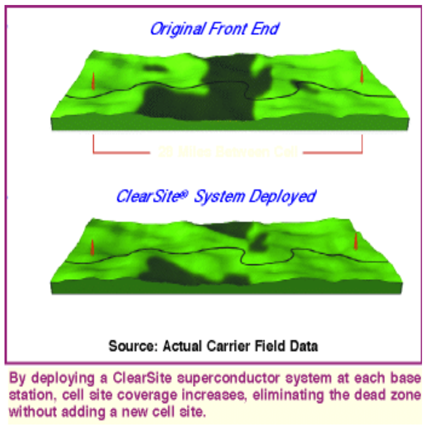

Figure 1. Coverage of a base station with and without a CRFE [6]

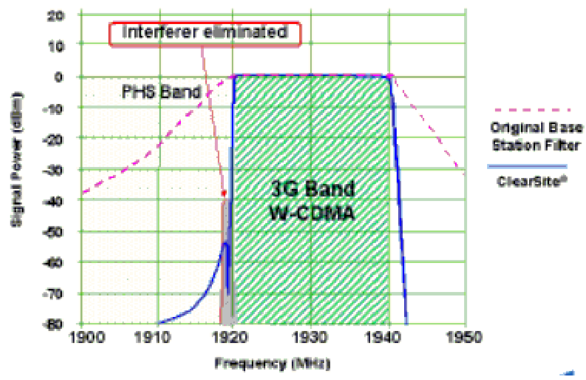

Figure 2. Elimination of an interferer in Japan using a CRFE [6]

II. MICROWAVE PROPERTIES OF HIGH TEMPERATURE SUPERCONDUCTORS

The reason for superior performance of superconducting planar filters over conventional filters is very unique properties of superconducting materials, namely zero resistance to DC current flow, perfect diamagnetism and lack of dispersion [7]. These properties make it possible to design very compact filters which exhibit a close to ideal frequency response.

However, the superconducting properties can be only exhibited if temperature, external magnetic field, current density through the material and the frequency of operation are below certain critical values characteristic for a given superconductor and inter-related. The critical temperatures for the HTS films are over 77K and critical frequency is in the THz range. The microwave impedance of superconducting materials is defined in the same way as for conventional conductors, namely as

$$Z_S = \left.\frac{E_x}{H_y}\right|_{z=0} = \sqrt{\frac{j\mu\omega}{\sigma}} = R_s + jX_s$$

where $\sigma = \sigma_1 - i\sigma_2$ where σ_1 and σ_2 are the conductivities of normal and superconducting electron pairs respectively (the conductivity of metals is exclusively real). The surface resistance of the superconductor is strongly dependent of temperature and frequency as shown in Fig. 3 and Fig. **4** respectively for $YBa_2Cu_3O_7$, the most commonly used HTS material.

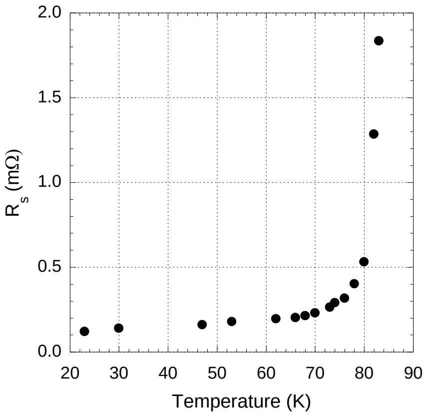

Fig. 3. Surface resistance of YBCuO vs. temperature [7]

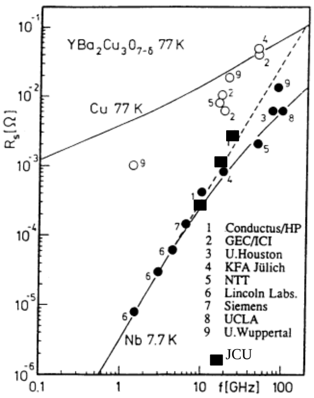

Fig. 4. R_S of YBCO and Cu measured by various groups [7, 8]

