# THE RF CHALLENGES OF ATC COMMUNICATIONS

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*Abstract - The backbone of an Air Traffic Control system is the communication network allowing controllers to communicate with pilots. Every civilian aircraft should be able to communicate with any ATC system across the world which leads to unique challenges in establishing and maintaining a standard system. Against a background of enormous growth in air traffic, upgrading a communications system on a worldwide basis with many different stakeholders has and will continue to place considerable demands on the RF parts of the communications networks. This non-mathematical paper will present aspects of the RF performance demanded of ground based ATC radios and the communications systems they are used in.*

## 1. Radios used in Civil ATC

Radios used to communicate between aircraft and the ground have historically never been the same at each end of the link. As a radio was once a bulky and heavy piece of equipment, airborne radios were always designed to be as simple and light as possible with consequently inferior performance. The inferior performance was compensated by superior performance in the ground based radio. Therefore, ground based radios have traditionally been designed and manufactured by specialists in the field leaving the design of airborne radios to avionics specialists. This paper concentrates solely on ground based radios. A typical radio in civil ATC communications has the following parameters:

- Double sideband AM waveform (i.e. simple envelope modulation) carrying voice and data
- D8PSK waveform carrying data
- Frequency range covering 118 MHz – 136.975 MHz in 25 kHz or 8.33 kHz steps
- Transmit carrier power of 50W or less
- Receiver Sensitivity of -107 dBm for 10 dB (S+N)/N

Most radios extend these basic capabilities for particular applications but a generic radio should have at least this level of performance. Standards also state many more requirements which will not be repeated here. Military ATC communications usually uses the higher frequency band of 225 MHz to 400 MHz.

## 2. Structure of civil ATC Communications

Although there are some variations, air traffic control communications infrastructure is divided into the following types:

- Tower (TWR)
- Approach (APP)
- Area Coverage (ACC)
- Oceanic

Whilst taxiing, the aircraft is under the control of the tower which controls the traffic on the ground at the airport. Once airborne, control is handed over to “approach” who manage air traffic into and out of the airport. Finally once clear of the airport, the aircraft is under the control of the “area coverage” service being handed over as it crosses airspaces of different authorities. If the flight is long-haul and involves crossing an ocean, then the aircraft leaves controlled airspace and controls its own flight path. There are agreed corridors and ATC services will be aware which flights are expected to leave and enter their airspace. Communications is still available to an aircraft over an ocean using satellite and/or HF systems but these are used by aircraft owners rather than the ATC providers. The sequence is then reversed as the aircraft approaches an airport. Tower and Approach communications systems are located at the airport. An area coverage sector has a single control centre and remote radio sites. An area coverage sector may serve a single nation’s airspace, but for larger areas, the airspace is divided into sectors each with its own control centre. For example, the UK has two: Swanwick and Prestwick. A larger country will have more. A pilot remains tuned to a single frequency whilst in an area coverage sector and performs a hand-over to a new controller and new frequency as the aircraft moves to a new sector.

### Waveforms Used in Civil ATC

In a world of constantly evolving new waveforms, ATC communications can look rather old-fashioned. There is some use of digital waveforms with data carrying capability in various parts of the world, but general voice communications are carried in forms that have changed little for many decades. Voice communication is mostly carried on double sideband AM waveforms as it has been since the beginning of aviation radio. There are two main reasons for this: firstly ATC is a global system and effecting any fundamental change across the entire world is challenging and costly; secondly the ATC industry is highly conservative never willing to do anything that introduces risk to a working system. It must also be added that AM works reasonably well over long ranges with its soft degradation.

### Handling Voice Traffic

The focus of nearly all technical advances in the past few decades has been on the need to provide reliable communications whilst air traffic and hence the congestion of the airwaves has been growing very rapidly. The most popular solution to increasing congestion has been to reduce channel separation which places more stringent performance demands on the radios and the radio sites. Digital data waveforms which allow some of the information once relayed by voice to be communicated automatically have been used for many years now and free up the crew from relaying much of the mundane numerical data. However, attempts to move the voice traffic to a fully digital system, have been less successful.

