Optimisation and Evaluation of Receiver Search Strategies for Electronic Support

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Abstract—**Two essential requirements of a non-communications Electronic Support system are a high Probability of Intercept and a high Probability of Detection against scanning microwave band emitters. High Probability of Intercept is typically achieved using a wideband receiver while high Probability of Detection requires a narrowband receiver. Achieving both has hitherto required the use of multiple receivers in a cascaded or channelised architecture. To minimise the cost for Radar Warning Receivers and anti-radiation systems, we propose that a single scanning narrowband receiver with inherently high Probability of Detection can achieve a high Probability of Intercept by using an optimised search strategy to control its frequency scan pattern.**

In this paper we have presented a new approach to assessing the performance of strategies based on Probability of Intercept and demonstrated the use of an Evolutionary Algorithm to optimise receiver search strategies. The optimised strategies show a significant performance improvement over traditional scheduling approaches.

I. Introduction

Electronic Support (ES) is the branch of Electronic Warfare that deals with the passive intercept, analysis and exploitation of electromagnetic radiation. Non-communications ES is an essential function of modern warfare as it is the only reliable form of timely threat warning against radar-guided missiles.

Radar-guided missiles are a prolific and lethal threat in modern warfare in the air, maritime and land environments. In order to effectively counter such weapons it is first necessary to detect the presence and identity of the threat. At the tactical level this role is performed by Radar Warning Receiver (RWR) and Electronic Support Measures (ESM) systems [1]. Throughout this paper we will refer to both RWR systems and ESM systems performing a threat warning role as 'ES systems', however the core focus of our work is towards RWR and anti-radiation systems where reduced hardware costs are a design goal.

The operation of an ES system can be described in terms of four successive activities: the intercept, detection, analysis of signals and the identification of emitters [2]. In this paper we focus on the first step of the ES process, the intercept of signals, and how the overall performance of an ES system can be improved by improving its intercept capabilities.

The overall effectiveness of the first two stages of an ES system can be measured by its 'Probability of Report' (P_R); the probability that an ES system will report the presence of an actively transmitting emitter. In order to report an emitter an ES system must first intercept and then detect the signal from that emitter. The P_R of an ES system is the combination of the 'Probability of Intercept' (P_I) and 'Probability of Detection' (P_D) of its intercept receiver. As P_R and P_I are statistically independent, P_R is the product of P_D and P_I.

P_I is the probability that a receiver could intercept the signal from an emitter within some specified observation period. A receiver can only intercept signals at carrier frequencies within the band covered by its instantaneous input bandwidth (or 'analysis bandwidth'), i.e. P_I is the probability that the intercept receiver is observing the correct frequency and that the transmitting and receiving antennas are aligned at the time when a transmitted pulse could be received. P_D is the probability that a receiver will detect an intercepted signal. A receiver can only detect signals that are intercepted with sufficient power to exceed the receiver thermal noise power by a specified threshold SNR, i.e. P_D is the probability that if a signal is present, it would cross the detection threshold. Low Probability of Intercept (LPI) radar systems that transmit with low peak powers therefore need a very sensitive receiver with low noise in order to achieve a useful P_D.

Although P_D and P_I are statistically independent, receiver thermal noise power depends on receiver analysis bandwidth, therefore both P_I and P_D, and consequently P_R, all are related to receiver analysis bandwidth. Wideband receivers tend to have high P_I and low P_D while narrowband receivers have low P_I and high P_D, unless the receiver is tuned to an appropriate frequency at the right time.

Achieving high P_R with an ES system has hitherto required the use of a channelised or cascaded receiver architecture. As microwave radars typically transmit pulsed signals, intercepts are brief and therefore the Fast Fourier Transform (FFT) methods for forming channelised receivers used in communications intercept systems cannot be easily applied to non-communications intercept systems; with pulses only being present for a portion of the sample time, spectral spreading of the pulses is significant and the dynamic range of the analogue-to-digital converter needs to be very large to allow weak signals to be captured in the presence of large signals, increasing cost significantly. A cascaded receiver architecture, where a high P_I wideband receiver monitors a large range of frequencies for signal activity and directs a high P_D narrowband receiver to target the frequencies where activity occurs, can be an effective but costly approach, although the narrowband receiver can only be targeted if a pulse is detected by the low P_D wideband receiver which can hinder detection

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of LPI radars.

