Abstract

The UK digital terrestrial television (DTT) network has completed its first phase of roll-out, with over 70% of the population now able to receive all six digital multiplexes. Whilst this is an impressive achievement, the current analogue TV network can cover 99.7% of the UK population and digital satellite systems can boast virtually 100% coverage, so DTT still has some way to go. DTT coverage must improve in order to make analogue switch-off a politically acceptable reality and to compete directly with satellite in value-added services, such as shopping or banking. Analogue switch-off is a particularly desirable goal, as it would release a significant amount of valuable spectrum for use by other commercial services (e.g. mobile telephony).

This paper will address the use of transposers, in a manner similar to that of the current analogue TV network, in order to cost-effectively extend coverage to those viewers currently unable to receive all of the digital multiplexes. A number of transposer designs are considered, employing both DSP and high-temperature superconducting (HTS) techniques, and results presented on some of the technologies employed.
Abbreviations

ACI  Adjacent Channel Interference  
ADC  Analogue to Digital Converter  
COFDM Coded Orthogonal Frequency Division Multiplexing  
DAC  Digital to Analogue Converter  
DSP  Digital Signal Processor (or Processing)  
DTT  Digital Terrestrial Television  
DVB  Digital Video Broadcast(ing)  
DVB-T  DVB-Terrestrial  
END  Equivalent Noise Degradation  
HTS  High-Temperature Superconductor  
IF  Intermediate Frequency  
LNA  Low Noise Amplifier  
LO  Local Oscillator  
MCPA  Multi-carrier Power Amplifier  
PA  Power Amplifier  
PSI  Programme Specific Information  
RF  Radio Frequency  
SFN  Single Frequency Network
1. Introduction

The initial roll-out of the UK digital terrestrial television (DTT) network has now completed its first phase, with 80 main stations fully operational and providing a high-quality service to viewers. There are still a substantial number of viewers who are currently able to receive analogue terrestrial broadcasts and who cannot yet receive DTT signals; this amounts to almost 30% of the population. Clearly the majority of these viewers will need to be served with a good quality DTT signal prior to the switch-off of the analogue network and one of the prime methods of achieving this enhanced coverage is through the use of transposers (repeaters, regenerators and frequency shifters). The design of these transposers is significantly different to their analogue counterparts and currently no products of this nature exist in the marketplace. Furthermore, these transposers need to operate within the existing analogue frequency plan and continue to support the full DTT network when the analogue network is withdrawn. There are therefore a number of new challenges presented by the requirements of the DTT system and these must be overcome by the use of novel design techniques and new architectures for both the network and the transposer itself.

There are strong commercial reasons why solving this problem is very important. The recent auction of third-generation cellular telephone licences clearly illustrates the value of prime radio spectrum and that currently occupied by analogue TV broadcasts attaches a very significant value. An early release of some of this spectrum, facilitated by an early analogue switch-off, clearly has significant financial implications for those involved.

The architectural and practical issues of a new form of DTT transposer, designed to address the new problems introduced by the adoption of the DTT standard, are being studied in a DTI LINK project called SATIRE (Simultaneous and Adaptive Transmission using Intelligent Re-configurable Equipment). As part of the project, architectures have been proposed and are being studied, both theoretically and practically which involve the use of digital transposition, high-linearity RF amplification and high-temperature superconducting (HTS) components. All of these technologies are either currently mature and being deployed in other systems (e.g. Cellular) or are close to maturity, and will be demonstrated in a field trial within the project (e.g. high-temperature superconducting elements and cryocoolers). They are each able to offer distinct advantages in a number of areas.

The architecture study is complete and has been verified by simulation, with practical demonstration of the key elements of the system (linear power amplification and HTS filtering) also now completed. The proposed architecture is therefore verified and will be demonstrated in a system during the remainder of the project.

This paper will describe the system architecture options for a DTT transposer and present both simulation and practical results demonstrating the key performance and system design parameters. It will also address the network-level issues of deploying transposers in a DTT system and explain why this situation differs significantly from that of the current analogue network.

2. Background to Transposers

To understand the potential benefits of transposers in a digital network it would be instructive to look at how they are employed in the current analogue networks. Although the network requirements are not entirely analogous there is still a lot to be gained from looking at the present implementation of transposer technology.
2.1 Analogue Networks

To re-broadcast signals from a relay station there are two primary techniques available. The first of these is the remodulator, which demodulates and remodulates the baseband signals, and the second is the transposer, which performs channel transposition in the radio-frequency domain without remodulation. A short description of each technique is given below, followed by an appraisal of the relative merits of each.

2.1.1 Re-modulator Station

Remodulator stations are used at strategic points in the analogue network. They receive a signal off-air from a parent station, perform demodulation of the constituent baseband signals and then remodulate the signal to be transmitted on a different output channel. A functional diagram of a typical current analogue remodulator installation is given in Figure 1.