The waveforms themselves may be relatively simple by the standards of other communications sectors, but the pressing need to achieve the maximum channel density in difficult co-location scenarios means the engineer’s design effort is focussed on achieving the best possible performance in the following parameters:

- Transmitter Spectral Purity
- Transmitter Noise
- Receiver Selectivity
- Receiver Linearity (for reception in the presence of large interfering signals)

## 3. Waveforms

### Voice Waveforms

In the past, voice communication used a simple AM carrier with 50 kHz separation and a “telephone” audio bandwidth of 300 Hz to 3.4 kHz. This became insufficient in the VHF band of 118 – 137 MHz and so the channel separation was reduced to 25 kHz. This has been the standard for many years now. In order to meet the demand for more channels, the channel separation in many areas has been reduced by a further factor of three to 8.33 kHz. This has the advantage of offering backwards compatibility to older radios which can still use every third channel on the original 25 kHz frequencies. This closer channel separation leaves very little guard band between adjacent carriers and so the audio bandwidth has been reduced to 350 Hz to 2.5 kHz which still gives acceptable voice quality.

### Data Waveforms

To counteract the problems with increasing congestion, one approach is to reduce the burden on the voice channels by handling the transfer of numerical information using an automatic data system. This means flight and aircraft data can be passed quickly as data bursts reducing channel occupancy.

#### *ACARS (using AM Voice Channel)*

ACARS (Aircraft Communications Addressing and Reporting System) has been in widespread use around the world for several decades. As channel congestion is high, it was not possible to designate VHF channels for the sole use of ACARS around the world. So ACARS data was originally carried on a standard VHF voice channel using a modem on the audio lines of a radio. The system uses CSMA (carrier sense multiple access) where a radio listens until a channel is clear before transmitting a burst of data. The ACARS standard defines a binary MSK signal with 1.2 kHz and 2.4 KHz tones with a data rate of 2.4 kbps. In congested regions with high channel usage, it has been calculated that the effective data rate could be as low as 300 bps. Over the years, new uses for ACARS have been implemented and the amount of data being passed has grown as the channel availability has reduced.

*VDL Mode 2/3/4*

In the 1990s a set of truly digital waveforms were agreed internationally by the International Civil Aviation Organisation which provide data communications at much higher rates. These are collectively called VDL (VHF Data Link) and come in several modes. The most widespread VDL mode 2 is based on a D8PSK (differential 8 phase shift keying) signal where the phase of the carrier is shifted between eight discrete phase points. The modulation rate is 10,500 symbols per second giving a data rate of 31.5 kbps (3 bits per symbol). This is over ten times faster than ACARS. Figure 1 below shows a constellation diagram of a D8PSK waveform where the 8 discrete phase points around a circle of constant amplitude can be seen. Although the amplitude is constant at the sample points shown by the red dots, transitions from one phase point to the next deviate from the constant amplitude circle meaning the amplitude of the continuous waveform changes markedly. The peak to average ratio is a little over 3 dB which is actually less demanding on the PA than the 6 dB required by an AM waveform.