III. PERFORMACE EVALUATION OF BASE STATIONS WITH CRFEs

A tool referred to as a CDMA uplink model has been developed [9] to investigate advantages made by individual components of a cryogenic receiver front end. According to the model the coverage radius of a base station, *d* can be expressed in term of *S* (where *S* is the required u[link signal strength), when using the Okumura-Hata path loss model for large cities [10], as,

$$d = \frac{10^{\left(\frac{P_{MS}+G_{MS}+G_{BS}-(69.55+26.16\log f-13.82\log h_{eff}-a(h_{BS}))}{44.9-6.55\log h_{eff}}\right)}}{S^{\left(\frac{10}{44.9-6.55\log h_{eff}}\right)}}$$

where P_{MS} is the strength of the signal coming from the mobile, G_{BS} is the gain of an antenna on the base station and G_{MS} is the gain of the mobile unit. h_{eff}, is the difference in height between the base station, h_{BS} and the height of the mobile station (subscriber), h_{MS} and $a(h_{BS})$ is given by,

$$a(h_{BS}) = 3.2\left[\log(1.25 h_{BS})\right]^2 - 4.97$$

The signal strength *S* is dependent on the number of subscribers, N_s as given in the equation below.

$$S = \frac{\eta + P_{IMD}}{\frac{G_p}{\left(\frac{E_b}{N_0 + I_0}\right)} - 0.247\,N_s - \alpha(N_s - 1)}$$

where G_p is the processing gain of the system, $E_b/(N_0+I_0)$ is the bit energy to noise plus interference ratio, P_{IMD} is the power of the inter-modulation distortion in the pass band, η is the environmental noise and α is the voice activity factor or the percentage of time that people actually speak in a call, (typically 37.5% [3, 11]).

The first series of simulations performed compared the performance of four different front ends installed in a CDMA base station. The four front ends analysed were:

- a conventional Ground-based Front End,
- a conventional Tower-mounted Front End,
- a Ground-based CRFE, and
- a Tower-mounted CRFE.

The centre frequency was selected to be 835MHz and the filters had a useful bandwidth of 10MHz. For each system the performance was computed in a presence of noise only and for noise plus interference, where the interferer was a hypothetical 20W narrow band interferer at 825MHz. 40dB isolation was assumed between the transmit antenna for the interfering signal and the CDMA receiver antenna.

Tower-mounted conventional receivers were assumed to have a Noise Figure of 1.4dB, and Ground-based conventional systems to have 0.5dB more. The Noise Figure of HTS Filter-LNA combination was taken to be 0.8dB and the selectivity as 25dB/MHz [12]. The selectivity of conventional filter was assumed as 5.4dB/MHz [13]. An antenna Noise Temperature of 250K was chosen for urban environments [11] and the maximum transmit power of a mobile station of 200mW (23dBm) was assumed in the simulations.

The same system linearity was assumed for four systems, namely IP3 equal to 35dBm, which in fact could only be true when a modern low noise amplifier is used in all systems. This assumption means that the system IP3 is kept as a constant and therefore noise and interference can be focused on. However, in practice, modern amplifiers are not typically used in all conventional receiver front ends and systems will have different linearity.

Table 1. Properties of Base Station Receiver Front Ends

	Ground-based Conventional Receiver	Tower Mounted Conventional Receiver	Ground-based CRFE	Tower Mounted CRFE
Noise Figure N_R [dB]	1.9	1.4	1.3	0.8
Selectivity L_F [dB/MHz]	5.4	5.4	25	25
System OIP3 [dBm]	+35	+35	+35	+35

The computed performance of four CDMA front ends in an urban environment in the presence of the receiver noise only is illustrated in Figure 5. For all receivers the coverage of the base station decreases with the increase in the number of users as expected.