![Figure 1: Re-modulator Functional Block Diagram](image)

The basic functional elements of this system are:

- Antenna and filtering/splitting system; in a multi-channel installation this provides an RF signal to each of the individual channel receivers. It may also provide stop-band filtering at the station transmit frequencies to prevent front-end overload being caused by the large signal strength of the station output.

- Receiver; this contains demodulators for the vision, analogue sound, and digital NICAM sound signals. The NICAM sound output is in the form of a digital data-and-clock signal.

- Teletext regenerator; this restores the teletext signal to optimum ‘eyeheight’ to remove impairments introduced by the parent transmitter and the demodulator.

- Modulators; these re-modulate the signal to the appropriate format. The vision modulator also applies pre-correction to counter the non-linearity of the power amplifier.

- Power amplifiers; these amplify the vision and combined sound signals separately to minimise system linearity requirements (if all three carriers were amplified in a common device the linearity requirements for acceptable intermodulation performance would render the system unacceptably inefficient).
• Combiner; the combiner operates in two stages. Firstly the sound and vision signals are combined to provide a complete ‘service’ and then the individual services are combined to feed the common antenna. The combiner needs to have a low through-loss whilst presenting the maximum practical isolation between inputs. To achieve this the combiner is generally a frequency selective, fixed-tune device.

In many cases the baseband signals will also pass through a switching system to introduce reserve feeds into the signal path. This has been omitted from the diagram to aid clarity.

2.1.2 Transposer Station

Transposers are used widely in the current analogue networks to fulfil the requirement for numerous relay stations to counter coverage deficiencies. A transposer receives an off-air signal from a ‘parent’ station and transposes it to a different channel. A typical installation will have common receive and transmit antennas and individual transposer systems for each channel. An equipment rack from an existing transposer is shown in Figure 2.

In the current analogue network approximately 97.5% of all rebroadcast stations employ transposers. The remaining 2.5% are rebroadcast ‘main’ stations (see 2.1.1 above). A functional block diagram of a typical current analogue transposer installation is given in Figure 3;

![Figure 2: Transposer equipment rack at a broadcast transmitter site (courtesy of Crown Castle International)](image-url)
2.2 Relative Merits of Rebroadcast Systems

2.2.1 System Flexibility

Sometimes it is advantageous to demodulate the incoming signal to its various baseband components prior to re-modulation and conversion to the new final output frequency. There are several reasons why this technique may be used:

- to process the baseband signals in some way e.g. regeneration of teletext signals to improve decoding margin.
- to overcome incompatibilities between input and output channels which prevent the use of a transposer e.g. a single-channel transposition
- to enable selection of alternative baseband signals e.g. ‘opt-out’ switching or selection of a reserve feed.

For these reasons the remodulator technique is used at strategic locations in the analogue network.
2.2.2 Monitoring
There are some drawbacks to the technique, despite its superior flexibility. Firstly, to ensure that all signals traverse the ‘baseband’ domain safely the output of the station needs to be fully demodulated to confirm the presence of video and audio content – just detecting the presence of the various radio-frequency carriers is insufficient. The numerous items of equipment, in both the programme chain and monitoring chains, require additional power and space. This requires a larger building and, ultimately, the cost of such a station is increased.

In the transposer system no processing is applied to the signal other than to change its channel and to amplify it, the output is therefore a faithful reproduction of the input. Since this equipment functionality is much simpler than the remodulator it is a lot smaller and consumes less power. Further, since the signals are never demodulated it is impossible for the audio and video content to be removed and the output can be monitored by simply detecting the presence of the various radio-frequency carriers. Overall this makes the transposer a smaller more power-efficient device and hence a very cost-effective solution.

2.2.3 Reliability
Since the remodulator system consists of numerous standalone units the reliability of the system needs to be carefully specified as the multiple interconnections and discrete units will decrease overall system reliability. The functional complexity of the various units will also have a significant impact upon the system reliability.

The transposer system is generally comprised of one integrated unit per broadcast channel. This degree of integration, together with the functional simplicity of the transposer system, provides high reliability.

2.3 Digital Networks
In theory it should be perfectly feasible to use both of these configurations in a digital network. It is therefore worth examining the digital equivalents of the remodulator and transposer solutions.

2.3.1 Re-modulator
Although no such systems have been put into operational service yet, a DTT re-modulator system would have the basic functionality shown in Figure 4.

![Digital Re-modulator Functional Block Diagram](image-url)
The key interface in this system is that shown at ❶. This interface occurs at DVB Transport Stream level, at least in terms of stream protocol, although not necessarily at Transport Stream electrical standard.