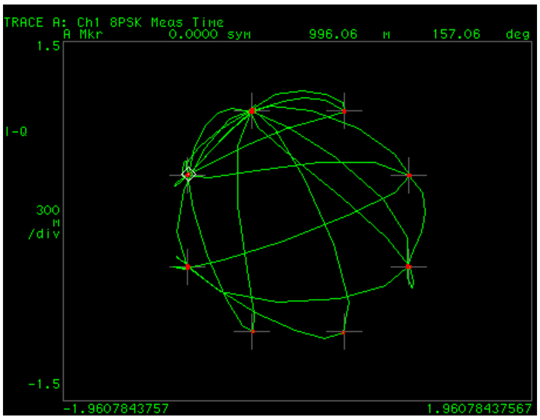


*Figure 1 - Constellation Diagram of D8PSK Waveform*

VDL Mode 2 uses the same access system as ACARS namely CSMA. This mode has achieved quite widespread adoption and is managed by service providers ARINC and SITA. The channel spacing is 25 kHz and the modulation is shaped to achieve spectral efficiency and low adjacent channel interference. VDL Mode 3 was intended to carry up to four channels of voice as well as data. The four channel voice facility was attractive as this gives a slightly higher channel density than the three channels per 25 kHz offered by 8.33 kHz AM Voice. CSMA with its unpredictable timing cannot be used to carry voice so Mode 3 was based on a TDMA system. Unfortunately, the complexity and cost of implementing a TDMA based waveform means that Mode 3 has failed to be adopted as widely as Mode 2 and is now effectively dead. VDL Mode 4 is a TDMA based system that overcomes some of the problems suffered by Mode 3 but is to date, much less widespread than Mode 2.

# 4. Maintaining Coverage

## Over-the-Horizon Systems

VHF communications is largely line-of-sight and radio sites will be placed at intervals to maintain continuous coverage. In some cases it is not possible to place a site where needed either because there is a large body of water such as a large lake or sea within the coverage area or because the ideal location is too costly to access. VHF range can extend beyond the horizon to solve such issues. There are a number of ways in which this happens such as tropospheric scattering, atmospheric refraction and diffraction. Whatever the means, the signal is likely to be significantly attenuated. So all over-the-horizon coverage systems involve the boosting of transmitted power and the reception of weak signals. This requires the use of some or all of the following:

- High Power Amplifiers on Transmitters
- Low-Noise Pre-Amplifiers on Receivers
- High Gain - and consequently directional - Antennas.

Clearly such systems can exacerbate the difficulties associated with interference between radios, so this must all be carefully considered in the system design.

### Offset Carrier Systems

Unlike a broadcast network, an area coverage sector consisting of several radio sites does not use different channels on neighbouring radio sites. This ensures that an aircraft does not have to change frequencies as it flies across a sector. The drawback is that an aircraft is going to suffer fading as it receives signals from multiple transmitter sites all on the same frequency. This problem can be overcome using carrier offset. A small offset in frequency between two carriers would result in a beat frequency that would be heard on the demodulated audio rather than slow fading. However, if the offset is larger than the highest audio frequency, then the beat frequency will be filtered out by the receiver audio stages. It is easy to see from the time domain representation of two signals in Figure 2 that an envelope demodulator would successfully recover the audio from both signals regardless of the different carrier frequencies. The demodulated audio will contain beat notes and these are filtered out by the 300 Hz – 3.4 kHz audio filter.

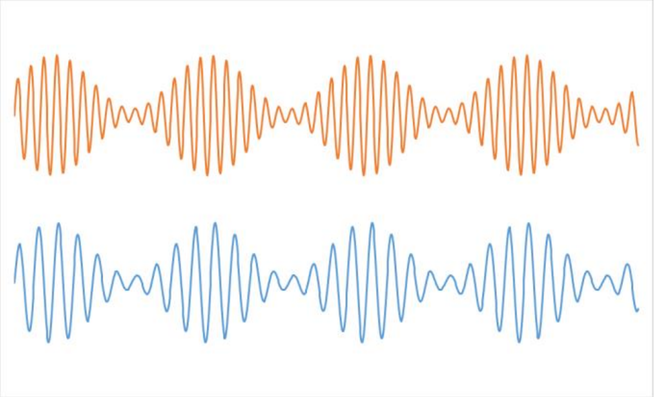

*Figure 2 - Multiple Received Signals with Offset Carrier*

Offset carrier works for the signal transmitted to an aircraft, but the signal transmitted by the aircraft will also be received by multiple receivers. This is handled on the ground between the receiver sites and the control centre using either audio delay or a switching system designed to only pass on the strongest received signal to the controller.