We propose that high P_R can be achieved using a single narrowband receiver with inherently high P_D by increasing its nominally low P_I using an optimised receiver search strategy. The high P_D narrowband receiver we examine is the Scanning Super-Heterodyne (SSH) receiver; we propose the use of an Evolutionary Algorithm (EA) to optimise a search strategy to maximise receiver P_I against a set of emitters with *a priori* known parameters. Adaptive receiver architectures that modify their schedule based on the parameters of detected pulses (e.g. predicting PRI and modifying the schedule to be observing the predicted frequency at an appropriate time in the future) can also be enhanced as having an optimal initial search strategy can improve the P_I of initial detections.

A SSH receiver typically divides its coverage band (in this case the 2-18 GHz microwave band) into a number of adjacent ‘channels’, each with a bandwidth matching the receiver analysis bandwidth. The default frequency scanning behaviour of such a receiver is to step its analysis bandwidth through these channels at a constant rate; we call this behaviour a ‘repeating sweep’ of the microwave band. The time required to complete a single scan through the coverage band is called the ‘receiver scan period’; in a step-tuned receiver the time spent tuned to each channel before stepping to the next channel is called the ‘receiver dwell time’.

A receiver search strategy controls the tuning of the receiver analysis bandwidth such that it scans the microwave band in a deliberate, pre-defined pattern rather than simply sweeping through the band in a repeating pattern. A step-tuned SSH receiver using a receiver search strategy should have a higher P_I against its emitters of interest compared to the same receiver performing a repeating sweep through the microwave band. As a result, such a receiver would be capable of simultaneously achieving both high P_I and P_D, and thus high overall P_R, and would be very well-suited to ES applications. The design of good strategies is a difficult optimisation problem; in this paper we will demonstrate that Evolutionary Algorithm optimisation techniques are suitable for optimising receiver search strategies.

From the perspective of a target, such as an ES platform, a search radar appears to be active for a short time while its beam is pointing at the intercept antenna and inactive while its beam is pointed elsewhere. This pattern of illumination and non-illumination by a search radar repeats with a period equal to the ‘emitter scan period’. The scanning emitter intercept problem is therefore one of being tuned to the right frequency at the right time.

Track radars, as well as target illumination radars and active missile seekers, do not scan their beams in a periodic pattern but instead dwell continuously upon their target, appearing to an ES system as a near-continuous illuminator. Such emitters should be intercepted whenever the receiver is tuned to the right frequency; non-scanning emitters are therefore trivial to intercept and are not addressed in this paper.

The unpredictable nature of multi-function systems that electronically scan their beams and can interleave tracking and surveillance dwells is beginning to make systems that rely on on-the-fly scheduling to predict the arrival of the next pulse more difficult to operate and therefore ’blind’ scanning systems will soon become as effective. Clarkson demonstrates in [3] that it is not possible to design a deterministic receiver search strategy with superior performance to a search strategy using a random pattern of frequency selection against emitters with unknown parameters. A receiver search strategy can only improve receiver intercept performance if it is first optimised against a specific target set of emitters with *a priori* known parameters, however currently in theatre, there are many emitters which do exhibit regular behaviour patterns and therefore schedule optimisation can be very effective.

II. Existing Methods

A. Receiver Effectiveness Evaluation

An intercept will occur whenever the emitter antenna beam is directed towards the intercept antenna and the intercept receiver is tuned to the transmission frequency of the emitter for a period of time that exceeds some minimum coincidence duration condition.

Self & Smith [4] use the earlier work on ‘window function’ coincidence in [5] to describe radar signal intercept conditions and the modelling of radar signal intercept as the coincidence of periodic binary pulse trains. The receiver measure of effectiveness examined in [4] is not P_I but ‘intercept time’. Intercept time is defined by [4] as, "that time required to achieve a given probability of intercept". Given that P_I is defined over some observation period, the approach taken in [4] arbitrarily sets P_I to some value then evaluates what length of observation period is required to achieve this P_I. This approach is common to most of the literature published on ES receiver search strategy optimisation.

Kelly, Perkins & Noone [6] introduce and address the problem of ‘pulse train synchronisation’, where under certain conditions two or more window functions may never coincide in time. They conclude that adding certain quantities of ‘jitter’ (small variations in the period of a pulse train) to the ES system window functions will minimise synchronisation problems.

Clarkson [7] builds on the earlier work in [4] by considering P_I prediction as well as intercept time prediction. The approach in [7] is still, however, constrained to only working with strictly periodic window functions. In [8] Clarkson identifies that predicting intercept time requires *a priori* knowledge of the phase shift between window functions; if the phase shift is unknown then intercept time cannot be meaningfully predicted. In a real world intercept scenario the phase shift between emitter and receiver window functions is unknown. He asserts that in such cases only P_I can be meaningfully predicted.