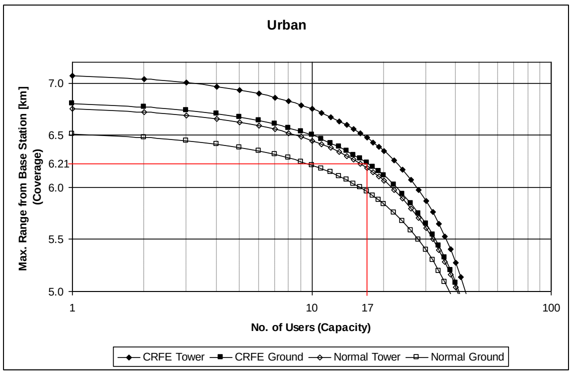

Figure 5. Computed Coverage vs. Capacity with Noise Only

The simulations have shown that the CRFE reduces the system noise by 0.7dB compared to conventional front ends, increasing the calculated maximum coverage for 10 users from 6.21km to 6.5km for a ground based receiver. This equates to a 5% improvement in coverage of the base station due to the reduced noise figure of the CRFE, which can be considered as a only a small improvement. Coverage improvements are most attractive for use in rural areas when there are few users or developing countries which are installing their first mobile communications systems. Most developed cities already have an extensive network of base station antennas. Extending the coverage in an existing network may lead to cells overlapping which can cause an increase in pilot signal pollution, therefore increasing the number of soft handoffs (make-before-break handoff) and therefore the total interference. By far the more attractive aspect of this technology is the increased capacity that CRFEs can provide while maintaining the same coverage. In the example of Figure 5 the number of users can be increased from 10 to 17 users while maintaining a 6.21km coverage radius when using a ground based CRFE rather than a conventional receiver front end.

The computed performance for the same four front ends when a 20W interferer is located 5MHz from the operational band edge (as illustrated in Figure 6) is presented in the Figure 7.

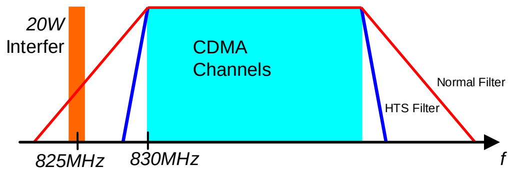

Figure 6. Schematic of 20W Out-of-Band Interferer, CDMA Channels and Filter Characteristics used in Simulations

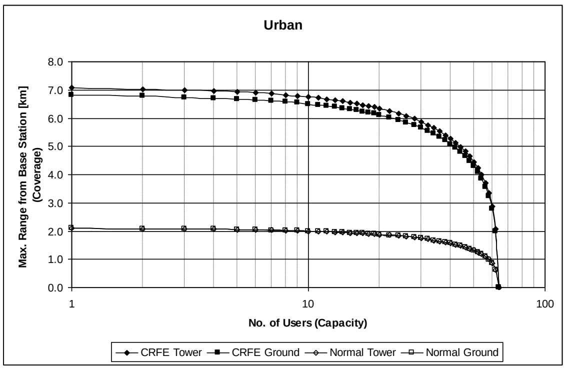

Figure 7. Computed Coverage vs. Capacity with Noise and a Narrowband Out-of-Band Interfernce of 20W @ 825MHz

In the presence of strong narrowband interference of 20W the Tower mounted and the Ground based conventional receivers have their range reduced from 6.21km for 10 users to approximately 2.1km. This is due to the non-linear effects of the amplifier and other non-linear components spreading the interfering signal into the CDMA channel of interest. The coverage of the CRFE is not affected and maintained the same 6.5km coverage as when there was no interference (Figure 5). This is due to the filter effectively suppressing the out-of-band interferer to a level such that the LNA is operating in its linear range, given by IP3 point. While situations of interferers close to the operating frequency are not very common today, heavy communications traffic can effectively utilise the higher selectivity of HTS filters to allow for more flexibility in spectrum allocation and cell site planning. Highly selective filters will be of particular benefit to 3G UMTS networks where they can be used to select an entire channel, effectively protecting it even from interference from other UMTS channels.