## 5. Designing an Area Coverage Network

The RF challenges faced by Air Traffic Control Communications are best understood by examination of an area coverage network. The network comprises distributed radio sites placed across the region at suitable locations to provide complete coverage. Transmitters and receivers are usually housed at geographically separate sites to reduce channel blocking issues, but transceivers or transmitter/receiver pairs may also be co-located where logistics dictate. Each radio site is linked back to its sector control centre using the public telephony infrastructure. The technology of the voice networks has undergone significant technological update and radios must be able to utilise modern networks. Analogue transmission lines with circuit switching are increasingly giving way to packet switched digital transmission and latterly VOIP (voice over internet).

### Tx Power and Rx Sensitivity

The area coverage planner is dealing with unknowns such as the transmit power of the airborne radio, the gain of its antenna and the atmospheric conditions. Fortunately, there are guidelines and assumptions provided by ICAO (International Civil Aviation Organisation) to provide a basis for the systems engineer to plan signal strength and range. It is not in the interests of the customer to simply maximise transmit power and receiver sensitivity for maximum range if this leads to co-location issues, therefore, transmit power will be reduced to a suitable level where necessary and receivers can trade reduced sensitivity for increased linearity.

### Co-Location Issues

Once sufficient transmitter power and receiver sensitivity have been ascertained to facilitate the required service area, the next challenge faced by the engineer is co-location of radios.

# 6. Radio Sites

### Safety

The ATC community is highly risk-averse which goes some way to explain the excellent safety record it enjoys considering the sheer volume of air traffic worldwide. Several aspects of a radio site's design reflect this.

#### *Redundancy*

Duplication is widely used in such a safety critical system and so radios are frequently deployed in "Main" and "Standby" pairs and radios have a "BIT" (built in test) system allowing them to automatically switch to another radio in case of failure. As a further safety measure, many site operators designate the two radios in a pair as "A" and "B" rather than "Main" and "Standby" so that each can take a turn at being the main radio on designated "A days" and "B days". This ensures that a failed standby radio does not go unnoticed until the day its main radio fails and neither works!

A radio site being remote from the control centre is critically dependent on the communications link carrying the voice traffic from the radios to the controller's desk. The link is usually duplicated to mitigate potential failure.

#### *Backup Power Supplies*

Radios used in ATC have historically operated from both AC mains and a 24V DC battery backup supply to provide continuous operation when the mains supply has failed. This can be a frequent occurrence in some parts of the world.

#### *BIT (Built-in-Test) and Radio Monitoring Systems*

In area coverage, radio sites are located at locations across the sector to provide full coverage. Therefore, they are mostly remote from the control centre and often located well away from populated areas where access may be difficult. Therefore, radios and other equipment must be able to automatically handle failures. If a critical failure is detected, the radio must signal this externally. This allows the failed radio to be shut down and its partner in a main/standby pair is then brought into service.

### Combining Systems for Antenna Sharing

#### *Relays*

A radio site can be configured in many ways depending on the number of radios and the number of antennas they have to share. Sharing of an antenna may be achieved with simple relays in the case of transmitter/receiver pairs or main/standby pairs on the same channel.

#### *Filters and Tuned Length Cables*

When radios on different frequencies share an antenna, a more complex arrangement is required especially as there will be simultaneous transmissions and receptions on different channels. To sufficiently isolate the radios from one another, a system of cavity filters is used as shown in Figure 3. In this simple two radio system, the length $L_1$ is chosen so that at the combined point the upper radio and cavity filter appear as an open-circuit at the frequency $f_2$. This means the lower radio operating at $f_2$ is unaffected by the presence of the other radio. Similarly, $L_2$ is chosen so that the lower radio and filter appear as an open-circuit at the upper radios operating frequency $f_1$. These two radios can now share the antenna without affecting each other. The frequencies $f_1$ and $f_2$ must be far enough apart that they are sufficiently isolated by cavity filters. This process can be repeated for larger numbers of radios but becomes increasingly difficult to achieve as more radios are added to the system and four is the limit in practice although higher numbers have been achieved.

