Radio-frequency interference to automotive radar sensors

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Abstract: Cases of interference between pulsed radars, frequency-modulated continuous wave and noise-modulated automotive radars at frequencies around 24 and 77 GHz are considered, and it is shown that pulse- and frequency-modulated waveforms are very robust to interference from each other if the radar receiver is properly designed. Noise modulations are much harder to handle efficiently. Interference from other sources and the potential for deliberate jamming are also considered.

1 Introduction

The problem of interference to automotive radars has been recognised for many years [1, 2] and it is often believed that as the uptake of automotive radars increases, and with it the issue of mutual interference between them, the problem is becoming more serious and should be addressed more seriously. The 2017 European Radar Conference also had a workshop dedicated to automotive radar interference and modulation schemes.

There is also the problem of deliberate interference in the future to radar sensors used to support higher levels of autonomy, the consequences of which could be very serious. Although the potential problem of deliberate interference with such sensors is unlikely to be significant for many years, but the issue should be considered now, in the early design phase if the systems are to be designed to be robust from their foundations.

It should be noted, however, that the potential for interference was in fact considered when existing long-range automotive radar sensors were first designed, more than 20 years ago, though there was no cause at that time to publish the work. Many of the recent, albeit informal, statements which imply that the issue will not then considered are incorrect.

This paper will first discuss the mechanisms, whereby signals which enter the front-end interfere with the operation of the radar, and will then consider some of the quantitative aspects. The next section will discuss how robust current sensors are to interference and what further work actually remains to be done in this field.

This paper considers interference between all these waveforms, interference by inadvertent interference and deliberate jamming. It will concentrate on cases where the different signals are in the same band as this is the most complex case to analyse. It should, therefore, be borne in mind that the probability of interference occurring will be reduced by the ratio between the bandwidths of the signals and that of the frequency band allocated to the radars. It should be noted that it is a matter of chance whether the spectra of an individual radar and an individual interferer overlap, but the situation can be randomised for an individual case if the radars are made agile across their frequency allocation, though the decision to do so will not be automatic as it may significantly increase the cost of the transceiver. It will be noted that the general form of the interference into frequency-modulated continuous wave (FMCW) radars has been shown in [1], though that contained no quantitative information on the probability of interference. That paper implied that blanking to suppress the interference was already known, but was not adequate for suppressing interference in automotive scenarios. The blanking technique was also described in [3]. This paper contends that the more sophisticated techniques discussed in [1] are not actually required. About 10 years later, Brooker [4] extended the analysis to consider pulse radars and included some quantitative results showing that the probability of interference appearing within the radar’s indicated range swathe is low. This paper extends the analysis by considering a wider range of automotive radar types and other types of interferences, as well as deliberate jamming and draws some general conclusions about the interactions between the different radar types.

2 Interference to signals

2.1 Radar types

This paper will consider two types of sensors – a typical current long-range autonomous cruise control (ACC) sensor operating at 77 GHz with a narrow beam and a short-range radar (SRR) working at 24 GHz with a broad beam.

The 77 GHz ACC sensor will be assumed to have a beamwidth of 5°, a range resolution of 1 m (150 MHz bandwidth), a waveform repetition rate of 10 kHz, a mean transmitter power of 10 mW and a maximum indicated range of 300 m (a range swathe of 2 µs in time).

The 24 GHz SRR sensor will have a beamwidth of 40° in azimuth by 20° in elevation and a maximum indicated range of 50 m (a range swathe of 330 ns), but its other parameters will be assumed to be the same as the ACC radar.

The ACC radar is assumed to have a noise figure of 3 dB, defined by a low-noise radio-frequency (RF) preamplifier. The radar will thus have a modest image-rejection capability to reject image noise from the preamplifier (or from interference), but this is assumed not to be good enough completely to reject interference from image frequencies – its rejection of the image need to be only of the order of 10 dB to reject image noise.

The simpler SRR is assumed to have no preamplifier, so its noise figure will be assumed to be 10 dB and it will be susceptible to interference at the image frequency.

The equivalent noise power at the front end of the receiver in the 150 MHz bandwidth of the signal will be about −89 dBm for the ACC radar and –82 dBm for the SRR.

The assumed beamwidth of 5° at 77 GHz gives an effective aperture of about −30 dBm² and would give a gain of about 29 dB.

The beamwidth of 40° by 20° 24 GHz gives an effective aperture of about −35 dBm² so that, other things being equal, the long-range ACC radar is more susceptible to interference,
If we assume that the mean power is 10 dBm, the peak power of the waveform and noise-like (continuous pseudo-random) waveforms. especially in view of its lower-noise figure and the limitation in dynamic range caused by the low-noise amplifier before the mixer. Taking account of the larger aperture and lower-noise figure of the ACC radar, it will be about 12 dB more sensitive to interference than the SRR.

### Table 1

| Waveform   | Mainlobe/ sidelobe, dB | Interference path, dB | Sidelobe/ mainlobe, dB | Processing gain, dB |
|------------|------------------------|-----------------------|------------------------|---------------------|
| pulse      | 102                    | 82                    | 62                     | 0                   |
| pulse      | 80                     | 50                    | 30                     | 22                  |
| FM/CW/noise | 60                     | 40                    | 20                     | 52                  |

2.2 Waveforms

Whilst the potential range of modulations which can be used for automotive radars is very wide, most automotive radars currently use FM/CW modulations [5–7]. The analysis of interference will consider radars using three modulation schemes: pulses, FM/CW and noise-like (continuous pseudo-random) waveforms.

2.2.1 Pulses: The waveform translates to a pulse width of 7 ns, and the pulse repetition frequency (PRF) may be taken as 10 kHz. If we assume that the mean power is 10 dBm, the peak power of such a waveform would have to be 142 W (51.5 dBm). This is impractically high, but will still be considered because simple pulse signals are a canonical waveform and the analysis of a simple pulse waveform will provide insights into how more complex waveforms behave. A higher PRF, as assumed in [4] will reduce the peak power, but will also reduce the time-bandwidth product of the waveform and increase the probability of interference, which is unhelpful when considering this ‘canonical’ waveform.

The analysis will also consider a more practical waveform with a peak power of 1 W, again with 10 kHz PRF. To obtain the required mean power and resolution, the pulse length must be 1 µs and it must have a modulation bandwidth, typically a linear chirp, of 150 MHz so the time-bandwidth product of the waveform will be 150. Of course to detect targets at shorter ranges than 150 m, the pulse-compressed radar will have to be able to either receive whilst it transmits or to process partially eclipsed signals, but that is a ‘detail’ which this paper does not consider.

2.2.2 FM continuous wave: The FM/CW radar will be assumed to use homodyne detection, so the intermediate frequency (IF) signal is a set of beat frequencies, each frequency being proportional to the range to a different target in the range swathe. It is noted in passing that [8] shows that such a receiver is equivalent to a matched filter. The waveform will be a linear chirp over 150 MHz and the duration of the waveform will be assumed to be 1 ms, so the noise bandwidth after detection will be 1 kHz. The time-bandwidth product of the waveform will be 150,000 (52 dB). Of course, the peak power of this waveform is the same as its mean power, 10 dBm.