B. Receiver Search Strategy Optimisation

The key concept introduced by Clarkson in [8] is that of receiver search strategy optimisation. His paper constrains its attempts at strategy optimisation to scenarios where the receiver is expected to intercept a number of emitters of interest, with *a priori* known parameters, and all these emitters are circularly-scanned radars. The measure of optimality used in the paper is stated as, "to minimise the maximum intercept time of all the emitters on the threat emitter list". The optimisation process employed is a simple 'random-search' process.

A receiver search strategy can be defined in terms of three parameters: its dwell sequence, dwell time and scan period. Dwell time can be equal for all dwells or specific to each individual dwell in the sequence. Scan period is the sum of all dwell times for the dwell sequence. Clarkson's optimisation method only optimises the scan period of the strategy; the dwell time is equal for all dwells and the dwell sequence is not modified, thus the search strategy is only a minor refinement to the default SSH receiver tuning behaviour: the repeating sweep of the microwave band. The only significant advantage gained by using the rudimentary adjustments to the search strategy is the avoidance of the synchronisation problems discussed in earlier papers [6].

Clarkson continues his optimisation attempts in [9] where both receiver scan period and dwell time are varied by the random search optimiser. However, like his previously presented optimisation model, the approach does not vary the dwell sequence thus it only produces improved versions of the repeating sweep rather than a truly optimal strategy. Furthermore, all of Clarkson's optimisation methods use intercept time minimisation as their objective rather than P_I maximisation and are therefore not valid in the general case where the phase shift between emitter and receiver window functions is initially unknown.

III. Probability of Intercept Evaluation

A. Introduction

In order to improve the intercept capability of an ES system against a set of emitters of interest we need a robust technique for measuring the effectiveness of the intercept receiver. This measure of effectiveness can then be used as the 'objective' in our search strategy optimisation process.

All of the reviewed papers published on radar signal intercept and receiver search strategy optimisation use intercept time as their measure of receiver effectiveness. Only one of these papers also uses P_I as an alternative measure of effectiveness [7] and its method of P_I evaluation is highly dependent on the intercept time prediction model.

Two key requirements of the intercept time prediction model originally presented in [4] and used by subsequent authors are:

- *a priori* knowledge of the phase shift between window functions (derived from the emitter antenna orientation at the commencement of the receiver scan period), and
- strict periodicity of the emitter and receiver window functions throughout the observation period.

In a real world intercept scenario the initial emitter antenna orientation is unknown; this is mathematically modelled by adding a phase shift to one or more of the window functions. The value of this phase shift is a continuous random variable between 0° and 360°. In the original intercept time prediction work [4] it was acknowledged that the phase shift between window functions was realistically unknown and a Monte Carlo approach was applied to produce results for the general case. Subsequent work on intercept time prediction [8], [3], [9], [7] assumes that *a priori* knowledge of the phase shift between window functions is available. This assumption is unrealistic and detracts from the general validity of the intercept time predictions presented in the reviewed papers. The original mathematical model for evaluating pulse train coincidences [5] was based on strictly periodic pulse trains and this requirement has persisted through to the most recent published work in this area.

In order to measure and thus optimise the effectiveness of practical intercept receivers, we need an alternative optimisation criteria that overcomes the limitations of existing intercept time based methods. We have developed a method that uses a novel approach of cross-correlation to perform a general case evaluation of P_I over all possible values of phase shift between window functions for a given observation period. Our method is based on the window function model of [4], but remains applicable even when the initial emitter antenna orientations are unknown and also when the emitter and receiver schedules are not repetitive within the observation time. As we are no longer limited by a requirement for strict periodicity of window functions the receiver search strategy is no longer constrained to a repetitive sweep of the microwave band and we are free to vary the receiver dwell sequence and thus truly optimise the search strategy.

B. Method

Each test emitter passed to the optimiser is defined in terms of three parameters: RF, scan rate and beam width. These parameters are contained within the test Emitter Parameter List (EPL) we have created for our experiments. Our test EPL is provided for reference in the Appendix. The emitters in our test EPL are loosely based on open-source parameters for some real world civil and military air and surface search radars, adjusted where necessary to ensure a diverse test set.

Figure 1 shows a simplified set of window functions for a scanning surveillance radar being observed by an ES system with a scanning observation antenna. The plot is for one frequency that is used by the surveillance radar.

Our assessment criteria is capable of evaluating systems with as many window functions as necessary. In a common case, 4 window functions may be employed (emitter spatial, emitter frequency, receiver spatial and receiver frequency) and would be beyond the capabilities of earlier assessment approaches [7] to evaluate.