- Demodulator; this demodulates the parent station signal. In doing so it also applies both the Viterbi and Reed-Solomon error correction inherent in the DVB-T standard. The output therefore exhibits the ‘cliff-edge’ characteristics of a digital system, providing an error free output but with a sudden failure point upon degradation of the input signal.
- Modulator; this performs modulation in accordance with the DVB-T standard. The output of the unit will be at an Intermediate Frequency.
- Up-convertor; this converts the IF signal to the required output frequency.
- Power amplifier; this amplifies the signal, at final frequency, to the required power
- Combining unit; this combines the various channel signal outputs for radiation by the common antenna. The combiner needs to have a low through-loss whilst presenting the maximum practical isolation between inputs.

2.3.2 Transposer
Since the fundamental overall functionality of a transposer for digital operation is very similar to that for analogue a re-appraisal of the transposer technique is not necessary for us to be able to consider it’s comparative merits against the remodulator.

2.4 Relative Merits of Remodulating Transposers in a Digital Network

2.4.1 Monitoring
Even though it is operating upon a single digital signal the remodulator architecture still employs the most complex processes of the two. The most unattractive aspect of this architecture is the fact that the signal is converted to baseband, where it is at it’s most vulnerable. It is possible to imagine a fault scenario in a demodulator that would produce a transport stream with no payload, but with perfect framing. The modulator section would readily accept this input as it is only sensitive to the frame structure of the transport stream and not to the stream payload. To account for this potential failure mode the monitoring of the system output would need to look for some indication of correct stream payload, PSI tables for instance. Should such monitoring be required it would increase the size and cost of the installation as a receiver and stream analyser would be needed for each channel. Also, monitoring of this nature would make the system sensitive to payload content which can, of course, be altered by the broadcaster. It is beneficial to avoid such sensitivity as it can constrain operational flexibility of the system.

Conversely, a transposer, although it may contain complex electronics, only performs relatively simple processes upon the incoming signal. Since these processes merely produce a replica of the input signal on a different channel without altering the information content of the signal in any way the monitoring requirement then becomes much simpler. Indeed, merely detecting the presence of RF power at the system output may provide sufficient confidence of correct operation. Such monitoring could be easily included in the power amplifier itself, reducing cost and complexity considerably. A transposer is not sensitive to the payload and therefore presents no operational constraint in this respect.
2.4.2 Reliability
In a similar manner to the analogue transposer, but possibly to a lesser extent, the transposer solution is likely to be more highly integrated than the remodulator. It would certainly use less complex processes and the likelihood is that, given this combination of factors, the transposer solution would be more reliable.

2.4.3 Cost
Two aspects of costs need to be considered; capital costs and running costs.

The capital cost of a station is determined to a large extent by the infrastructure costs i.e. the building costs. At the moment it can be envisaged that a digital transposer may be smaller than an equivalent re-modulator. Added to this may be the requirement for enhanced monitoring of a remodulator system, as discussed above. Therefore it seems that transposers would represent the most space-efficient, and hence capital-cost-efficient solution.

The running costs of a station are determined by two primary factors, reliability and power consumption. Decreased reliability will lead to increased site visits and hence increased costs. The running costs of the station will increase sharply with decreased reliability as the cost of staff, transportation and general overheads are all impacted. As discussed above it can be anticipated that the transposer solution will be more reliable than a re-modulator and therefore require less attendance by field staff.

The proposed highly integrated nature of a digital transposer implies that power consumption will be reduced, with respect to the anticipated architecture of a remodulator system.

In conclusion, in terms of both capital and running costs the transposer would appear to present the most cost-effective solution.

2.4.4 Performance
An area where the absolute performance of the transposer may limit it’s usefulness in a digital scenario is that of decoding margin. Some impairments introduced by a transposer will affect the overall decodability of the signal; noise, linearity and frequency response are all examples of such impairments. Once the signal has been degraded in this way the overall decoding margin at the viewer’s receiver is also degraded. With the ‘cliff-edge’ failure characteristic of digital modulation schemes this could ultimately lead to a loss of coverage, rather than a small reduction of service quality as would be the case with analogue. Initial tests performed using analogue transposers for digital signals have indicated that such an erosion of the decoding margin can be reduced to acceptable levels.

2.5 The Digital Transposer
It would seem from the above appraisal of the available techniques that it is worth pursuing the option of a digital transposer. However, despite the transposer technique being fundamentally similar for analogue and digital operation, the digital scenario does present some new challenges.