2.2.3 Noise waveforms: The ‘noise’ waveform will behave in the same way as, for example, random binary phase shift keyed (BPSK) modulation or other modulations of a similar form using more complex phase and amplitude modulation constellations. It will be seen to be potentially significant that waveforms such as BPSK which employ only phase modulation have a nominally constant amplitude which may reduce the effect of interference from such waveforms under some circumstances.

The waveform will again have a bandwidth of 150 MHz and duration of 1 ms, so the noise bandwidth after detection will be 1 kHz such as the FM/CW waveform. The time-bandwidth product of this waveform will again be 150,000 and the peak power of this waveform is again the same as the peak power, i.e. 10 dBm.

2.3 Interference levels from radars

The worst interference occurs when the radars are in the closest proximity, but in the near field the power density does not increase significantly as the range decreases, so the separation to consider is either the start of the far-field region of the antennas or else the minimum likely separation of the sensors, whichever is greater.

The start of the far field of an antenna may be simply approximated as the range where the far-field beam width is equal to the width of the aperture, i.e.

\[ r_{ff} \theta = d \]  

where \( r_{ff} \) is the range of the far field, \( \theta \) is the beamwidth and \( d \) is the width of the aperture. Taking the approximation that

\[ \theta \approx \lambda d \]  

where \( \lambda \) is the wavelength, then

\[ r_{ff} \theta \approx \lambda d^2. \]  

The far-field width for the 77 GHz ACC radar can thus be taken as 0.5 m and for the SRR only a few centimetres. The closest range for an interfering radar will be the separation to the nearest vehicle, which will be about 10 m longitudinally, which is applicable to the ACC and 1 m laterally, which is applicable to the SRR.

For the mean-power ACC radar, the worst-case interfering power will be −29 dBm. For the SRR it may be −21 dBm. Given that the ACC radar as a noise figure which is 7 dB lower than that of the SRR, the ratio of interference-to-noise ratio will be almost the same for both systems. Given the uncertainties in being able to estimate the dynamic ranges of the receivers a priori and that the simpler SRR radar front end will be able to handle slightly stronger signals at its front end than the more complex ACC receiver, the large signal handling properties of the two radar types can also be considered to be the same so that, in general, the detailed consideration of the effects of mutual interference between radars need to only consider ACC radars and can assume that the SRR radars will behave similarly.

It will be noted, however, that the calculations above assume the worst case where the mainlobe of the radar antenna is aligned to the mainlobe of the antenna. If the antenna sidelobes are perhaps 20 dB below the mainlobe, then the level of mainlobe/sidelobe interference will be 20 dB below the mainlobe/mainlobe interference and the sidelobe/sidelobe interference levels will be 40 dB lower. About −20 dB might seem a relatively modest sidelobe performance, but is probably typical of the relatively simple automotive radar antennas. Table 1 shows the various interference levels.

The interference-to-noise levels are quoted in the total signal bandwidth of 150 MHz. This level will be reduced for mismatched waveforms by the processing gain (time-bandwidth product) of the waveform.

The geometry of ACC systems, looking along the road, mean that mainlobe/mainlobe interference will be the most common case with the radars of vehicles travelling in opposite directions looking straight at each other. Sidelobe interference will be more common for SRR radars.

2.4 Interference to pulse radar signals

2.4.1 Inadvertent interference: Characteristics of interference: The interference standards do not define the temporal or amplitude characteristics of radar interference. A very basic radar design assumption is that the background is noise with a Rayleigh power distribution. In fact, it can be shown that providing the radar has been well-designed Gaussian noise can be assumed as a worst case [9]. We may assume that the radar receiver's detection follows something such as the scheme shown in Fig. 1.

This general scheme will apply to all types of radars, in our case to FM/CW and noise radars as well as pulse radars. A well-
design a radar can try to ensure that this ideal is approached by the careful design of its detection scheme. It will contain a constant false alarm rate (CFAR) system that will try to maintain the required false alarm rate both when the mean level of the background changes and also when its amplitude distribution changes. If the background ‘noise’ is contaminated with interference which is less variable than noise, then a well-designed CFAR system will be able to estimate the statistics of the ‘noise’ and can set its detection thresholds appropriately, since less ‘headroom’ is needed to account for the fluctuations in the background than would be the case for noise. In the extreme, CW interference, which adds nothing to the variance of the background, need not lead to any increase in the detection threshold.

At the other extreme, impulsive interference such as is typical of much electronic interference and of some deliberate jamming and which is only intermittently present, is best rejected by correlation from sample to sample. This is lossy as a detection scheme, but is very robust to unexpected interference and is, therefore, a good technique to improve the practical robustness of the radar. A ‘classical’ way of achieving this is by a binary integrator which demands at least ‘M’ detections from ‘N’ measurements in order to declare a target. In practice, this may be achieved by other means than an explicit integrator such as by the tracker, where a track need not be updated from each measurement if a detection is not made and where a new track will not be initialsed on a single detection.

The form of noise which cannot be mitigated by these means is Gaussian noise. We may, therefore, assume as a worst case that the background ‘noise’ is contaminated with interference which is less variable than noise, then a well-designed CFAR system that will try to maintain the false alarm rate (CFAR) system will be able to estimate the statistics of the ‘noise’ and can set its detection thresholds appropriately, since less ‘headroom’ is needed to account for the fluctuations in the background than would be the case for noise. In the extreme, CW interference, which adds nothing to the variance of the background, need not lead to any increase in the detection threshold.

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The form of noise which cannot be mitigated by these means is Gaussian noise. We may, therefore, assume as a worst case that the interference may be treated as Gaussian noise.

It may also be noted in passing that interference from a well-designed communication system will also tend toward having Gaussian statistics because this produces the most efficient way of transmitting information [10] because it is the least ‘predictable’ waveform.

It may also be reported in passing that the M/N binary integrator can also be implemented by taking the M’th strongest out of the N samples of the signal before detection. This approximately as effective as detection followed by binary integration, but has certain other advantages [11]. Such a scheme was certainly used many years ago to reject impulsive interference generated by the fuel injectors in the vehicle engine and entering into the ‘back end’ of automotive radars.

There are two standards for interference against which the performance of the radar may be measured: MIL-461 and International Telecom Union (ITU)-R SM 239-10. MIL-461/MIL-461 is the American military standard for electromagnetic compatibility. The latest version is MIL-461G [12]. It specifies a maximum radiated interference level of 69 dB µV m⁻¹ at 18 GHz for equipment in land vehicles which is not shielded by the body of the vehicle. This is the flux density to which a radar aperture may be exposed. The specification does not extend above 18 GHz and rises with frequency up to that point. As the number of sources of interference decreases at millimetric frequencies, so does their mean-power output, a useful comparison would be to assume that this field strength also applies as a limit up to 77 GHz.

A field strength of 69 dB µV m⁻¹ corresponds to a power flux of 22.3 dBm m⁻². The power into the receiver of the 77 GHz ACC radar will be about −7.5 dBm. The first point to note is that this level of input power is not likely to damage the receiver. If the radar includes a preamplifier with 20 dB gain, the interference at the output of the preamplifier may, however, in the worst case exceed 10 mW and so may overload the preamplifier and the subsequent mixer.

