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Introduction of Low Probability of Recognition to Radar System Classification

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***Abstract*—This paper proposes the addition of low probability of recognition (LPR) to the electronic warfare classification of radar systems. LPR radars focus on deceiving electronic support (ES) receivers by selecting waveforms which are agile in their parameter spaces, or by mimicking existing transmitters. LPR provides an additional mechanism to achieve covert operation in a way which builds on low probability of interception (LPI) and low probability of detection (LPD) techniques. The challenges and opportunities of LPR techniques are considered, and some examples of existing waveforms which are suitable for LPR radars are provided.**

***Index Terms*—Low probability of interception (LPI), low probability of detection (LPD), low probability of recognition (LPR), radar system classification, electronic surveillance, electronic warfare.**

I. Introduction

While radar systems have a wide range of benefits from the perspective of an operational user, they do suffer from one tremendous disadvantage: They require signals to be transmitted, and any radar emitter which performs a tactically useful function can usually be detected [1]. To make matters worse, the fact that the path loss in the radar range equation is inversely proportional to the fourth power of range means that these transmissions generally have to be extremely powerful, thereby increasing the likelihood that they will be detected [2].

Exploitation of radar transmissions has taken place since the first operational use of radar in World War II with German U-Boats having radar warning receivers (RWRs) to warn them of the approach of Allied aircraft [3], for example. The development of Wild Weasel tactics combined with the anti-radiation missile (ARM) in the Vietnam War meant that the only way for radar-based systems to survive for any length of time was to practice strict emissions control (EMCON) – only transmitting when absolutely necessary, and even then, only for the shortest possible time – which contradicts the point of having a radar for constant surveillance or early warning of a battlespace [4].

More recently, the advent of low-observable (LO) (stealth) technologies has made operational platforms more difficult for an adversary to detect [1]. Placing a conventional radar on such platforms would be counterproductive as the operational benefit achieved by the LO characteristics of the platform would be negated by the radar transmissions. As a result, radar systems on LO platforms require significant changes from those on conventional platforms [5], [6].

The operational drawbacks of radar transmissions have led to the development and implementation of a number of approaches to minimising this danger.

The first of these is passive radar systems where the system transmitter is external to the radar system.[1] Again, this concept dates back to World War II, where a German passive radar system used the British Chain Home radar signals [7], [8]. Recently, passive coherent location (PCL) systems based on commercial transmissions have attracted significant interest within the radar community [9], [10]. However, passive radars are generally sub-optimal as they are limited by the availability, positioning and waveforms of the transmitters used. Coverage is also not designed for high altitudes. As a result, it is reasonable to assume that the majority of operational radars will remain active into the future.

The most common approach to reducing the danger posed by radar transmissions is to use low probability of interception (LPI) and low probability of detection (LPD) techniques [4]. LPI techniques aim to make it less likely that an adversary's electronic support (ES) receiver will be correctly configured to detect a radar's transmissions at any given time, while LPD techniques seek to make a radar's transmissions more difficult to detect. The distinction between LPI and LPD is subtle enough that many authors simply speak of "LPI radar" as a catchall term.

Given the potential of LPI and LPD techniques to radically change the way radar systems are operationally employed and countered, extensive research into techniques suitable for the detection of LPI radars has been conducted, most noticeably resulting in an 857-page book on the topic [11]. It is thus likely that the operational benefit of LPI and LPD techniques will be reduced in future, and a new approach to reducing the operational danger posed by radar transmissions is required.

The extension of the concepts underlying LPI and LPD to

[1]The terms "covert radar" and "passive radar" will not be considered synonymous here. The term "passive radar" will be used to denote a radar which uses an emitter of opportunity, while the term "covert radar" will be used to refer to any radar system which attempts to hide its transmissions.