2.5.1 Spectrum Congestion
Digital channels are generally added to the existing network by interleaving them with the analogue channels. A typical spectrum, that of Crystal Palace in London, is shown in Figure 6. Note the adjacent digital and analogue channels and the large difference in power levels between the two. As none of these analogue assignments can currently be relinquished the spectrum is becoming increasingly congested. Also, it is possible to assign a digital signal to a channel adjacent to another digital signal or to an analogue signal; this is one of the fundamental planning enablers for an
interleaved network. Thus, to make the most of this increasingly scarce spectrum resource, it would clearly be very beneficial to be able to perform a transposition of only one channel i.e. the output channel centre frequency is 8MHz different to the input channel. However, current analogue transposer technology has not been developed to the point where it is capable of transposition between adjacent channels because the requirement has never existed before. This, allied with the higher absolute performance requirements for digital operation, limits the use of current transposer designs for digital operation.

2.5.2 Adjacent Channel Operation

As already discussed one fundamental feature of digital television that has facilitated the current interleaved network is the ability of digital services to occupy channels adjacent to other digital and analogue signals. Figure 5 and Table 1, below, illustrate the scale of adjacent channel operation in the current 80-station network, which utilises a total of 502 digital channel allocations.

The filtering employed in the IF stage of current transposers is not selective enough to reject the signals immediately adjacent to the wanted channel. This means that the output of the transposer would also contain transposed signals immediately adjacent to the wanted output. This is clearly undesirable from the point of view of spectrum ‘pollution’ as well as the effect it has on limiting the situations in which transposers could be used.

<table>
<thead>
<tr>
<th></th>
<th>Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pontypool</td>
<td>D3</td>
</tr>
<tr>
<td>Presely</td>
<td>D3</td>
</tr>
<tr>
<td>Redruth</td>
<td>D1</td>
</tr>
<tr>
<td>Reigate</td>
<td>D5</td>
</tr>
<tr>
<td>Ridge Hill</td>
<td>D4</td>
</tr>
<tr>
<td>Rosemarkie</td>
<td>1</td>
</tr>
</tbody>
</table>

Dn = Digital Channel  n = Analogue Channel

Figure 5: Extract from DTT Channel Allocation Chart

<table>
<thead>
<tr>
<th>Relationship with Respect to an Occupied Channel</th>
<th>% of Digital Channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lower-adjacent</td>
<td>34%</td>
</tr>
<tr>
<td>Upper adjacent</td>
<td>38%</td>
</tr>
<tr>
<td>‘Sandwiched’ (upper and lower adjacent)</td>
<td>9%</td>
</tr>
<tr>
<td>Upper and/or lower adjacent</td>
<td>65%</td>
</tr>
<tr>
<td>Isolated from other channels</td>
<td>35%</td>
</tr>
</tbody>
</table>

Table 1 : Adjacent Channel Statistics
2.5.3 Loss of Decoding Margin
As discussed above the existing transposer designs do reduce the available decoding margin at the viewer’s receiver in a non-recoverable way. Although such impairment can be reduced to acceptable levels, with current technology the reduction is generally not sufficient to allow the current types of transposer to be used in tandem. Chains of transposer stations can be a very cost-effective solution to the coverage of remote hilly areas such as the valleys of South Wales and the Highlands of Scotland. Therefore a further design challenge for the digital transposer is an improvement in performance sufficient to allow chains of, say, 2 to 3 transposer stations.

2.5.4 The Development Challenge
To overcome these various design challenges, state of the art technology is to be applied to the transposer technique and initial indications are that the digital transposer will become a working reality.

3. SATIRE Transposer Architecture

3.1 Incorporated Technologies

3.1.1 Introduction
The architectures chosen for investigation within the project draw on technologies not normally associated with terrestrial broadcast systems, the potential advantages of which have been outlined above: Multi-carrier power amplifiers (MCPA) normally applied in cellular base station transmitters, DSP techniques normally found in cellular base-stations and handsets and HTS systems normally associated with military communications. A brief introduction to these technologies is provided below.

3.1.2 Multi-carrier power amplifiers
Multi-carrier power amplification allows a number of carriers to be amplified simultaneously by the same amplifier hardware. It has a number of advantages over the traditional approach of utilising a number of single-carrier power amplifiers, followed by either a hybrid or cavity combiner. This
combiner sums the amplifier outputs to feed a single antenna. These three approaches are summarised in Figure 7.

Multi-carrier power amplifiers generally employ sophisticated amplifier linearisation techniques in order to minimise intermodulation distortion and consequent adjacent channel interference (ACI). Examples of such techniques include feedforward and predistortion, with both being considered for use in the SATIRE transposer design. Further details of these schemes may be found in the literature [1,2]. A picture of a commercial multi-carrier power amplifier, on which the SATIRE MCPA concept is based, is provided in Figure 8.

\[\text{Figure 7: Cavity (a), hybrid (b) combining and multi-carrier PA (c) techniques in for use in a cellular base-station}\]
3.1.3 Digital signal processing

Sophisticated digital signal processing techniques are now employed in most communications system designs. They are generally utilised for modulation generation, coding, demodulation and some aspects of channel filtering. Whilst conventional digital signal processors are capable of operating at ever increasing clock frequencies, the ultimate performance in this area is still only obtainable from FPGA devices and ASICs. The former often provide a convenient design route to the latter, although the boundaries are becoming blurred with the introduction of low-cost parts by the FPGA manufacturers.