As noted above, the worst case as regards degrading the sensitivity of the radar is if the interference is noise like. In this case, the worst case also occurs when the bandwidth of the interference matches that of the signal. For ACC radar, the receiver-noise power will be about −89 dBm. The interference will thus be about 80 dB above the thermal noise, effectively blinding the radar even if the interference does not overload the receiver. Overloading may also occur before the receiver mixer due to signals which are outside the bandwidth of the signal, but within the bandwidth of the receiver. Hence, though a limiter to protect the receiver from damage is not necessary, front-end RF filtering might become worthwhile to protect the receiver from interference from out-of-band signals.

The interference level into the SRR will be about −12.5 dBm which is about 70 dB above the noise which will also effectively blind the radar. Although this radar is less likely to be overloaded by the interference, and thus less susceptible to out-of-band interference, though such blocking is still possible.

Of course, the equipment is expected to function in the presence of interference at any frequency. Signals outside the band of the radar may be assumed not to enter through the ‘normal’ receiver path and the radar must be designed to operate in their presence using normal electromagnetic compatibility design techniques, a subject which is outside the scope of this paper.

Spurious emissions: The ITU specifies [13] that the out-of-band emissions from any device should not exceed −43 dBm/Hz. For a single emitter at a range of 10 m, the power density at the automotive radar receiver will be −74 dBs/mHz². For a signal bandwidth of 150 MHz, this will be a power flux of 8 dBm/m², so the noise power entering the ACC receiver will be −22 dBm. It is noteworthy that this level is only about 15 dB below the military standard level. It will degrade the sensitivity of the ACC by roughly 65 dB and of the SRR by about 50 dB, effectively disabling the sensor, but probably not blocking the receiver mixer of the ACC radar.

The calculations above suggest that spurious emissions from other sources may disable automotive radars. It should be noted, however, that the effect is probably less severe than it might appear because the dynamic nature of the automotive environment means that any such interference will be short lived, leading to only temporary dropout of the signals which the system can ‘ride through.’ The difficulty of generating millimetric signals also suggests that the chances of a device producing spurious emissions at the ITU limit are quite small.

Whilst there is likely to be more than one device in the vicinity of the radar, the one device which is closest to the radar will dominate the interference, especially as the interference from devices further from the radar is likely to travel to it via indirect propagation paths which will have a greater loss.

2.4.2 Interference from pulse radars: For simple pulse radars, the peak level of the interfering radar entering another radar will be about +13 dBm. This will overload the receiver and is on the verge of damaging it. Assuming, however, that the only effect of overloading is to clip the interfering signal and that the PRFs of the interfering and victim radars are approximately equal, there is a probability of only 2 μs/100 μs, i.e. 2% that the interfering pulse will appear within the indicated range swathe and thus be ‘seen’ at all. If it is seen, then the nominal signal-to-noise ratio of the interfering pulse will be about 100 dB as shown previously in Table 1.

The solution which has long been used for suppressing of pulse interference into pulse radars is to jitter the PRF of the radar, so the interference moves in time relative to the pulse transmitted by the radar, so that it does not correlate from PRF to PRF and is rejected in the M/N stage of the detection process (Fig. 1). The chance of a pulse appearing in any one range cell is the ratio of the range cell width to the ambiguous range. This may be equated with the time-bandwidth product of the waveform, where the ‘time’ is the ambiguous range rather than the width of the pulse. In this case, the
product is 15,000. This means that there is only a probability of $7 \times 10^{-5}$ that the interfering pulses will correlate and lead to a spurious detection. In a likely worst case where there are 100 interfering radars, there is a $<1\%$ chance that two pulses will be correlated, and a probability of $\sim 1 \times 10^{-4}$ that they will correlate within the indicated range swathe.

Since the maximum indicated the range of the SRR is only one sixth that of the ACC radar, but the PRFs of the radars are the same, the chance of a correlated false alarm appearing within the indicated range swathe is six times lower for the SRR.

Note that a spurious detection is generally a ‘safe’ or ‘right side’ failure in that unlike a missed detection it will not lead directly to a collision with the missed object, but even the least severe case the user will be inconvenienced by the vehicle taking measures to avoid an object which is not there. In the worst cases, this avoidance might take the form of an emergency stop, which might itself cause a collision, or it may deliberately hit another object to avoid the ‘phantom’, so spurious detections cannot be ignored.

In the case of the modulated pulse, the peak interference into the receivers will be $\sim 9$ dBm which will not damage the receiver, but may still overload it. If the same waveform is used by the interferers and by the receiver, then, if the effects of overloading are ignored, the signal will compress perfectly and the behaviour will be the same as for a simple pulse with one difference: because the interfering signal is weak, as the interference will be well above the noise. The CFAR system will probably prevent these from causing false detections, but it will suppress the sensitivity, perhaps by 30 dB, within the length of the expanded pulse. If such a pulse occurs, then there is, as discussed above, $\sim 2\%$ chance that the interference will appear within the indicated range swathe. It will then obliterate about half of this swathe. There is thus about $1\%$ probability, i.e. about the ratio between the expanded pulse width and the unambiguous range, that a particular section of the range swathe will be suppressed. It can no longer be argued that the system can cope comfortably with 100 interferers because the probability of a particular swathe being blocked on a single swathe is about 100%. With 30 interferers, the probability is about 30% and the probability that two sections of interference will overlap on successive PRFs will be about 10%, so the probability of blocking of part of the indicated range swathe on two successive PRFs will be of the order of $10^{-4}$. Hence, the system will be able to cope with at least 30 interferers.

If the waveforms of the radar signal and the interference are different, then the waveforms will not compress and the output of the matched filter will be as long as the sum of the length of the two signals. The interfering signals may thus be considered as just sidelobes with no mainlobe. If the waveforms may be assumed to have a time-bandwidth product of at least 20 dB, then mismatched signal will have a level 20 dB below the peak level of a properly matched waveform. If we may optimistically assume that the sidelobes of the properly compressed waveform will be 40 dB below the peak, the worst case will be that mismatched waveforms will produce interference levels after pulse compression which is 20 dB above the levels of the sidelobes of a properly compressed waveform. Since, however, the level of the interference is already assumed to be so high level that the sidelobes of the waveform are already often much stronger than valid signals and prevent detection of them, the higher level of the mismatched signals will not have a worst effect than interference from a matched waveform since the time extent of the interference at the detection is the same.

It should be noted that if some of the detections are ‘lost’ by interference, and factor ‘M’ in the M/N integrator, i.e. the number of detections required to declare the presence of a target must be at least two in order to suppress the impulsive interference, then the total number of pulse repetition intervals (PRIs) must be at least three, and four would be less lossy. The ‘missing’ detections reduce the sensitivity of the radar, but this can be compensated by, for example, increasing the transmitter power. Whilst this is not desirable, it is possible and serves as part of the process of rejecting interference.

Although orthogonal polarisations will reduce the level of the interference by perhaps 20 dB, it will not eliminate it and the levels of interference will still be very high, so there is no point in going to this complexity.

2.4.3 FMCW interference to pulse radars: Since FMCW interference is by definition at a continuous constant level, the CFAR system can ideally reject it completely, as discussed in Section 2.4.1. Moreover, the level, as noted in Section 2.3, the maximum interference level will be $\sim 29$ dBm, which the receiver should be able to handle. In practise, the interfering signal levels may not be perfectly flat because the passband of the pulse radar may not be completely flat and this will impose amplitude modulation onto the interference, so that the interference-to-noise ratio, and hence the statistics of the background against which the targets must be detected, will change across the range swathe. The changes, however, will be relatively slow so that the CFAR should be able to adjust to the changes. This will also apply if the interference partially overlaps the passband of the pulse radar, in which case the interfering signal will be present only intermittently.