Instead of just multiplying the time-domain window functions to produce a time-domain coincidence function (valid only for a single possible phase shift of the antenna scans) as presented in [4], we *cross-correlate* the window functions to produce a *Phase Domain* coincidence function. This technique 'slides' the respective emitter and receiver window functions across one another in the time domain, counts the number of coincidences at each time/phase offset and outputs a coincidence function in the phase domain. An example of such a correlation function is shown in Figure 2, however the time offset of each scanning pattern is plotted rather than phase so that the cyclic nature of the problem is visible.

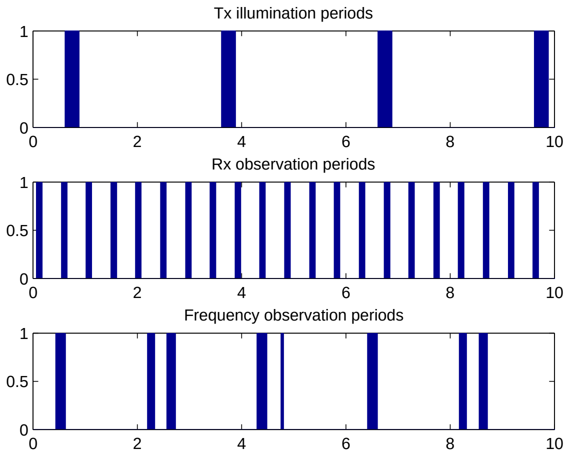

Figure 1. Example window functions for a surveillance radar rotating at 20rpm (upper plot) against an ES system with a scan antenna rotating at 120rpm (middle plot) and a non-periodic receiver dwell schedule for the one frequency channel corresponding to the emitter transmissions (lower plot). The x-axis represents a 10 second observation time and the y-axis represents whether a detection is possible at a given time or not.

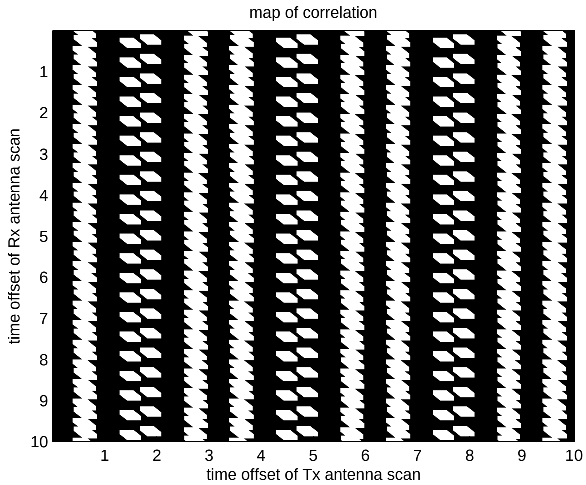

Figure 2. Single emitter, single frequency Binary plot for $R(j,k) > 0$ for time offsets of the emitter and receiving antenna scan patterns that cover thhe full observation period, therefore showing the cyclic nature of the scans on the correlation process. The figure is white where there is at least one coincidence in all of the window functions at the time offsets indicated by the x and y axes and black if no coincidence would occur. P_I for the emitter is given by the percentage of white in the figure.

The correlation of the four window functions may be further simplified by recognising that a frequency-hopping emitter may be represented as a set of time-correlated single frequency emitters.

The process of assessing P_I may be described mathematically by (1), where P_I is the aggregate probability of intercept of the emitters in the EPL and is the quantity to be maximised by the optimiser, P_{I_e} is the Probability of intercept of emitter e, W_e is a weighting that allows the priority of emitter e to be adjusted (normally $W_e = 1$), N_E is the total number of emitters in the EPL, $R_{e_f}(j,k)$ is the correlation count of the number of times that the windows overlap for emitter e in frequency band f when the scan pattern of the observed emitter is offset by j receiver dwell periods and the scan pattern of our receiving antenna is offset by k receiver dwell periods, N_{F_e} is the total number of frequency channels used by emitter e, N_{A_e} is the total number of receiver dwell periods within one scan of emitter e, N_B is the total number of receiver dwell periods within one scan of our receiving antenna, N_S is the total number of dwell periods in the observation period of interest, $\mathcal{A}_{e_{f_i}}(j)$ is the binary value of the window function for emitter e for transmission frequency f at receiver dwell period i with a time offset of j receiver dwell periods, $\mathcal{B}_i(k)$ is the binary value of the window function for the scanning receive antenna at receiver dwell period i and offset by k receiver dwell periods and $\mathcal{C}_{f_i}$ is the binary value of the window function for our receiver frequency dwell schedule for emitter frequency f at receiver dwell period i.