In the case of the SATIRE transposer it is the high-performance filtering capabilities of DSP which is of greatest benefit, particularly in the elimination of close adjacent channel signal components, e.g. the NICAM carrier of an adjacent analogue service.

3.1.4 High-temperature superconductors and Cryocooling

In contrast to the digital solution, an all-analogue alternative requires the use of advanced HTS (High Temperature Superconducting) materials [3,4] to realise an almost ideal “brick-wall” RF filter to solve the problem of channel filtering. The availability of an almost ideal filter response thus opens up possibilities for the system designer/frequency planner that hitherto were not even considered. HTS materials offer the potential for extremely low loss and compact structures to be fabricated [5,6,7]. This allows the use of novel filtering structures (see Figure 9) to realise a filter performance that simply cannot be achieved using conventional room temperature technology. Various types of materials now exist, most notably those based on the Ti-Ba-Ca-Cu-O system, which can have
transition temperatures (the temperature at which the phenomenon of superconductivity appears in
the material) as high as 125K. A fundamental property of interest to the broadcast community is the
surface resistivity, or $R_s$, that can be realised from these ceramic materials. Normal, pure copper at
room temperature and when passing a signal at a frequency of 10GHz, for example, has an $R_s$ of
around 24m$\Omega$, this compares with less than 0.1m$\Omega$ for a good superconducting thin film at 80K. To
translate this to Q values, a sapphire dielectric resonator with HTS end plates can be routinely
demonstrated with a Q value in excess of 1 million (5GHz, 80K) which compares to 30,000 for a
copper implementation under the same conditions.

Cryocooler technology is clearly essential in order to realise the benefits of the HTS filtering system.
The key innovation in this area is in achieving a very high degree of reliability from the design; this is
essential in ensuring a low cost of ownership and a high quality of broadcast service for the service
provider. Stirling Cycle Cryogenic Engines will fail primarily because of wear, gas leakage and
contamination. Wear can only be caused by rubbing contact between moving parts. Since lubricants
contaminate the system and dry bearings wear, long life can only be achieved by eliminating rubbing
contact pressure seals. A key design aim in the SATIRE system is therefore the elimination of these
elements, with the design being undertaken having the base minimum of rubbing contact points.

Figure 9: Close-up of an HTS resonator

3.2 Applications to Broadcast Systems

3.2.1 MCPA

MCPA technology has the potential to offer both space and cost savings to the designer of multi-
channel broadcast transmitters and transposers. In many cases, a single MCPA will take up a fraction
of the bay space of a bank of six or more single-channel amplifiers. Additionally, the cost of an MCPA should be considerably less than the totality of the single-channel units it replaces. Even if two MCPAs (one and a spare) replace \( N+1 \) conventional (\( N \) and a spare) the cost equation will probably still favour the MCPA approach.

The MCPA architecture also obviates the need for a high-power channel combiner which is potentially both bulky and expensive. This would typically be replaced by a more compact ‘cover’ filter as wide as the total group of output signals. Indeed, as MCPA technology advances, no filter at all may be necessary.

A drawback of employing an MCPA is the resulting interdependence of the services; if the MCPA fails then all services are lost together. Unless exceptional reliability can be demonstrated a ‘hot spare’ becomes essential with effective monitoring and control protocols to allow a virtually seamless hand-over.

### 3.2.2 DSP

The current availability of high performance DSP together with recent advances in D/A and A/D converter technology allows processing of baseband or IF broadcast signals to be entertained. In particular, this is now true for digital television signals to the DVB-T standard occupying 8MHz of bandwidth. Consequently, tightly specified baseband or IF filtering may now be performed with accuracy and stability within the DSP domain without recourse to conventional analogue filters. Other processes which are difficult to implement in an analogue circuit become possible, such as adaptive amplifier linearisation.

Potential drawbacks of high-speed DSP may include size, power consumption and the capacity to introduce RFI into a sensitive environment. The first two of these are constantly improving as the technology advances, the latter inevitably requires care and attention to be paid to layout and screening.

### 3.2.3 HTS

HTS filter technology promises to deliver a combination of compact size and exceptionally high component ‘Q’ factors. Within the broadcast arena, this technology will allow the fabrication of high performance channel filters, for example 8MHz wide at UHF frequencies. Such is the potential performance that unusually simple architectures may become possible, as are discussed below.