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give low probability of recognition (LPR) radar is proposed. One of the key challenges facing ES receivers is that the veritable explosion of commercial wireless systems has made it far more difficult to identify users of the electromagnetic spectrum (EMS) [12]. LPR radar seeks to exploit this difficulty by creating radar signals which resemble other, non-radar signals. In the best case, this would result in a radar system being ignored by an ES receiver as a result of incorrect classification thus allowing the radar to operate without danger. But even if this is not possible, LPR radar has the potential to delay an adversary's response to a radar transmission by requiring significant additional processing to be performed before the radar system can be identified.

This work seeks to formalise and extend the relevant concepts. The implications of covert radar techniques are considered in Section II, and examples of possible LPR systems are outlined in Section III.

II. Assessment of LPR Radar

LPI, LPD and LPR techniques all aim to allow a radar to operate without any interference by an adversary by operating in a covert manner. The evaluation of these covert radar techniques inherently requires an evaluation of the effect on both the radar system employing the technique and the ES system attempting to detect the radar [13]. The implications of covert techniques on the operation of the radar system employing them will first be considered, followed by an evaluation of how these techniques affect an ES system.

A. Implications of Covert Radar Techniques on Radars

Covert techniques focus on protecting the radar system by reducing the efficient operation of ES systems [14]. An ES system intercepts radar pulses and then measures the properties of the radar emissions. These properties are converted to pulse descriptor words (PDWs) which are then used for system recognition [1], [15].

To reduce the recognition capability of a ES receiver, the PDW capability of the receiver can be attacked through altering the properties in the following ways:

- angle of arrival - blinking transmitter or multiple transmitters;
- pulse width - amplitude modulation, with modulation on the pulse to cross the electronic support measure (ESM) receiver's threshold for pulse width measurement;
- frequency - transmitting at another frequency simultaneously;
- pulse repetition interval (PRI) - jitter, interleaved or range ambiguous;
- pulse modulation - adding communication data [16], [17], random coding and pulse agility; and
- active eletronically scanned array (AESA) techniques - adaptive beam scheduling to limit the estimation of coherent processing intervals, beamwidths and revisit times.

To reduce the efficiency of an ES system, a system should change its emissions in some of the following ways: [14]

- Reducing the transmission power reduces detectability.
- Use frequency bands with high absorption properties for close range operations or terminal stage guidance.
- Dynamically and unpredictably changing the transmitted signal, also known as radar agility (e.g. PRI staggering, frequency hopping, waveform variation, etc.), has been shown to reduce the likelihood of detection by an ES system [18].
- The likelihood of a signal being intercepted may be reduced by reducing the transmissions in both the time (EMCON) and spatial domains (narrower antenna beamwidths and lower sidelobes).

LPI systems exploit spatial, temporal and spectral characteristics of a system, such that the probability of interception is minimised [14], [19]. LPD systems focus on employing techniques which reduce the probability that ES receivers will detect the presence of a radar, usually by the use of spread spectrum techniques through waveform coding [18].

An ES system should first intercept, then detect and finally recognise a radar system. Consequently a covert radar should first employ LPI, then if the system can be intercepted, it should employ LPD, and finally if it is detected, it should employ LPR. Note than LPI, LPD and LPR techniques can be implemented separately or in conjunction in a system.

Ultimately, the highest level of covertness is achieved by passive systems. PCL uses emitters of opportunity, so no emitter is required. As no emitter is present, an ES receiver does not have a signal to evaluate. As a result, an ES receiver is incapable of detecting the PCL system due to the lack of transmissions from the radar system itself. However, the inability to influence the transmitted signal may significantly constrain the performance of a PCL system.

There is thus always trade-off between covert operation and radar performance. Some examples are listed below.

- The use of LPD to achieve low spectral density requires a large bandwidth.
- The use of LPI to reduce the beamwidth of a search radar will also reduce the illumination time of a target resulting in reduced detection performance.
- The use of LPR to limit the waveform of a radar to communication-type signals will imply the use of waveforms with suboptimal radar properties.
- Passive radars are fully dependent on the emitters of opportunity which are used.