It has been observed that FMCW interference into marine radars can be more serious because these radars must be able to detect extended targets. It has been shown that if the radar uses a logarithmic IF amplifier, the receiver is AC coupled at its output [14], so that the processing chain approximates a CFAR system by removing the mean-power level of the signal, the FMCW interference has no sensible effect on the sensitivity of the pulse radar. On the other hand, FMCW interference can have a major effect on pulse radars if the radar uses an IF amplifier with a linear characteristic, particularly since in the marine case both the transmitter and receiver are scanning. It is notable that civil marine radars using more exotic modulations use different parts of the frequency allocations than the pulse radars. The problem should be less severe for current automotive radars, however, since these are only required to detect point-like targets. Future radar sensors for autonomous cars may, however, require more sophisticated processing because their task of providing situational awareness is more akin to the case of the marine radars any they may well be required to detect range-extensive targets.

Interference from airborne radars: It is likely that the usage of the automotive radar band around 77 GHz will be broadened to include other transportation applications. One such application is likely to be landing radars for aircraft to image the runway [15]. Such a radar may have an antenna gain of 45 dB and a mean power of 300 mW, so the effective radiated power may be about 37 dB higher than that of an automotive radar. The minimum range is likely to be 100 m, however, so that the interfering power density at the radar aperture will be of the same order as that of the worst-case interference from ACC radars.

There is, however, another factor to be taken into account which is that the airborne radar is quite likely to be scanning. It is likely to scan something like 100 beam positions in a second, so the dwell, i.e. the period over which the interference will be at the peak level, will be about 10 ms. The detection scheme will need to respond to changes in the characteristics over timescales of this order. Note that this period is of the same order as the update rate of an automotive radar sensor, so it is not obvious that the interference will be able to be rejected by an M/N process.

Interference from pseudo-noise-modulated radars into pulse radars: Since the waveform of a noise-modulated radar approximates to random noise, noise-modulated signals will behave similarly to noise such that interference such as was considered in Section 2.1.1.

As noted above, in Section 2.3, the level of the interfering signal at 77 GHz entering the front of the radar will again be $\sim 29$ dBm. The interference into the ACC radar will be about 22 dB below the MIL-STD 464 levels. As with the case of the FMCW radar, the interference is not likely to block the receiver, but it will be about 58 dB above the thermal noise, effectively blinding the radar. This will prevent the radar from receiving any signals and the noise-like nature of the signals means that nothing can be done about the interference, except to separate the noise like and pulse signals in frequency.
FMCW radar will generate harmonics and intermodulation reach any size, in fact, the design of any CW radar must have probably less severe for current automotive radars than for other interference. A modulation level of $-160\,\text{dBc}\,\text{Hz}$ contains amplitude modulated noise which will also cause and hence at longer range than the nearest target, so a radar system modulation. On the other hand, an ideal phase-coded waveform is to contain some amplitude modulation, especially at the phase transition. Note also that if a practical FMCW waveform also be able to handle, i.e. of what can be called the maximum size of target (MST). Any overload will generate spurious targets, for example, the set of frequency components in the IF stage of an FMCW radar will generate harmonics and intermodulation products which will generate false targets. Once again, this effect is probably less severe for current automotive radars than for other radars. Most of the false targets will be harmonics of real targets, and hence at longer range than the nearest target, so a radar system which must only respond to the closest target will not be affected by harmonics. Two large targets close together at long range may, however, intermodulated to form a phantom target at short range. Once again, the problem is potentially worst for sensors for more sophisticated systems where the sensor must provide a greater degree of situational awareness.

In fact, the success of FMCW marine radars is evidence that defining an MST is possible in practise.

As stated in [16] the MST can be assumed to be

$$\sigma_{\text{max}} = 1000\lambda r$$

The derivation of this comes from observing that a very large target cannot appear as a coherent ‘flat plate’ reflector because of the curvature of the incident phase fronts. The maximum effective length of a reflector is thus of the order of the Fresnel length $\sqrt{\lambda r}$ and the effective area from which a reflector can absorb the incident energy is thus of the order $\lambda r$. A reflector with a large radar cross section (RCS) will preferentially scatter the incident energy back toward its source, but the examination of the curves for the reduction in gain of a corner reflector as their shapes deviated from the ideal suggested that a practical reflector would not have a re-radiation gain of greater than about a thousand. This reasoning leads to the semi-empirical formula given by (4), which actually seems to work very well in practise.

**MST for the ACC radar:** At the maximum indicated range of 300 m, the MST for the ACC radar is 1200 m² and the power received from it is $-89\,\text{dBm}$, giving a signal-to-noise ratio of about 52 dB for a system noise power of $-141\,\text{dBm}$ per range cell, with 1 ms integration time and 3 dB noise figure.

At shorter ranges, the size of the MST increases in proportion to the decrease in range, but as the path loss decreases as the fourth power of range, the power into the receiver increases as the range decreases in proportion to the inverse third power.

To reduce the dynamic range demands on the IF strip, however, the gain normally increases at higher frequencies, which corresponds to targets at a longer range, where the path loss is higher. The increase will typically follow an $r^3$ law to partially, but not completely, compensate for the decrease in the power received from a point target as the range increases. This has the effect that the return from the MST will be constant with range.

The required dynamic range between the MST at maximum range and the noise floor of 52 dB is close to the maximum which can be obtained from the analogue IF amplifiers without excessive difficulty.

**MST for the SRR sensor:** The MST for the SRR is similarly 625 m² at the maximum indicated range of 50 m and the power received from it is $-72\,\text{dBm}$, again giving a signal-to-noise ratio of about 60 dB given a system noise power of $-134\,\text{dBm}$ per range cell, with, again, 1 ms integration time and 10 dB noise figure.

2.5.2 MIL-STD 461G and spurious emissions: Since the worst-case inadvertent interference is wideband noise, then the inadvertent interference will have the same effect on FMCW radars as on pulse radars. It can be seen that narrowband interference can be treated as another FMCW signal with zero slopes and will be considered as mutual interference between FMCW radars in Section 2.5.3 below.

2.5.3 Pulse radar interference into FMCW radars: Historically, pulse radar interference into FMCW radars was the first form of interference to be considered involving FMCW radars, since it was immediately apparent that FMCW navigation radars such as Pilot [17] had to be able to operate satisfactorily in the presence of pulse radars in the same band.

The principle of rejecting pulse interference by limiting the signal levels is illustrated in Figs. 2 and 3.

Fig. 2 shows a simulation of the A-scope of an FMCW radar which approximates to that defined at the start of Section 2. It differs only in that, for convenience, the maximum indicated range is 256 m rather than 300 m.

Fig. 2 shows the system with no interference, but with a single target at 128 m with a signal-to-noise ratio of 20 dB. The signal is
slightly broadened because a Hann (or cosine squared) weighting [18] has been applied to it.