The major drawback is the need to provide cooling to very low temperatures (typically 80K), entailing the use of a relatively expensive cryocooler. However, costs in this area are falling and exceptional cryocooler reliability has already been demonstrated within the SATIRE project.

### 3.3 Architecture Options

#### 3.3.1 DSP/MCPA Architecture

A possible DSP and MCPA-based transposer architecture (with no HTS) is shown in outline form in Figure 10. A wide input ‘cover’ filter passing the whole UHF band (470-860MHz) precedes a multi-carrier LNA (MCLNA). Each wanted signal is then downconverted to an IF suitable for subsequent A/D conversion. The IF filter shown can be relatively broad; the demanding filtering is carried out later in the DSP. The DSP also carries out any necessary group delay equalisation, particularly if it employs IIR structures. The processed IF signals are then up-mixed and summed into an MCPA, which is followed by an output ‘cover’ filter. An alternative arrangement is to sum the digital baseband signals before D/A conversion. If this is done, MCPA linearisation may also be performed at this stage, simplifying the MCPA.
The great advantage of this arrangement is that changing the input and/or output frequencies of operation is simply a matter of re-tuning oscillators, an action which may be quickly performed from the equipment front-panel or even remotely. It is not necessary to change any channel filters.

One disadvantage of the design shown is the limited image rejection, perhaps only 30-35dB. If this is insufficient, but the broad input filtering is to be retained for the reasons stated above, then a first IF of perhaps 1.2GHz should be used employing a high-side LO and a relatively wide (~100MHz) filter. A further mixer then provides the second IF at ~70MHz.
3.3.2 HTS-based Architecture

A proposed HTS-based direct transposition architecture is shown in Figure 11.

Central to this topology is elimination of the need for an IF or any baseband processing. To achieve this, very high performance HTS input and output channel filters are specified.

Referring to Figure 11, the input signal is passed to a low-noise amplifier via an HTS channel filter. The resultant signal is then fed to an image-cancelling mixer operating with a LO frequency equal to the desired transposition. Following power amplification, a second HTS channel filter helps provide a clean output spectrum.

The architecture of Figure 11 is single-channel. For multi-channel operation, a number of HTS filters would be configured in a harness to form a star-point combiner or splitter. Each channel would then be provided with an appropriate frequency changing stage and power amplifier. Note these amplifiers need not be highly linear. Sufficient performance to keep in-band intermodulation within reasonable limits is all that is necessary, since the out-of-band energy is rejected by the HTS filters.

The required performance of the filters will be outlined later.

3.3.3 Hybrid Architectures

Of the two architectures described above, one contains MCPA/DSP components and no HTS, the other HTS but no MCPA/DSP. As such, they represent the extreme cases of what may be achieved with these differing technologies when taken in isolation. Hybrid architectures, utilising all three technologies, are also possible. Indeed, a proposed SATIRE test transposer, to be installed at a trial relay site, employs a hybrid architecture based on that shown in Figure 12.

This architecture is based on the HTS single-channel transposer of Figure 11. The difference is that an MCPA is introduced following the output-side HTS filter, to allow the latter to operate at low power levels. One reason for this is uncertainty over the power handling capability of the HTS filtering, a matter which is still under investigation. Of course, the reduction in the total number of power amplifiers in an N-way system is also an important factor as mentioned earlier.

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Figure 11: Transposer architecture employing high-temperature superconducting filters
3.4 Results

3.4.1 Specifications of HTS and MCPA/DSP components

3.4.1.1 Background
The specifications tabulated below are based on the results of simulations to find the performance levels required from each component to allow the design of a DVB-T transposer capable of performing an adjacent-channel transposition (8MHz) in the presence of an adjacent channel PAL-I signal. The latter is taken as 25dB higher in level than the wanted DVB-T signal at the transposer input.

The transposer is also to be capable of producing an output of +40dBm (10W) per OFDM output whilst receiving an input of –60dBm. For the multi-channel architecture, four channels have been assumed in defining the specifications below.

The minimum isolation between transmit and receive antennas is taken as 75dB, based on measurements taken at existing analogue UHF transposer sites.

The overall performance requirement is defined principally in terms of Equivalent Noise Degradation (END). This is a measure of how far decoding margins have been eroded and is set here at 0.1dB, to allow a number of transposers to be used in cascade. In addition, out-of-band emissions have been constrained to comply with the mask published in the Digital Television Group’s ‘D’ book [8].

3.4.1.2 Specifications for DSP/MCPA architecture
Table 2 specifies a set of performance figures for the key DSP/MCPA and conventional components within the architecture of Figure 10, to allow the criteria above to be met. The particular combination of component performance shown is not unique in satisfying the requirements, and may be revised in practice at the discretion of a system designer as long as the overall requirements are still met.