This shows that an adoption of covert techniques may result in a reduction the radar system's performance.

Figure 1 provides an idealised representation of the trade-off between radar performance and covertness inherent in any radar system. As indicated, the ideal would be to both achieve high radar performance while maintaining covert operation, but unfortunately, this is not possible in practice. At the one extreme is a non-covert radar which optimises radar performance without any consideration of covert operation, while the other extreme is a passive radar which relies on the non-ideal properties of available emitters while being fully covert as it has no transmitter. Between these two extremes lie the possibilities offered by LPI, LPD, LPR and various

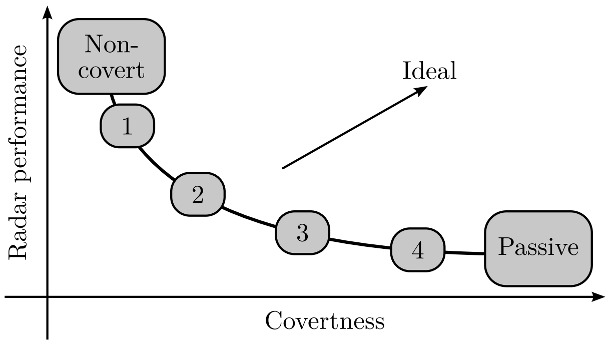

Fig. 1. Idealised graphical representation of the trade-off between radar performance and covertness.

combinations of these techniques.

Some examples of LPR techniques and their implications on the trade-off shown in Fig. 1 are highlighted below with the numbers corresponding to those in Fig. 1.

1) Operating in a frequency band allocated to other services. Minimal changes would be required to the radar except for interference cancellation techniques temporally and spatially such as sidelobe cancellation and adaptive interference cancellation, but covertness would be limited to ES systems such as those which ignore the busy cellular communications bands.
2) Utilising pulse properties similar to those of time-division multiple access (TDMA) networks because many TDMA systems have pulsed transmissions which are similar to those of radars. The pulse structure of the radar would have to change, but covertness would be ensured against an ES system which ignores TDMA pulse waveforms. Covert operation may even be possible without transmitting at the correct frequency if the ES system is unable to determine transmitter frequency (e.g. older RWRs based on crystal receivers).
3) Using the same modulation scheme as a existing transmitter. This could lead to significant radar performance compromises as the modulation scheme used is unlikely to have desirable radar properties, but an ES system will have great difficulty distinguishing between the original transmitter and the radar without demodulating the signal.
4) Recreating the transmissions of an existing transmitter with correct modulation, frame structure, error-correction codes, etc.. Radar performance is likely to be significantly reduced as the transmitted signal was developed without consideration of its radar properties. However, an ES system would be extremely unlikely to correctly identify the signal as a radar transmission as the existing transmitter's signal would be perfectly recreated.

Clearly, the effectiveness of an LPR technique needs to be coupled to the type of ES system being countered as with LPI and LPD techniques [13]. Dynamically altering the radar properties can improve LPR success even further.

B. *Effect of Covert Radar Techniques on ES Systems*

While there are methods to counter covert radar techniques, the success of the ES system is determined by many factors including the characteristics of the ES receiver [13].

LPI systems can be countered [20]–[22]. For example, the use of staring systems as opposed to scanning systems increases the probability of intercept (POI) of ES receiver systems, as beam-on-beam interception is only dependent on the radar system. Similarly, the use of wideband channelized receivers increases POI against frequency-hopping radars as large portions of the radar's operating frequency range (potentially the entire range) are continuously monitored. However, including such capabilities in an ES system will lead to substantial increases in the complexity and cost of the system.

LPD systems can be countered through the use of receivers with a high sensitivity. The necessary sensitivity can be achieved both through the use of improved radio frequency (RF) front ends and by exploiting appropriate signal processing. For example, many techniques exist to detect Frequency Modulated Continuous Wave (FMCW) [11] and direct-sequence spread spectrum (DSSS) waveforms [23]. However, while these techniques are effective, the ES system requires significant processing to detect this class of radar waveforms, which again increases ES system cost, and in many cases, may exceed the capability of an ES system's digital signal processing (DSP) hardware. Increased space required for the system, or the amount of power the systems draws from the platform are other factors to also consider.