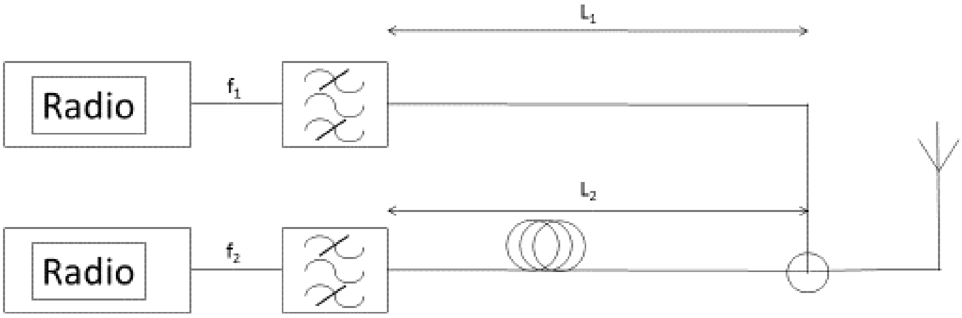


*Figure 3 - Tuned Length Filter Combining*

## 7. RF Challenges

### Mitigating Co-Location Issues

The close proximity of multiple radios in a single site is probably the greatest challenge. Radios can interfere with each other in a number of ways which all have the effect of blocking or degrading channels.

#### *Filtering*

Filtering is perhaps the most obvious way of isolating radios operating at different frequencies. However, the congested ATC spectrum can often demand very high-Q filters operating at high RF power. For these reasons cavity filters are the preferred choice. Cavity filters will often comprise two or three individual filters in series to obtain the required selectivity. Individual cavity filters can cost several hundred pounds each and take up significant rack space.

#### *Circulators*

Circulators are used in the ATC radio environment to ensure any interfering signals or reflected signal are prevented from flowing back into a transmitter as shown in Figure 4. This protects the transmitter from the effects of a mismatched antenna but also prevents interfering signals from other transmitters entering the RF output of the transmitter where further unwanted signal frequencies can be generated by intermodulation.

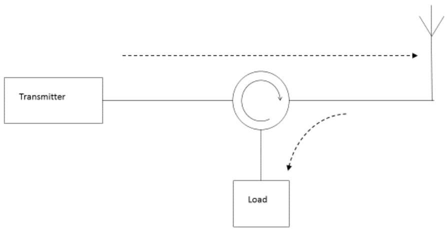


*Figure 4 - Transmitter Protected with a Circulator*

### Basic Radio Performance

Both cavity filters and circulators can be highly effective at allowing a number of radios to operate together within a congested part of the RF spectrum. However, both of these devices are expensive and would only be used when absolutely necessary. If the inherent performance of the radio can be optimised, the cost savings realised from having fewer filters and circulators can be considerable. This need to keep down the cost of associated costly components is one of the main drivers for the RF designer.

### Receiver

There are several key ways in which the presence of signals on other channels can degrade the performance of an AM receiver. These are intermodulation, cross-modulation and de-sensitisation.

They are all linked and usually have a fixed relationship between them but are considered and tested individually.

#### *Intermodulation*

Intermodulation occurs when two or more frequencies are incident upon any non-linear device. Figure 5 shows a classic frequency domain view of the process. Two unwanted signals at frequencies $f_1$ and $f_2$ produce a host of other signals at frequencies at the sum and differences of integer multiples of $f_1$ and $f_2$. The odd-order products are of most concern as they occupy channels close to the original signals. Figure 5 shows the third-order intermodulation products which are usually the closest and the largest signals as well as the fifth order which are the next closest and largest. There will be higher orders too getting progressively further away and weaker. The issue is that two signals generate further signals that can block other receiver channels rather than just those occupied by the transmitters themselves.