Figure 12: Hybrid HTS and MCPA transposer architecture intended for technology proving at a test site.
Note that the required 1dB-compression point for the amplifier refers to a third-order system without linearisation. A linearised amplifier of equivalent intermodulation performance (as indicated) at the required output power will suffice.

<table>
<thead>
<tr>
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<th>Specification</th>
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<td>Antenna coupling</td>
<td>-75dB</td>
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<tr>
<td>Input channel filter</td>
<td>none</td>
</tr>
<tr>
<td>MCLNA input intercept</td>
<td>+8dBm</td>
</tr>
<tr>
<td>1st IF filter</td>
<td>3.8MHz half-width, n=9 0.1dB Chebychev</td>
</tr>
<tr>
<td>DSP filter</td>
<td>3.8MHz half-width, -60dB @ 4.0MHz, 0.2dB p-p ripple</td>
</tr>
<tr>
<td>MCPA 1dB-compression</td>
<td>+73dBm</td>
</tr>
<tr>
<td>MCPA shoulder level</td>
<td>-74dBc</td>
</tr>
<tr>
<td>Output channel filter</td>
<td>none</td>
</tr>
</tbody>
</table>

Table 2: DSP/MCPA architecture compatible parameter set (lower-adjacent PAL with offset)

### 3.4.1.3 Specifications for HTS direct conversion architecture

Table 3 specifies a set of performance figures for the key HTS and conventional components within the architecture of Figure 11, to allow the criteria above to be met. The note above about the uniqueness of the solution applies equally here.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input HTS filter</td>
<td>3.8MHz half-width, -70dB @ 4.0MHz, 0.2dB p-p ripple</td>
</tr>
<tr>
<td>Front-end input intercept</td>
<td>-10dBm</td>
</tr>
<tr>
<td>Mixer image rejection</td>
<td>-26dB</td>
</tr>
<tr>
<td>Mixer direct breakthrough</td>
<td>-26dB</td>
</tr>
<tr>
<td>Output amplifier 1dB-comp</td>
<td>+54dBm</td>
</tr>
<tr>
<td>Output amplifier shoulder level</td>
<td>-48dBc</td>
</tr>
<tr>
<td>Output HTS filter</td>
<td>3.8MHz half-width, -70dB @ 4.0MHz, 0.2dB p-p ripple</td>
</tr>
</tbody>
</table>

Table 3: HTS-based direct-conversion architecture compatible parameter set (lower-adjacent PAL with offset)

### 3.4.1.4 Discussion

Notice that the above results refer to the PAL signal as being lower adjacent to the wanted DVB-T signal. This is the more stringent case; for upper adjacent operation the requirement is eased slightly. Notice also an ‘offset’ is called for with respect to the incoming PAL signal (as is usually the case when it is placed lower adjacent). This offset is 167kHz and it allows the HTS filters to reject the incoming NICAM carrier. If no offset is used, the direct-conversion HTS architecture cannot be used in its simplest form. The MCPA/DSP architecture can cope with this condition if additional (fairly straightforward) filtering stages are introduced.

### 3.4.2 HTS hardware

The fundamental element in any filter structure is a resonator. The use of HTS materials allows the designer the freedom in the choice of resonator structures, which can have distinct advantages over a
more conventional design approach. The route taken within the context of the SATIRE project is to adopt a quasi-lumped element resonator, investigate its performance and then to fabricate an initial five pole prototype. The reasoning behind the lumped element approximation is two fold;

1. To have a basic building block that is small and can be readily scaled over the frequency ranges of interest. This precludes the use of any resonant structure, which would be physically too large.
2. To have a stop band that is free of spurious signals at potentially more than twice its fundamental resonance frequency. Once again, this rules out the possibility of a resonant structure.

The basic element is illustrated in Figure 9, and shows a parallel inductor-capacitor structure. If fabricated as a series device, this type of structure forms a simple notch filter. The results for such a device are shown in Figure 13. As can be seen, this yields an extremely narrow and deep filter characteristic which is indicative of a good quality film and of a suitable structure optimised for high Q and low loss. Following on from these successful first devices, a more complex filter prototype has been designed. The mask layout for this five pole design is shown in Figure 14. The measured response of the filter is given in Figure 15. As can be seen, this is an 8MHz wide filter that demonstrates an insertion loss of around 1.5dB (improved samples of the substrate material should reduce this substantially). This structure simply would not function at all if fabricated from normal conductors, and such a narrow filter would require cavity type filter structures to even approach this kind of performance (the filter would then be very large indeed).

The potential of these high performance filters in highly populated spectral regions is obvious. These results demonstrate that extremely effective adjacent channel rejection is realisable in an extremely small structure. This has implications not only in the digital broadcast domain but also in applications such as cellular communications in situations where high power carriers in adjacent channels can be effectively suppressed.