Fig. 3 shows the A-scope in the presence of a single 2 µs pulse at the level of the return from MST at maximum range, i.e. −89 dBm, and placed in the centre of the time-domain signal.

The interference is about 13 dB above the noise. This is actually a worst case because if the return is higher than the MST, then the radar receiver can recognise that it is not a genuine return and suppress it. The simplest way to suppress it is to blank it and accept that the genuine signal will now have a gap in it. The A-scope with the pulse signal suppressed is not shown because the resulting A-scope, obtained with two samples out of 512 in the time domain set to zero, is sensibly the same as with no interference present. The same applies if the pulse radar waveform is a train of ten pulses, i.e. at the assumed 10 kHz repetition rate.

The level of interference is about −130 dBm. It is expected to be reduced from its peak level of −89 dBm by a factor of 512 because it only lasts for one of the 512 samples of the time-domain signal, so its energy if about 27 dB below that of the equivalent CW signal, and that energy is then spread over 256 bins in the frequency spectrum (the A-scope). The expected reduction on this basis would be 51 dB. The observed reduction of about 40 dB is less, due to the over-simplification in the argument presented above.

The level of pulse interference which is just below the level at which the interfering pulses are blanked is thus the worst case. Ten pulses would produce an interleveling level which is 10 dB higher than that shown in Fig. 2, which would tend to suppress the weak targets. It will be observed, however, that the variability of the interference is much less than that of the noise and a clever CFAR could recognise this and so recover much of the sensitivity.

Another factor which will improve the rejection of pulse interference into an FMCW radar in the automotive case, but that has not been included in the simulation, is that the bandwidth of the interfering pulse will be much wider than the FMCW beat frequency spectrum. For example, the energy in the pulse will be spread over about 150 MHz whilst the IF bandwidth is only 300 kHz, so if the power of −89 dBm in the interference only about −116 Bm will fall within the IF bandwidth. The interference-rejection circuit can, however, still have a bandwidth of 15 MHz, so can still reject interference at levels above −89 dBm [3]. It can be seen, therefore, that any interference which is not rejected will have only a very minor effect on the sensitivity of the FMCW radar. Interference into automotive FMCW radars from automotive pulse radars can, therefore, be effectively rejected.

It may be pointed out in passing that if the interfering pulse is shorter than the reciprocal of the IF bandwidth and the blanking circuit is sufficiently fast, then the anti-aliasing filter before the analogue-to-digital converters will completely ’reconstruct’ the missing sections of the signal without any special effort being taken in that regard.

Fig. 4 is a somewhat historical picture taken from a bench test [19] of an FMCW interference-rejecting receiver which demonstrates that the principles outlined above can work in practice.

The picture shows a radar A-scope, averaged over 100 sweeps. The lowest trace is the system noise floor. The highest trace shows the effect of pulse radar interference and a target of ~30 dB signal-to-noise ratio which in this case was generated by a TV delay line. The original purpose of this was to generate the alternating phase references on alternate lines for a phase alternating line television signal [20]. The delay line used in the artificial target was one for a television transmitter. Although each receiver included such a delay line, so they could be very cheap that for a transmitter was used because it had a wider bandwidth. The pulse came from a klystron oscillator. It can be seen that the interference is much smoother than the noise, as predicted, and the target can easily be seen above it, though weaker signals might have been lost.

The central curve shows the effect of blanking the interference. There is still some increase in the background level, but it can be seen that the principal is essentially working.

2.5.4 Mutual interference between FMCW radars: The case of mutual interference between FMCW radars is probably of most practical interest for automotive radars, as so many automotive radars use this modulation.

The simplest case to consider is when the interfering and victim radars use the same waveform, but offset in time. In this case, if the interfering signal is close enough in time to the radar’s own transmissions, a conventional homodyne FMCW receiver [6] will correlate the interfering signal correctly and the interference will appear as point targets in the receiver and the argument is the same as for mutual interference between simple pulse radars, but with the difference that because the sweep repetition interval is 1 ms rather than 100 µs, i.e. because the time-bandwidth product is ten times greater, there is only a probability of $2 \times 10^{-3}$ that an interfering signal will fall into the indicated range swath and only a probability of about $10^{-8}$ of two interferers correlating with the indicated range swath if the sweep timings are jittered.

In the past, waveforms having identical characteristics, to one part in the time-bandwidth product of 150,000, was unlikely, but it is a case worth considering when the radars come from the same manufacturer, i.e. have the same nominal characteristics, and are digitally synthesised.

In fact, the worst case is when sweep is nearly the same. In this case, the two frequencies are close enough for the beat frequency to be in the passband of the receiver for a relatively long time. This situation is illustrated in Fig. 5.

If the sweep rates of the signal and the interferer differ by $\delta \alpha$ and the IF bandwidth is $B_{IF}$, then the interference is present for a time of

$$
\tau = \frac{2B_{IF}}{\delta \alpha}
$$

The factor of 2 arises because in the simple case the receiver cannot distinguish between positive and negative frequencies. Even if an image-reject capability is included, it is unlikely to be good enough completely to reject the interference.

For example, in the case of the ACC radars, the IF bandwidth is 300 kHz, so if the difference in sweep rates is 3 GHz/s, i.e. 2% of

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Fig. 4 Practical rejection of pulse interference – reproduced by permission of Royal Philips

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Fig. 5 Illustration of crossing FMCW sweeps

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the radar’s sweep rate of 150 GHz/s, the interference will be present in the receiver for about 200 µs or 20% of the sweep time. Fig. 6 shows the effect of such interference at the MST level of −89 dBm.

The lower trace shows the A-scope with no interference, as shown in Fig. 2. The level of the interference is about −112 dBm, i.e. 30 dB above the noise level. It would be expected to be reduced from the peak level of −89 dBm by a factor of five because it is present for only 20% of the time and also by 24 dB because the energy is spread over all frequencies. The expected level is then −113 dBm, which is in accord with what has been observed. It will be noted, however, that the chirped structure of the interfering signal in the IF gives it deep nulls so that though it is very smooth, it would be very difficult to design a CFAR which could ‘ride over’ it.

Fig. 7 shows what the A-scope would look such as if the interfering signal was a little higher and the interference was blanked. As noted in Section 2.3, the worst-case mean interference level entering the ACC radar will be −29 dBm, i.e. about 60 dB above the MST.

In this case, it can be seen that removing a significant part of the signal has significantly broadened the return and reduced the signal-to-noise ratio. Tullson [1] noted the potentially serious problems which this sort of interference could cause for automotive radars and proposes more sophisticated ways of reconstructing the signal which would have been seen without the interference.

Once again an example of this technique working on the bench is shown. Fig. 8 shows a point-like target produced by interference with its sweep synchronised with that of the radar.

The system used to generate Fig. 8 was the same as that used for Fig. 4, with the same reference target signal in a slightly lower range cell because the sweep excursion had been reduced slightly as part of the process of synchronising the two signals. The synchronisation of the two sweeps required a lot of care and a certain degree of luck since the signal sources were a pair of yttrium iron garnet (YIG) oscillators. It will be noted that the variance of the noise floor is much higher than in Fig. 4 because the A-scope shows only one sample of the signal. The peak of the interfering signal is much the same shape as that of the true target, but it is spread wider at lower levels, probably in part due to different limitations on the linearities of the sweeps and in part to the fact that the FM noise sidebands of the two oscillators are uncorrelated.