The aim of LPR systems is to confuse an ES receiver into wrongfully classifying an emitter. For example, an ES system may incorrectly classify a radar emitter as a communications link causing an adversary to respond inappropriately or not at all. This may either allow the radar system to operate unhindered or to delay an adversary's response long enough to allow the radar system to complete its mission (e.g. missile guidance). But even if countermeasures to LPR techniques can be developed, they will again increase the cost of ES systems and potentially require higher performance beyond the capabilities of existing ES systems.

Some examples of ways in which LPR techniques could be countered are listed below with the numbers corresponding to those of the numbered list in Section II-A.

1) Monitoring all frequency bands for signals with radar characteristics.
2) Consider signal parameters other than just the envelope of the signal including the frequency, bandwidth, modulation, etc..
3) Demodulate signals to ensure that they have the correct structure.
4) Use other parameters to classify signals. Many signal types are expected to have very low power levels, so a signal with unusually high power levels would be suspect. The known positions of existing transmitters could be used to isolate suspicious signals on the basis of their direction-of-arrival (DOA) (e.g. satellite signals do not

originate from ground level). Certain communications protocols are only used in relatively limited geographic areas, so detecting a specific signal in an area where it is not used would be indicative of an LPR system.

While this list demonstrates that there is little doubt that LPR systems will eventually be countered, it is equally clear that such countermeasures will be complex and costly. Additionally, many of these proposed countermeasures only indicate the possible presence of an LPR signal. Additional confirmation will thus be required, thereby delaying an adversary's reaction to an LPR system. So even when LPR systems are countered, they are likely to remain useful from an operational viewpoint.

III. Existing Transmitters Suitable for LPR Radar

A brief evaluation of the suitability of some existing transmitter classes for application in LPR radars is provided below.

A. Civilian Radars

There is a wide range of civilian radar systems including air-traffic control (ATC), weather and navigation radars [24]. From an LPR perspective, emulating civilian radar systems has the benefit of ensuring that the waveforms used are suitable for radar use. The one drawback is that civilian radar systems are increasingly being incorporated into integrated air-defence systems (IADSs) and as a result are attacked [25], thereby diminishing the LPR benefits of mimicking civilian radars.

B. Broadcasting Services

Broadcasting services, such as television and audio, transmit with the goal of providing media coverage over wide areas. Broadcasting services, including digital audio broadcasting (DAB), digital video broadcasting – terrestrial (DVB-T) and frequency modulation (FM) radio, are often exploited in PCL [9], [26]–[28], clearly demonstrating that these waveforms can be used in LPR radar. DAB and DVB-T use orthogonal frequency division multiplexing (OFDM) which has the benefit of efficient bandwidth utilisation, and has thus already been considered for radar use [29]. Satellite-based broadcast signals also have potential for application in LPR radar as a result of their large bandwidths, desirable frequency ranges (e.g. X and Ka Bands) and the fact that they are present all over the world.

C. Mobile Communications

Cellular communication systems like Global System for Mobile Communications (GSM), Universal Mobile Telecommunications System (UMTS), Long-Term Evolution (LTE) and wireless local area network (WLAN) systems have the tremendous benefit that they cover vast, ever-increasing areas. Again, mobile communications transmitters been used for PCL systems [30], [31], thereby demonstrating the feasibility of these waveforms for radar design. The code-division multiple access (CDMA) modulation scheme used by a number of mobile communications standards (e.g. UMTS) bears strong similarities to the DSSS waveforms already used by LPD radar systems [32]. OFDM is also popular for mobile communications (e.g. LTE and WLAN), and as highlighted previously, has already been considered for radar applications [29], [33]. The likely future use of multiple-input, multiple-output (MIMO) techniques in mobile communications is mirrored by the ongoing evaluation of MIMO for radar systems [34], and its effect of ESM systems [35].