![Figure 13: Measured narrow band response of notch resonator at 60K](image-url)
Figure 14: Layout of the 800MHz five pole prototype quasi-lumped element filter. Filter size is 5cm by 1cm. Fabricated on a LaAlO₃ substrate using Ti-Ba-Ca-Cu-O HTS thin film.

Figure 15: Measured response of superconducting filter.

As discussed earlier, the elimination of rubbing contacts is essential in achieving a high level of reliability from a cryocooler. The cryocooler developed for the SATIRE project eliminates rubbing contact by the use of clearance seals; i.e. the clearance between the piston and the cylinder is controlled down to a few microns. The seal is achieved by supporting the moving cylinder with photo-etched stainless steel suspension springs. These springs provide large axial displacement, but very little radial movement.

A linear motor drives the cylinder along the axis of the piston without imposing any side loads. Because the moving coil is rigidly attached to the cylinder, it is not necessary to use any mechanical drive linkages or dynamic pressure seals.
The cryogenic cooling is produced by pneumatically controlling the phase angle between the compressor and the displacer. The cryocooler operates on a closed thermodynamic regenerative cycle with near isothermal compression and expansion of the working gas (pure helium) at various temperature levels.

The cryocooler developed as part of the SATIRE project utilises state-of-the-art technology and process techniques which combine to produce cryocoolers that are continuously achieving run times of greater than five years.

A diagram of the SATIRE cryocooler and microwave encapsulation assembly is provided in Figure 16. The design of the encapsulation assembly is key in realising a cost-effective solution, and in particular achieving good RF connections with a minimal heat-load on the cryogenic part of the system. The design of this element is one of the key areas of research and innovation within the project.

![Figure 16: Cryocooler and microwave subsystem encapsulation assembly](image)

### 3.4.3 MCPA

Results from a linearised multi-carrier power amplifier are provided in Figure 17 using a broadband noise-like modulation format (in this case, wideband CDMA). This modulation format is similar, in terms of its envelope characteristics, to the OFDM modulation format used in broadcast applications. The results indicate that it is possible to achieve a significant improvement in unwanted adjacent channel energy by the application of a linearisation technique. In the case of the transposer architectures outlined above, this equates to a reduction in the amount of unwanted feedback from the output of the transposer to its input when considering adjacent-channel transposition. This is a significantly more difficult specification to meet than the DVB-T adjacent channel requirement (which is the other determining factor on power amplifier linearity).
Figure 17: Results from a multi-carrier power amplifier with broadband modulation

(a) Unlinearised response of the amplifier
(b) Linearised response of the amplifier
4. Conclusions

4.1 Transposers vs Re-modulators

It has been shown that transposers are likely to represent the optimum solution in terms of:

- **System monitoring requirements**
  
  Transposers will probably require less complex monitoring than re-modulators. This will lead to reduced system size and power consumption and hence lower capital and running costs.

- **Quality of Service**
  
  Transposers will offer a superior performance in terms of recovery time following a network disturbance that causes transport stream synchronisation to be lost. This advantage makes the transposer the only viable option for use in chains of relay stations. Such chains can be required to reach remote locations where the terrain prevents direct reception of the parent station. The re-modulator does offer a level of performance, in terms of decoding margin, equivalent to the parent station. However, it is noted that the proposed Satire transposer specification assumes a Loss of Noise Margin performance of 0.1dB, making it suitable for use in chains of up to five stations.

- **Reliability**
  
  Transposers potentially offer an improved level of reliability due to the higher levels of unit integration that is anticipated. This implies lower running costs due to the reduced amount of maintenance effort required.

- **Cost**
  
  It is anticipated that transposers will exhibit a lower lifetime cost due to a reduction of both capital costs and operating costs. This is due to the smaller size, lower power consumption, and reduced monitoring requirements of the transposer topology.

  The relative cost of demod/remod transposition and DSP/MCPA-based transposition have been examined within the SATIRE project. The results from this study indicate that the hardware cost of the DSP/MCPA-based solution is roughly one third of that of an equivalent demod/remod solution. The effect on the overall installed cost of a rebroadcast station will be less dramatic, due to the other, large, fixed costs in a complete installation. This cost saving is still, however, significant and useful to the operator.

4.2 General Benefits

There are some aspects of the Satire development that would provide benefit whichever design architecture is employed. The most notable example of this is the multi-carrier power amplifier that could be used in both the transposer and re-modulator architectures. The use of such an amplifier can prevent the need for complex low-loss combiner systems and reduce both system complexity and size considerably. The lack of frequency conscious fixed-tune components would also improve system flexibility greatly, perhaps facilitating remotely re-configurable station architectures in both transposer and re-modulator forms.
5. Acknowledgements

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6. References