The cases where the sweep rates are different and the interference is seen as a slow ‘chirp’ across the IF band of the receiver is shown in Fig. 9. This is the case which was shown as an RF versus time plot in Fig. 4.

This figure shows four cases. As before, the lowest curve is the reference with no interference. For the other cases, the low mutual slopes mean that the interfering signal stays within the receiver’s bandwidth for about a quarter of the time. The highest curve was obtained with a level of interference just below that at which the blanking started to operate. The intermediate curves were obtained with interference 15 and 30 dB above this level. It can be seen that the worst-case interference, just before the interfering signal starts to be blanked, the interference is about 30 dB above the noise level. As the level of the signal rises to 15 dB above the MST level, the blanking reduces the interference by about 10 dB and when the signal has reached 30 dB above the blanking level, the relatively simple blanking circuit becomes more effective and the interference is reduced nearly down to the noise level. In this case, the rise in the range sidelobes of the target due to the blanking of a significant proportion of the signal is clearly apparent.

It can be seen that if (5) is applied to the case of crossed sweeps, i.e. sweeps with the same absolute chirp rate, but sweeping in opposite directions, where the mutual sweep rate will then be 300 GHz/s, then the interference is only present for 2 µs, making it much like pulse interference into the radar, which has been discussed above. In this case, the interference will have only a relatively minor effect and need not be considered further.

Note that the suppression of mutual interference between FMCW signals cannot use exactly the same circuitry as that which rejects pulse interference or else if an FMCW interference is to
blanked at all, it will be blanked all the time because the interfering signal is always present. It has to trigger only for interfering signals which are within the IF bandwidth.

It will be noted that unlike [1, 4], this analysis has not explicitly considered the effects of interference with the ‘flyback’ of the sweep with what [1] calls a ‘resting’ CW section. The analysis presented above in terms of the differential sweep rate, however, provides a framework for handling these cases and it is noted that the very high sweep rates associated, for example, with a fast flyback at the end of the sweep will mean that there is very little energy associated with this signal. It is also noted that the case of a ‘saw tooth’ sweep with a slow sweep followed by a fast flyback and then by the next sweep is probably more common in practice than either the waveform with the relatively long CW section considered by Tullsson [1] or the triangular sweep considered by Brooker [4].

2.5.5 Noise–radar interference into FMCW radars: The case of noise–radar interference into FMCW radars is of some importance because such modulations have been proposed for automotive radars [21]. The situation with such interference is basically the same as for noise-modulated interference into pulse radars, as discussed in Section 2.4.4. Although the noise power in the IF amplifier chain is reduced by the ratio of the RF bandwidth of interference to the IF bandwidth of the receiver, i.e. 300 kHz/150 MHz and this is spread over all the range cells, this is countered by the fact that the sensitivity has been increased by the same amount, so the severity of the effect of the interference is the same.

Differences are that the coherent nature of the receiver makes it even less likely that rejecting a constant amplitude (phase coded) signal will be practical in an FMCW receiver.

The level of noise-like interference will be enough to trigger the detector which blanks FMCW interference and will blank the whole of the sweep period as the worst-case interference is likely to be −56 dBm, i.e. 33 dB above the MST.

The calculation for the ACC radar assumes some modest image-rejection circuitry to achieve the assumed noise figure of 3 dB, as discussed in Section 2.1. The SRR radar was, however, assumed to have no such circuitry the effect of noise-like interference would thus be 3 dB worst than for the ACC radar.

It should, therefore, be noted that, as discussed in Section 2.4.4, the only solution to interference from noise-modulated interference is frequency agility in order to be able to find spectrum which is free of interference.

2.6 Interference-to-noise-modulated radars

2.6.1 MIL-STD 461G and spurious emissions: Once again, since the worst-case inadvertent interference is wideband noise, then this will have the same effect on noise–radars as on pulse radars, as discussed in Section 2.4.1.

2.6.2 Radar interference into noise radars: Interference from pulse radars: The case of interference from other radars into noise radars can be simply considered because as mentioned above the noise–radar’s matched filter will turn all other waveforms into noise themselves. If the peak pulse level is above the MST, it can be rejected. As with the case of the FMCW radars, the subsequent blanking will have only a minimal effect on the performance of the radar. For the ACC radar, the limiting value of −89 dBm which is the same as the noise level of −89 dBm (i.e. even the strongest signals will not be above the noise before pulse compression). The energy in the interference will be reduced by the ratio of the pulse length to the integration time and so will be typically 23 dB below the thermal noise even if the radar uses pulse compression.

Interference from FMCW radars into noise radars: The case of interference from FMCW can be simply considered because, as discussed above, the noise–radar’s matched filter will turn all the interfering waveforms into noise. This will be at a worst-case level of −29 dBm mean power for the ACC radar. For a fair comparison, this must be compared with the power of the receiver noise in the full signal bandwidth of 150 MHz, i.e. −89 dBm. As for the case of noise–radar interference into FMCW radars, since the interfering signal is present continuously, blanking is not an option and the only solution to interference is the use of frequency agility to find spectrum which is free of interference.

Mutual interference between noise radars: The case of an unmatched interfering noise signal can be simply considered since the effects will be the same as the FMCW case considered above since the interfering signal will still be noise like at the output of the radar’s matched filter. Once again this will be 60 dB above the thermal noise, and the only practical solution to interference is the use of frequency agility to find spectrum which is free of interference.

The only exception to the argument above is when the radar and interferer have identical waveforms, in which case the interfering radar correlates, i.e. its signal is compressed into a single range cell and, as for the cases of mutual interference between FMCW waveforms or modulated pulses, the case reduces to that of interference between simple pulses. This case is less likely than with other waveforms, however, because even if the radar and interferer use the same waveform pattern, the waveforms will not correlate between successive integration periods if they change between integration periods, so the signals from different radars will not correlate unless the waveform sequences are correlated.

3 Deliberate jamming

Although deliberate jamming of automotive radar has not, to the author’s knowledge, been reported, it would be unwise to assume that it will never be attempted. As with inadvertent interference, there are two potential effects on the detection of targets: the first effect is to fail to detect genuine targets, the second is to report targets which are not really there. For an ACC radar failure to detect the target may result in the vehicle hitting it, i.e. cause an accident. On a busy road, this may lead to further accidents and widespread disruption. As discussed in Section 2.4.2, if a false target is detected the vehicle may stop to avoid an accident. As it is at least severe this will be very annoying, but can be solved by switching off the ACC system, but it may be a prelude to a more serious crime such as a hijack or a kidnap attempt. For an SRR, the consequences will probably be less severe such as failure to warn of a potential collision or excessive warnings, which may be very annoying.

For sensors for more sophisticated systems, interference may also change the classification of a target allowing it to be mis-identified. This will be noted, but not considered further because the behaviour will be very dependent on the details of the classification algorithms. It will be noted, however, that in order to create a particular effect, the jammer must know the details of the way, in which the victim radar’s classification algorithm works.

Two types of jamming will however, be discussed: noise jamming and false target jamming.

Since jamming of an ACC radar would potentially have more serious consequences than jamming of an SRR, the rest of this section will only consider jamming of an ACC radar.