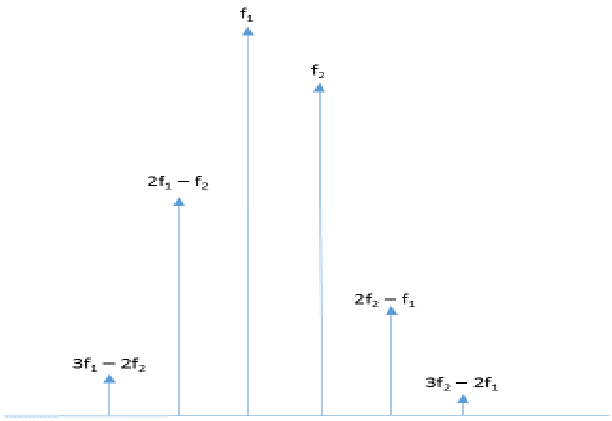


*Figure 5 - Receiver Intermodulation*

#### *Cross-Modulation*

Cross Modulation is a phenomenon that is most pronounced in AM systems (or signals with some AM component in them). This process occurs when a strong off-channel signal is incident upon a receiver front-end. The process can be visualised as the AM on the interfering signal causing small perturbations in the receiver gain as it swings between low and high power. These gain perturbations will modulate any wanted signal so transferring some of the AM from the interfering to the wanted signal. As with intermodulation, this effect can be reduced by improving the linearity of the receiver or attempting to reduce the level of the interfering signal through filtering.

#### *De-Sensitisation*

A large signal can reduce the gain of a receiver so reducing its sensitivity to weaker signals. It is important to differentiate this phenomenon from that caused simply by noise from the interferer at the wanted frequency. Again, this type of degradation can be improved with enhanced linearity in the receiver or by attempting to reduce the level of the interfering signal with filtering.

### Transmitter

#### *Spectral Mask*

Any transmitter will not only produce RF power in the wanted channel, but some power will inevitably spill over into neighbouring channels. The amount of spill-over tends to reduce at greater offsets from the wanted frequency. This places a limit on the frequency separation of radio channels and so reduces the number of radio channels available for use in the band. Figure 6 shows a receiver channel being swamped by the off-channel noise generated by a transmitter. There are two distinct sources of the unwanted power in neighbouring channels: phase noise and distortion. Broadband noise is generated by the oscillator source and the RF chain in the radio and tends to dominate at the larger offsets from the carrier. Close in to the transmitted carrier, distortion tends to dominate as non-linearities in the RF chain in the radio generate unwanted extra frequencies which spill over into neighbouring channels. Clearly any receiver tuned to a channel affected by the spectral mask of a nearby transmitter is going to fail to receive weaker signals.

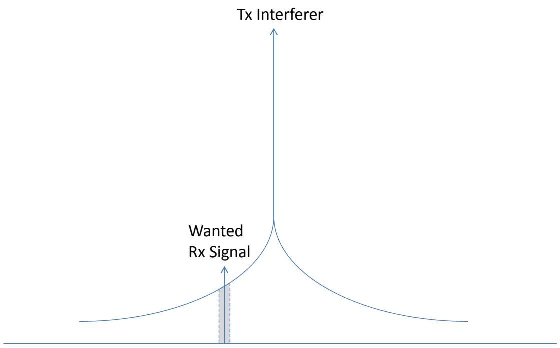


*Figure 6 - Effect of Tx Spectral Mask*

### *Broadband Noise*

The spectral mask of a transmitter eventually flattens out away from the carrier to a fixed noise level called the Broadband Noise. This noise level generated by the transmitter can still be higher than the background noise seen by a receiver at some distance away and so impairs the receiver's ability to detect weak signals. In effect, a transmitter raises the noise floor at the receiver.