The second set of simulations using the developed CDMA Uplink model analysed the effects of system linearity on capacity and coverage of ground based receiver front ends. The IIP3 of 5dBm is typical for conventional receivers and 15dBm for CRFEs. A hypothetical modern front end with an IIP3 of 10dBm has also been simulated. The same selectivity (5.4dB/MHz) was assumed for all systems as shown in Table 2., The computed results of maximum coverage and number of users are shown graphically in Figure 8 for the case where there is no external interferer and Figure 9, which shows the A 20W interferer was assumed to be present at 825MHz.

Table 2. Parameters uses in Linearity Analyses

	Conventional Amplifier [14]	Theoretical Amplifier	Cooled LNA [7]
Noise Figure[dB]	1.9	1.9	1.3
Selectivity [dB/MHz]	5.4	5.4	5.4
Amplifier IIP3 [dBm]	+5	+10	+15

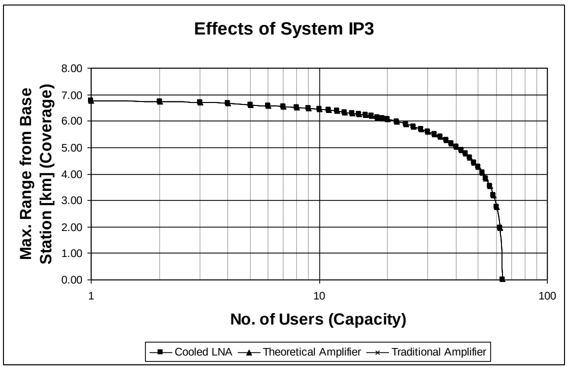

Figure 8. Computed Coverage vs. Capacity for differing IP3 with No Interference

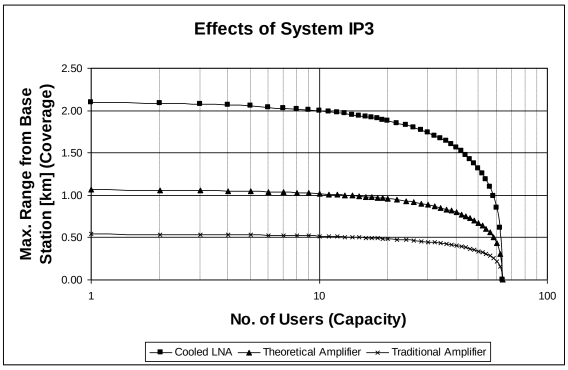

Figure 9. Computed Coverage vs. Capacity for differing IP3 in the presence of interference of 20W

In the case where there is no external interferer to generate intermodulation distortion in the non-linear components (in this case assumed to be dominated by the amplifier) improving the linearity of the amplifier does not affect performance. In this situation the coverage obtained with each of the LNA was 6.8km. However the situation is quiet different when a 20W interfere is present. For a base station using a ground mounted receiver with an amplifier IIP3 point of +5dBm and a conventional filter of 5.4dB/MHz selectivity the coverage of the base station of only 0.54km was obtained. Improving the IIP3 point of the amplifier to +10dBm increases the coverage to 1.07km, giving almost a 100% improvement. Using a cooled LNA of the IIP3 of +15dBm yielded a 2.09km coverage radius. The results suggest that when there is an out-of-band interferer (which may produces IM products due to non-linear components) improving the linearity (IIP3) of the amplifier alone will reduce the impact the interferer has on coverage and capacity. Theoretically if the amplifier and rest of the system electronics were linear no filtering of out-of-band interference would be required.

The developed CDMA uplink model has demonstrated the importance of having a linear system, which is typically limited by the input IP3 point of the amplifier. Increasing the linear range of the amplifier has a significant effect on improving the coverage and capacity of the CDMA systems, particularly in high traffic areas where out-of-band interference is prevalent. Replacing traditional amplifiers with more modern or cooled LNAs may be a good option for current installations of CDMA cellular base station receivers, in terms of performance and cost. Indeed if a perfectly linear system could be developed, intermodulation products would not be an issue and filtering would be unnecessary.