IV. Conclusion

The term LPR has been introduced as a natural extension to the radar techniques covered under the terms LPI and LPD. While some techniques which fall under the heading of LPR have been proposed in the past, it has been shown that a far broader range of possibilities exists.

The trade-off between radar system performance and covertness was evaluated, and a wide range of possibilities was shown to exist. Unfortunately, increased covertness is generally associated with waveforms which are less suitable for use in radar systems. However, the requirement for significant additional development and cost on the part of an ES receiver will be significant, and potentially, beyond the capability of existing ES systems.

Lastly, the suitability of a number of existing emitters for LPR purposes was evaluated. Significantly, even this brief initial study identified a number of widely-used signal types which are suitable for LPR radar applications, thereby demonstrating the potential of the concept of LPR radar.

References

[1] F. Neri, *Introduction to Electronic Defense Systems*. SciTech, 2006.

[2] G. W. Stimson, *Introduction to airborne radar*, 2nd ed. SciTech Publishing, 1998.

[3] K. Doenitz, *Memoirs Ten Years and Twenty Days*. Shenval Press, 1958.

[4] A. De Martino, *Introduction to modern EW systems*. Artech House, 2012.

[5] C. Smith, "The B-2 radar," in *IEEE Systems Readiness Technology Conference (AUTOTESTCON)*, Sept. 1991, pp. 17–33.

[6] J. Malas, "F-22 radar development," in *IEEE National Aerospace and Electronics Conference*, vol. 2, Jul. 1997, pp. 831–839 vol.2.

[7] N. J. Willis and H. Griffiths, *Advances in Bistatic Radar*. SciTech Publishing, 2007.

[8] H. Kuschel, "Approaching 80 years of passive radar," in *Radar (Radar), 2013 International Conference on*, Sept 2013, pp. 213–217.

[9] H. Griffiths and C. Baker, "Passive coherent location radar systems. Part 1: performance prediction," *IEE Proceedings Radar, Sonar and Navigation*, vol. 152, no. 3, pp. 153–159, June 2005.

[10] C. Baker, H. Griffiths, and I. Papoutsis, "Passive coherent location radar systems. Part 2: waveform properties," *IEE Proceedings Radar, Sonar and Navigation*, vol. 152, no. 3, pp. 160–168, June 2005.

[11] P. E. Pace, *Detecting and classifying low probability of intercept radar*, 2nd ed. Artech House, 2009.

[12] J. P. London, "The new wave of warfare – battling to dominate the electromagnetic spectrum," *Journal of Electronic Defense (JED)*, vol. 38, no. 9, pp. 68–76, Sept. 2015.

[13] D. Schleher, "LPI radar: Fact or fiction," *IEEE Aerospace and Electronic Systems Magazine*, vol. 21, no. 5, pp. 3–6, May 2006.

[14] A. Stove, A. Hume, and C. Baker, "Low probability of intercept radar strategies," *IEE Proceedings Radar, Sonar and Navigation*, vol. 151, no. 5, pp. 249–260, Oct. 2004.

[15] M. Conning and F. Potgieter, "Analysis of measured radar data for specific emitter identification," in *Radar Conference, 2010 IEEE*, May 2010, pp. 35–38.

[16] J. G. Metcalf, C. Sahin, S. D. Blunt, and M. Rangaswamy, "Analysis of symbol-design strategies for intrapulse radar-embedded communications," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 4, pp. 2914 – 2931, Oct 2015.

[17] D. Ciuonzo, A. De Maio, G. Foglia, and M. Piezzo, "Intrapulse radar-embedded communications via multi-objective optimization," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 4, pp. 2960 – 2974, Oct 2015.