### *Reverse Intermodulation*

Reverse Intermodulation is a process in which two carriers generate further frequencies through non-linearity. However, rather than occurring in a victim receiver, this occurs in the output stage of a transmitter. Figure 7 shows the process. The transmission from the transmitter at $f_1$ is received at the second transmitter which is producing a carrier at $f_2$. As the output stage of the transmitter is operating in large-signal mode, it is much more non-linear than a receiver front end and $f_1$ and $f_2$ intermodulate to produce a third unwanted signal at $2f_2$-$f_1$. There will be other frequencies too but this is almost certain to be the largest. The unwanted signal is then transmitted from the antenna along with the wanted signal. As shown in Figure 7, if a victim receiver happens to be tuned to the same frequency as $2f_2$-$f_1$, then it will be blocked from receiving the intended signal. Unlike intermodulation that occurs in the receiver, attempting to filter out $f_1$ and $f_2$ will not improve the situation as $2f_2$-$f_1$ has been generated remotely by the transmitter and now falls onto the wanted channel to which the filter is tuned.

This is a much more insidious type of interference as it not possible mitigate this problem at the receiver, it can only be dealt with by filtering at the transmitter site.

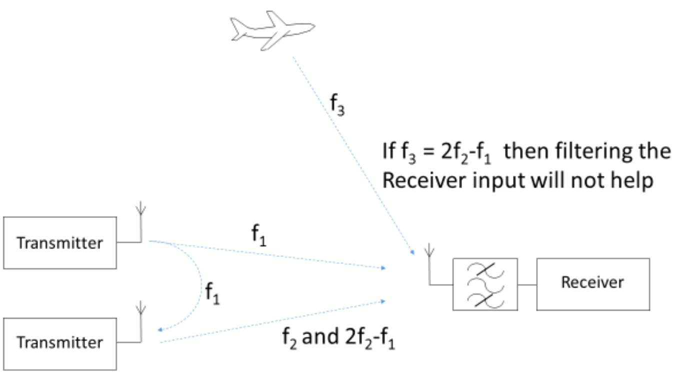


*Figure 7 - Reverse Intermodulation Effect on a Receiver*

# 8. Reverse Intermodulation

A particular real scenario was assessed during a former project and each of the principal co-location issues was quantified. This scenario showed that Transmitter Reverse Intermodulation was the strongest cause of channel blocking. As it will be shown, none of the techniques available to reduce reverse intermodulation are particularly attractive as they will always add considerable cost to a system.

### *Filtering*

Looking again at Figure 7 it can be seen that a band-pass filter between Transmitter 2 and its antenna tuned to $f_2$ would reduce the level of $f_1$ and the third-order intermodulation product at $2f_2$-$f_1$ would reduce by a corresponding amount. This is certainly effective but there are two drawbacks to consider:

- The filter would need to be able to handle transmit power levels of at least tens of Watts so would need to be an expensive and bulky cavity filter to have reasonable selectivity.
- The use of filtering relies on a good frequency separation between $f_1$ and $f_2$ to ensure the unwanted product is well into the filter stop-band to maximise its attenuation. This separation reduces the number of channels available for use in a congested spectrum.

### *Circulators*

RF circulators as shown in Figure 4 would seem to offer the ideal solution to the issue of Reverse Intermodulation as well as providing the benefit of mismatched load protection to a transmitter. However, circulators at the relatively low frequencies of the VHF ATC band are generally larger and more expensive than those used at microwave frequencies. The added expense of a circulator cannot usually be borne in what is a price-sensitive market. So circulators are used, but usually outside the radio and only when no cheaper alternative is available.