3.1 Jammer location

Two jamming scenarios will be considered. One will be a jammer located at a range of 300 m from the radar and looking directly along the road so that the path between the jammer and the interferer is the main beam to the main beam. A longer range is probably not generally practical for a ground-based jammer. The other scenario will be for a jammer beside the road again at a range of 300 m. In this case, the path between the jammer and the interferer is into the radar’s side lobes. Although the sidelobes of the radar had previously been assumed to be 20 dB below the mainlobe, a value of 30 dB will be assumed to allow the jammer a margin in case the sidelobes into which the jamming must be injected are below the highest value.

For simplicity, the jammer will also be assumed to have a pencil beam with a width of 5°. This is a reasonable value and is quite likely to be the case for a jammer which is based on an ACC radar sensor transmitter.
3.2 Noise jamming

Noise jamming is, of course, the process of broadcasting noise into the receiver, raising its noise floor. A simple radar will detect the noise, creating a string of false targets. The more sophisticated CFAR systems which are in any case assumed to be needed by automotive radar sensors will, however, ‘ride over’ the interference and lead to a loss of sensitivity. Since the radar range spoke usually only contains a few targets, which is a necessary condition for the CFAR to work, it may well be able to recognise that the system is being jammed and switch itself off. This course of action would not really be acceptable for systems designed to offer a high level of autonomy so that the driver is not required to take over control of the vehicle (SAE International autonomy levels [22] four and five).

A suitable level of jamming to consider would be to raise the noise level by 40 dB. The ACC radar’s receiver noise level is \(-89\ \text{dBm}\) in 150 MHz bandwidth. To ensure that the radar cannot avoid the jamming by frequency agility, the jammer may have to jam the entire radar bandwidth of 2.5 GHz, so the equivalent noise power into the radar over this bandwidth is \(-77\ \text{dBm}\). The 40 dB jam-to-noise ratio requires an input power of \(-37\ \text{dBm}\) which requires a power of 25 dBm (300 mW) to be transmitted by the jammer, which is probably practical at these frequencies, but challenging. The sidelobe jammer would need a power 30 dB higher, i.e. about 300 W. This would only be possible with a very sophisticated vacuum-tube source and is probably not practical. If the maximum practical power level is 1 W, then the stand-off range of the jammer will have to be reduced to about 20 m to be practical. The power required and the effects of the jamming will be the same for all radar types, but it should be noted that the jamming power is above the return from the MST.

If the jammer can concentrate its interference into the 150 MHz band used by the radar at any time, then the power in the main-beam jammer can be reduced to 13 dB to about 12 dBm which is very practical. The stand-off range to the sidelobe jammer could similarly be increased to the order of 100 m.

3.3 Detection of the radar

The mean radar power level from the main beam of an ACC radar at 300 m into a receiver with 5° beamwidth is \(-59\ \text{dBm}\). An intercept receiver may be assumed to have a bandwidth of 2.5 GHz and a noise figure of 15 dB. The noise power referred to the input practical power level is 1 W, then the stand-off range of the jammer will have to be reduced to about 20 m to be practical. The power required and the effects of the jamming will be the same for all radar types, but it should be noted that the jamming power is above the return from the MST.

If the jammer can concentrate its interference into the 150 MHz band used by the radar at any time, then the power in the main-beam jammer can be reduced to 13 dB to about 12 dBm which is very practical. The stand-off range to the sidelobe jammer could similarly be increased to the order of 100 m.

\[ B_{\text{int}} \approx \sqrt{(2B_{\text{RF}}T_{\text{int}})} \]  

where \(B_{\text{RF}}\) is the RF bandwidth of the signal and \(T_{\text{int}}\) is the integration time. This is the principle of the matched incoherent receiver (MIR) [23]. This will reduce the effective bandwidth to about 2 MHz, increasing the sensitivity by a factor of 1250 and increasing the signal-to-noise ratio by 31–37 dB. This would be more than adequate for detection, even if the video bandwidth must be increased in order to recognise the radar. At 100 m stand-off, the radar sidelobes will be detectable with about 17 dB signal-to-noise ratio. If there is only one automotive radar present, its carrier frequency can easily be measured. If there are multiple vehicles equipped with similar radars present in the scene, it is not immediately clear how the radar of interest will be identified. Identification of the vehicle to be attacked by the jammer at the side of the road will be easier because the beamwidth of the intercept receiver will be only of the order of 10 m.

On the assumption that the problem can be solved of identifying which radars seen by the intercept receiver should be attacked, an intercept receiver can detect the automotive radars well enough to measure their frequency and concentrate the jamming power on the frequency band currently being used by the radar. Although such a receiver will inevitably be quite complex, that complexity may be justified to reduce the power of the mainlobe jammer and would seem to be necessary in order to give the sidelobe jammer a useful stand-off range.

It should be noted, however, that it is possible to buy an intercept receiver for a Ku-band police radar for a few hundred dollars. Although such a radar does not report the frequency of the radar, one way to implement the MIR is by a scanning superheterodyne receiver [23] which will measure the carrier frequency of the radar for free.

If the radar uses pulse compression, the integration time of the MIR must be reduced to 1 μs, increasing the effective noise level by 15 dB. Since the peak power of this radar will be 20 dB higher than that of the FMCW or noise radars, the sensitivity of the receiver will be 5 dB higher and the pulse trains can be detected and deinterleaved to separate the radars, which is much harder with CW waveforms. Indeed as a general principle [23], if it desired to reduce the ability to exploit a waveform once it detected, the waveform design should try to remove features which could allow it to be identified. The question of associating the waveform with the vehicle may remain an issue, however.

3.4 False target jamming

False target jamming consists of injecting discrete false targets into the radar. The power needed to achieve this much lower than that of the noise jammer since a discrete target will be subject to matched filtering in the radar, and hence its power can be much lower at the front end. For the pulse radar, the power need to be only \(-60\ \text{dBm}\) at the front of the receiver to generate a false target 40 dB above the noise level, reducing the peak power needed from the sidelobe jammer to 2 dBm at 100 m range and for the main-beam jammer to about 0 dBm at 300 m range. For jamming of CW radars, with much more processing gain, the power can be reduced by another 30 dB, to very low levels.

The usual way of generating false targets with a modern radar is to use a digital RF memory (DRFM) to receive the radar’s signal, delay it, perhaps modify it, for example, to simulate a Doppler shift, and retransmit it to generate a false target. At 77 GHz, a true ‘RF’ memory is impractical, so the signal will be downconverted to IF before being digitized and upconverted again before being retransmitted. Since the process is inherently coherent, the recreated signal will be a very good match to the original signal and will be subject to the same compression gain in the receiver.

Since it is necessary that the false targets will be closer to the vehicle than is the jammer, the latter must make use of the repetitive nature of the waveform in order to delay the signal by just less than the repetition interval in order to place the false target at the correct range. Since the delay is implemented digitally, there is no problem with using a timing delay. This in principle requires the jammer to know the range to the radar. There is also a potential issue in that the target for the automotive radar must be placed accurately, with a tolerance of perhaps 10 m (60 ns) whilst the most sophisticated DRFMs can produce multiple returns which have separations of this order, in order to simulate complex targets, it is not known whether they can be economically constructed with absolute accuracies this high.