[18] M. Modarres-Hashemi and M. Nayebi, "LPD feature improvement in random PRF radar signals," *IEE Proceedings Radar, Sonar and Navigation*, vol. 151, no. 4, pp. 225–230, Aug. 2004.

[19] G. Schrick and R. Wiley, "Interception of LPI radar signals," in *IEEE 1990 International Radar Conference*, May 1990, pp. 108–111.

[20] D. Zeng, X. Zeng, H. Cheng, and B. Tang, "Automatic modulation classification of radar signals using the Rihaczek distribution and Hough transform," *IET Radar, Sonar Navigation*, vol. 6, no. 5, pp. 322–331, June 2012.

[21] K. Konopko, "A detection algorithm of LPI radar signals," in *Signal Processing Algorithms, Architectures, Arrangements and Applications*, Sept. 2007, pp. 103–108.

[22] R. Ardoino and A. Megna, "LPI radar detection: SNR performances for a dual channel cross-correlation based ESM receiver," in *European Radar Conference (EuRAD)*, Sept. 2009, pp. 113–116.

[23] J. Vlok and J. Olivier, "Non-cooperative detection of weak spread-spectrum signals in additive white Gaussian noise," *IET Communications*, vol. 6, no. 16, pp. 2513–2524, November 2012.

[24] W. L. Melvin and J. A. Scheer, Eds., *Principles of Modern Radar: Radar Applications*. SciTech Publishing, 2014.

[25] J. Kasssebaum, "The art of SEAD: Lessons from Libya," *Journal of Electronic Defense (JED)*, vol. 34, no. 12, pp. 58–62, Dec. 2011.

[26] J. Palmer, H. Harms, S. Searle, and L. Davis, "DVB-T passive radar signal processing," *IEEE Transactions on Signal Processing*, vol. 61, no. 8, pp. 2116–2126, April 2013.

[27] D. Poullin, "Passive detection using digital broadcasters (DAB, DVB) with COFDM modulation," *IEE Proceedings Radar, Sonar and Navigation*, vol. 152, no. 3, pp. 143–152, June 2005.

[28] F. D. V. Maasdorp, J. E. Cilliers, M. R. Inggs, and C. A. Tong, "Fm band commensal radar technology used for the detection of small aircraft and the measurement of propeller modulation," in *Radar Conference (RadarCon), 2015 IEEE*, May 2015, pp. 0664–0668.

[29] S. Sen and A. Nehorai, "Adaptive design of OFDM radar signal with improved wideband ambiguity function," *IEEE Transactions on Signal Processing*, vol. 58, no. 2, pp. 928–933, Feb. 2010.

[30] R. Zemmari, M. Broetje, G. Battistello, and U. Nickel, "GSM passive coherent location system: Performance prediction and measurement evaluation," *IET Radar, Sonar Navigation*, vol. 8, no. 2, pp. 94–105, Feb. 2014.

[31] D. Pastina, F. Colone, T. Martelli, and P. Falcone, "Parasitic exploitation of Wi-Fi signals for indoor radar surveillance," *IEEE Transactions on Vehicular Technology*, vol. 64, no. 4, pp. 1401–1415, April 2015.

[32] J. D. Taylor, *Ultrawideband Radar: Applications and Design*. CRC Press, 2012.

[33] G. Lellouch, A. K. Mishra, and M. Inggs, "Stepped ofdm radar technique to resolve range and doppler simultaneously," *IEEE Transactions on Aerospace and Electronic Systems*, vol. 51, no. 2, pp. 937–950, April 2015.

[34] F. Robey, S. Coutts, D. Weikle, J. McHarg, and K. Cuomo, "MIMO radar theory and experimental results," in *Asilomar Conference on Signals, Systems and Computers*, vol. 1, Nov. 2004, pp. 300–304.

[35] Y.-H. Huang, M. A. van Wyk, and J. E. Cilliers, "On the detectability of multiple input multiple output (MIMO) radar signals using conventional electronic warfare support (ES) receivers," in *IEEE Radar Conferance*, 2015.