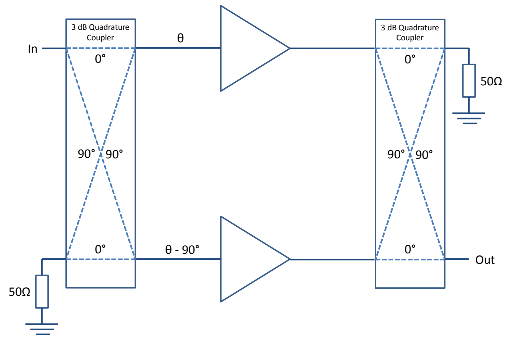


*Figure 8 - Balanced Amplifier*

### *Balanced Amplifier*

A balanced amplifier is shown in Figure 8. This consists of two identical amplifier stages. The input signal is split into two equal amplitude signals but with a 90° phase shift between them. The output is combined by a similar network that applies a 90° phase shift to the other branch bringing the two signals back into phase. The balanced amplifier has a very beneficial feature that any signal reflected from the inputs or the outputs of the two gain stages is directed mostly to the dummy loads. This means the apparent return loss (and hence match) of the input and output of the amplifier appears to be very good. It can be relatively easily shown that an interfering signal incident at the output of a balanced amplifier will generate a reverse intermodulation product that is also directed to the dummy load and not back out of the antenna. A very considerable improvement in reverse intermodulation is possible this way (30 dB typically). The balanced amplifier is a very attractive solution to the problem of reverse intermodulation as it does not rely on expensive and bulky extra items such as circulators and filters. However, using two devices rather than one, especially at power levels where one device is quite sufficient does add cost and size to a PA, both of which proved to be unacceptable for our market.

### Understanding Reverse Intermodulation in a PA

During recent design work, the requirement arose to understand the causes of reverse intermodulation in an RF PA and to attempt to enhance this aspect of the PA's performance at source rather than relying on external devices or costly topologies. Various possible sources were investigated. The chief difference between a transistor used in a PA and that in a small signal amplifier is that the RF output signal can easily cover the whole range of drain voltages from peak-to-trough. The transistor contains a number of parasitic capacitances which all have a voltage variable capacitance. This makes the transistor output non-linear and the large signal can actually be viewed as the local oscillator driving a mixer. When a smaller unwanted signal enters the output of the transistor, other frequency components equal to the sum and difference of the various harmonics of the wanted signal (the LO) and the unwanted signal (the RF) will be generated. As shown in Figure 5, the product resulting from the difference between the second harmonic of the wanted signal and the first harmonic of the unwanted signal is of the most concern being close-in. Adjusting the level of the unwanted signal in 1 dB steps confirms that the main intermodulation product does indeed change by the same amount as the unwanted signal. So the fixed ratio of the unwanted interfering signal and the intermodulation product is analogous to the action of a mixer and can be thought of as conversion loss. This conversion loss is surprisingly constant over a very wide range of unwanted signal levels. Several possible hypotheses were tested in a standard push-pull amplifier to try to understand the dominant effects on reverse intermodulation. These were: drain-to-gate feedback; ferrites; low frequency impedance of bias and supply networks and device symmetry. These will not be dealt with in detail here, the investigation may be the subject of a future paper. Suffice to say, all of the hypotheses proved to be false (or at least not significant) with the exception of device symmetry. The role of symmetry in reverse intermodulation can be understood by the fact that a push-pull amplifier design tends to reduce even-order harmonics. The signals in each side of the push-pull transistor are 180° out of phase due to the use of baluns to split and combine the RF signal. The second harmonics are actually in-phase and so cancel in the output balun. As the reverse intermodulation product is dependent upon the second harmonic of the wanted signal, the better the cancellation of even harmonics, the better the reverse intermodulation performance. Giving close attention to the performance of the baluns and ensuring the circuits on each side of the push-pull transistor are well matched can bring significant improvements in performance. Improving the overall linearity of the transistor by backing-off the signal output is also very effective but this must then be traded-off against the need for efficiency and cost-effectiveness, both of which deteriorate when the potential output power of a transistor is not fully used.

## 9. Conclusions

The main challenge around RF communications in civilian ATC systems concerns co-location. Congestion is growing and likely to only get worse in the foreseeable future. Although channel congestion is not unique to ATC communications, the extreme conservatism of the industry is a considerable impediment to deploying some of the more sophisticated solutions that are available to other industries. Increasing channel congestion problems are probably most likely to be met in the near-term by continuing to improve the RF performance of the radios themselves and of the radio sites. Many of the solutions to achieve acceptable operation in a congested spectrum can involve the addition of expensive and bulky items at radio sites, improving the radio's inherent RF performance can reduce the need for such items and yield an overall reduction in “cost per channel”. Reverse Intermodulation has been identified as a key area for performance improvement.

## 10. Acknowledgements

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