This principle is also disrupted if the radar uses a variable repetition interval to decorrelate inadvertent interference unless the jitter sequence is known to the jammer. In practise, however, current ACC radars normally transmit coherent bursts within which the repetition interval is constant, in order to measure the Doppler shift of the targets. A false target jammer can, therefore, operate in the presence of such a waveform though it will then fail to put the false target in the right place when the repetition interval changes.

A noise radar is potentially immune to such jamming if its waveform changes from one integration period to the next [24]. A false target jammer is normally associated with an intercept receiver which would be used, for example, to measure the waveform repetition interval. If this is not necessary, then a DRFM can, in fact, be used ‘blind’, using a priori knowledge of the repetition interval, and there is no need for the radar signal to have a positive signal-to-noise ratio in the DRFM, for the radar’s own match filter will be able to extract the false signal from the noise.
4 Conclusions

One general principle which underlies the analysis above is that the resistance of the waveforms to interference from each other is the time-bandwidth product of the signals. However, because interference often leads to overloading of the receiver and is often suppressed by limiting, this principle is more of theoretical interest than of practical use. The practical approach must be an ad hoc analysis of the behaviour of different types of interferences into the particular radar design. Some general principles do, however, emerge from the large set of cases examined in this paper.

The ability to reject different types of interferences depends on the design of the detection scheme in the radar receiver. The mutual interference following the ‘normal’ receiver path and the radar must, of course, be designed to cope with a background which is smoother than Gaussian noise, whereas for detection in clutter it generally only has to handle distributions which are more spiky than noise.

The case of inadvertent interference has been considered for two types of sensors, an ACC sensor operating at 77 GHz with a narrow beam and an SRR working at 24 GHz with a broad beam. The mutual interference, in fact, has very similar effects on these two sensor types despite their very different characteristics. It should be noted that the two radar types have comparable power-aperture and time-bandwidth product values.

The case where the 77 GHz sensor is used to provide situation awareness for a future system with a higher level of autonomy has also been considered, within the limits where this is possible without a specific design of target classifier to consider.

The case of deliberate interference has been considered, but only for the 77 GHz ACC radar for which the consequences of interference might be much more serious.

Three representative radars are considered: pulse trains, FMCW signals and noise-like (random continuous) waveforms. These are ‘canonical’ forms of modulation: pulse signals carry the range profile of the targets purely in the time domain, FMCW carries it purely in the frequency domain and noise radar requires a correlation-based match, a filter which in any case could be applied to any waveform. It is noted that most current automotive radars use FMCW modulation. Pure, simple, pulses are probably impractical for automotive radars since the peak power required is of the order of 100 W. Such a waveform is, however, worth considering for the general insights it gives into the mutual interference process. It is also noted that if the radar and the interferer use the same waveform, then the interference is compressed by the radar's matched filter and the situation reduces to that of the pure pulse radars. This situation is actually quite possible when there are only a relatively small number of automotive radar manufacturers and they use digitally generated waveforms.

A modulated pulse with a length of 1 µs, a bandwidth of 150 MHz and a peak power of 1 W could, however, be practical.

The interference which would be caused by spurious signals at levels corresponding MIL-461G has been considered and to the ITU spurious emission standards has been considered. If the former limit can be extrapolated to 24 and 77 GHz, interference at these levels would have very serious consequences to the operation of the radar and if continuously present would prevent the radars from working. The fact that automotive radars generally do not suffer from problems due to interference suggests that in practise the interference levels must be much lower than the possible limits.

The difficulty of generating millimetric signals also suggests that the chances of a device producing spurious emissions at the ITU limit are quite small. Signals outside the band of the radar will not enter through the ‘normal’ receiver path and the radar must, of course, be designed to operate in their presence using normal electromagnetic compatibility design techniques.

Whilst there are areas to be more than one device in the vicinity of the radar, the one device which is closest to the radar will dominate the interference, especially as the interference from devices further from the radar is likely to travel to it via indirect propagation paths which will be lossier. In practise, interference between pulse radars can be rejected well by jittering the PRF and using the correlation between PRIs.

Interference into FMCW radars from either FMCW or pulse signals can be rejected by suppression of signals which are greater than the maximum return from the genuine targets which the receiver is designed to handle. Interference below these limiting levels is suppressed by the time-bandwidth product of the radar and will not cause serious interference.

In all these cases, the radar can cope with simultaneous interference from a hundred or more other radars in the same band. Interference from FMCW radars to pulse radars will be suppressed by the CFAR system.

Interference into FMCW and pulse radars from noise-like signals can be suppressed by the CFAR system to the extent that the ‘noise-like’ signals are of constant amplitude. Other than that they can only be mitigated by the use of frequency agility, i.e. by the individual radar only occupying a (random) part of the total frequency band allocated to the radars.

Interference from pulses into noise radars can be suppressed by blanking interfering pulses which are stronger than the designed MST. Other interference into noise radars can only be suppressed by frequency agility.

The importance of any CW radar design of being able to estimate the largest target which the radar is likely to see at any range is noted. This is necessary in order to allow the radar receiver to be designed to handle those signals without distortion. The practical success of FMCW automotive radars shows that though such a technique has limited theoretical justification, it appears to work in practice.

It is shown that it is relatively easy to deliberately jam the mainlobe of any automotive radar with noise from the sort of stand-off ranges which are likely to be found in automotive scenarios, and possible to jam the sidelobes from a useful stand-off range provided that the instantaneous frequency of radar can be estimated using an intercept receiver.

False target jamming is easy, though placing the false target at a knock-on range would probably be difficult. In a scenario with multiple vehicles, associating a particular radar with a particular vehicle might be difficult.

Radars which change their waveform between transmissions in a random manner such as noise–radars are resistant from the placement of false targets at defined ranges close to the target.

Although deliberate jamming of automotive radars is technologically possible, the relative complexity of the jammers means that building one will require quite a lot of cost and expertise. They are thus likely to be used only for quite sophisticated attacks against high-value targets and are likely to be used against future systems with a higher level of autonomy than an ACC system.

Some examples of experimental interference measurements obtained during bench tests have been shown, though this was with a radar at lower frequencies with a lower time-bandwidth product than automotive radars use, they provide valuable confirmation of the modelling results. The majority of the results presented are based on theory and simulation and it is important that some more representative practical measurements are made.

It should also be noted that this paper has not considered the effects of interference or jamming on the radar’s azimuth estimation process, which in current ACC radars is generally performed by some form of monopulse. SSR radars do not generally have an azimuth estimation capability and the form of
azimuth estimation which will be used by situational awareness sensors for autonomous systems is still the subject of research.

As a general conclusion, it will be noted that the FMCW modulations most commonly used for current automotive radars, because of the simplicity of its implementation, are potentially quite robust to interference and there is no particular need to change the waveforms on that account. In particular, the fact that the interference-to-noise levels can be much higher than the time-bandwidth products of noise-like signals means that such waveforms cannot suppress the mutual interference between themselves and are not to be recommended.

At present, the automotive radar standards allow a wide variety of waveforms to be freely used. This was appropriate when the use of such radars was started, as it allowed experimentation in the radar design and there were few radars to interfere with one another. However, because some combinations of waveforms are much more compatible than others, it may be advisable to standardise how the modulations can be used. It may be advisable as part of the same process to create standards for the resistance of the receivers to interference.

5 References

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