The third series of simulations examined the filter steepness affecting the performance of the base station. The LNA for all systems was assumed to have a very high IIP3 of 15dBm. Simulations were performed assuming a filter of Narda Components [13] of steepness of 5.4dB/MHz, a hypothetical filter with a steepness of 10dB/MHz and a HTS 16 pole HTS filter [12] with a steepness of 25dB/MHz. The noise in each scenario was assumed to be that of a conventional ground mounted front end (1.9dB). Three cases have been considered, the first is with noise only (Figure 10), the second with the familiar 20W interferer located at 825MHz (Figure 11) and a third (more extreme case) where the interferer is placed at 828.5MHz only 1.5MHz from the operation band edge (Figure 12).

Table 3. Parameters of Filters used in Filter Selectivity Analyses

	Conventional Filter	Theoretical Filter	HTS Filter [15]
Selectivity [dB/MHz]	5.4	10	25
Noise Figure [dB]	1.9	1.9	1.9

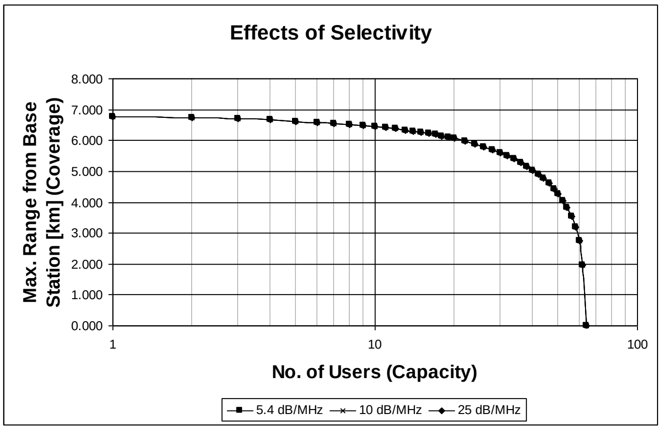

Figure 10. Computed Coverage vs. Capacity for Filters of Different Selectivity with Noise Only

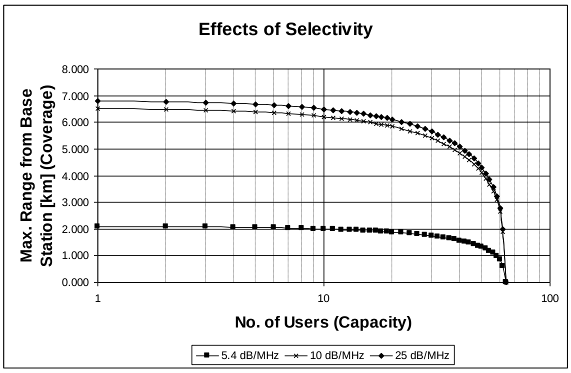

Figure 11. Computed Coverage vs. Capacity for Filters of Different Selectivity with Noise and a Narrowband Out-of-Band Interference of 20W @ 825MHz

As was the case with in the previous set of simulations, when there is no interferer to cause intermodulation distortion there was no coverage or capacity improvement gained from a better filter (see Figure 10). In practice this may not be strictly correct as interference will be generated by the surrounding CDMA channels depending on how busy the network is and the frequency reuse factor. This particular source of interference is not specifically account for in the model as only an average value is used.

When the 20W interferer was present the simulation results of the performance of the base stations, pictured in Figure 11, show the receiver with the traditional filter of steepness of 5dB/MHz provided a 2km coverage radius when 10 users were connected simultaneously. Improving the filter steepness to 10dB/MHz resulted in a three times larger coverage radius with the same number of users. Further improving the filter beyond the point where the out-of-band interferer is attenuated such that inter-modulation distortion is no longer generated in non-linear components has very little effect. Hence, dielectric filters which can achieve a steepness of up to 25dB/MHz (with only slightly higher insertion loss than HTS filters) and are significantly less expensive than a CRFE should be attractive as base station front end filters.

The simulations were repeated for an extreme case where there is a 20W interferer at 828.5MHz, very close to the 830MHz edge of the passband. This time 5.4dB/MHz, 15dB/MHz, 20dB/MHz and 25dB/MHz filters were compared using the same setup parameters as in the previous simulation. This was to consider not only out-of-band signals generated from another source, but out-of-band signals generated by neighbouring CDMA channels (which can also cause IM products in high usage areas). Due to cellular site planning this is not typically an issue in today's mobile environment, but as user numbers increase and data services become more accessible, maximising the capacity of networks will become more important.

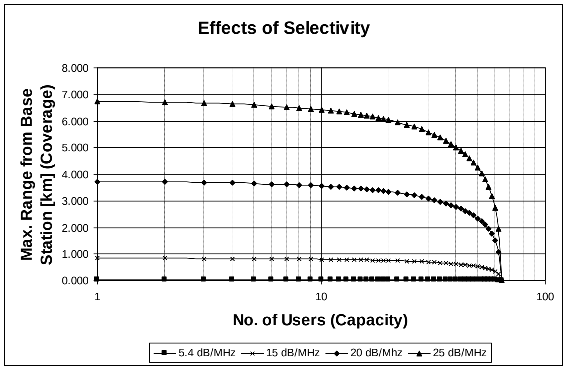

Figure 12. Computed Coverage vs. Capacity for Filters of Different Selectivity with Noise and a Narrowband Out-of-Band Interference of 20W @ 828.5MHz

The traditional filter in the presence of such a close strong out-of-band interferer provided almost no coverage (due to extreme interference from IM products) while the HTS filter with selectivity of 25dB/MHz maintained the coverage and capacity at almost the same levels as when the interferer was not present. This simulation result shows the potential importance of high selectivity filters to the future cellular communication industry.

On the basis of performed simulations and analysis of fields trials one can say that early reports on base station performance results and market assessments of CRFE were indicative of installations in base stations which suffered from a phenomenon of having a strong out-of-band interferer close to the passband. Results obtained with the CDMA uplink model suggests that the improvement was due to the very high selectivity of the filter attenuating the interferer such that it no longer causes excessive interference in the passband. However, in most situations, no such interferer exists and the improvements are only in the order of about 80% coverage improvement. More significantly for service providers, capacity improvements in this situation are close to 100% if the coverage is unchanged. The results of performance evaluations also suggest that achieving these improvements does not require HTS filters, simply using a modern LNA and conventional or dielectric resonator filters, which do not require expensive cryogenic cooling equipment, would be sufficient.

IV. CONCLUSIONS

The analysis of the cryogenic receiver front ends suggested that, in many 2G and 3G cellular networks, the very high selectivity achievable with HTS planar filters is not required provided highly linear amplifiers are available and used. Additionally, high cost of cryogenic systems required for cooling of the HTS planar filters and LNAs has a negative impact on price versus performance factor. Hence, an antenna sharing solution called a Multi-operator Combiner, which utilises the selectivity of the HTS planar filters and allows the cost of a base station to be shared between operators, as discussed in the Authors PhD thesis [16]. The thesis also includes details of the Multi-operator Combiner concept and the implementation of the other filter solutions for receive and transmit which are required for the success of the Multi-operator Combiner and can be used individually in current cellular base stations.

At this time, due to network specifications being designed to take advantage of older filter technology, it is unlikely that cryogenic receiver front ends will find large market acceptance in current day cellular base stations. However, Multi-operator Combiner technology implies that HTS planar filters may yet have a role in current cellular networks although primarily as specialised antenna sharing technology rather than as the well known cryogenic receiver front end. Possibly in the future, cellular network generations will be designed to take full advantage of the benefits of HTS planar filters installed in cryogenic receiver front ends in order to satisfy the expanding customer base, at which time HTS planar filters will become an essential part of everyday life.

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