$$P_I = \frac{\sum_{e=1}^{N_E} W_e P_{I_e}}{\sum_{q=1}^{N_E} W_q} \tag{1}$$

where

$$P_{I_e} = \frac{\sum_{j=1}^{N_{A_e}} \sum_{k=1}^{N_B} \left(\left(\sum_{f=1}^{N_{F_e}} R_{e_f}(j,k) \right) > 0 \right)}{N_{A_e} N_B}$$

and

$$R_{e_f}(j,k) = \sum_{i=1}^{N_S} \mathcal{A}_{e_{f_i}}(j) \mathcal{B}_i(k) \mathcal{C}_{f_i}$$

The phase/time domain coincidence function, $R_{e_f}(j,k$, represents the number of coincidences that occur for each quantised phase/time shift. The minimum receiver dwell time and therefore the phase quantisation resolution is set to the required minimum coincidence duration condition which is determined by the PRI of the slowest-pulsing radar in the EPL set (time to capture 3 pulses at the longest PRI for example), thus ensuring that all intercepts counted by the cross-correlation operation satisfy all the requirements for a valid intercept. For the EPL in this paper, a minimum dwell time of $10ms$ is appropriate.

IV. Evolutionary Algorithms

Evolutionary Algorithms (EAs) are optimisers which use an approach inspired by the natural phenomenon of biological evolution [10] and directly exploit the Darwinian concept of 'survival of the fittest' where the best specimens of a species live long and produce many offspring while the weaker members of the population die young and have few or no offspring.

In the context of mathematical optimisation, each member of a population is a potential solution to the optimisation problem, which in this paper is a receiver search strategy. The 'fitness' (quality) of each population member is measured by an 'objective function', which in this paper is the overall P_I of the ES system against the emitters of interest, evaluated using the technique described earlier.

EA optimisation is an iterative process with each iteration representing one 'generation'. Each generation should comprise members that are generally fitter than their predecessors as a result of selective breeding and replacement. As the population becomes fitter as a whole, the individual members will begin to appear very similar to one another until the population eventually converges to an optimal solution.

We found that the best results were obtained using a 'Genetic Algorithm' (GA) [11]. In the terminology of the GA, each population member is called a 'chromosome' which comprises a number of individual 'genes'. In this paper, a chromosome represents the dwell sequence of a receiver search strategy and each gene represents the frequency channel number to which the receiver is tuned during each dwell. The GA is very well suited to operation with an integer chromosome.

The optimisation process performed by the GA can be described by [10]:

1) Generate an initial population of random chromosomes,
2) evaluate the fitness (P_I) of each member of the population,
3) select a subset of the population to be allowed to 'reproduce',
4) combine the selected subset of 'parents' into 'offspring',
5) introduce some 'mutations' (changes) into the new offspring,
6) select a subset of the population to replace with the new offspring (worst 90% of parents replaced with best 90% of offspring),
7) repeat from step 2 for a given number of generations.

V. Experimental Design

In this paper, we present the common scenario of a multi-port antenna system that provides omni-directional coverage coupled with a scanning SSH receiver intercepting circularly-scanned emitters, which requires only three window functions to model; emitter spatial, emitter frequency and receiver dwell. For simplicity, the 10 emitters we have modelled for the experiments in this paper are assumed to be non-frequency-agile and thus operate at a fixed RF at all times.

The emitters in our test EPL have a variety of scan rates between 3 and 15 rpm. The slowest-rotating emitter in the EPL has a scan rate of 3 rpm, representing the slowest-rotating search radars typically encountered during ES operations [2] and will set the minimum observation time, T_{obs}, to 20 seconds for our example.

The ES system we model uses a step-tuned 250 MHz SSH receiver. This receiver operates over a coverage band of 2-18 GHz in order to provide intercept capability against all microwave band pulsed radars. The coverage band is divided into 64 adjacent channels each of 250 MHz bandwidth to match to the receiver analysis bandwidth.

The chromosome used in our experiments is a discrete integer representation of the receiver search strategy dwell sequence. Each chromosome is a vector of integer genes; each gene represents a single receiver dwell. The integer value of each gene represents the channel number to which the receiver analysis bandwidth is tuned during that dwell. Thus any pattern of frequency scanning can be created; no hitherto published literature on receiver search strategy optimisation has allowed the optimiser to manipulate the strategy dwell sequence to such a high degree.

The number of genes within each chromosome is determined by the observation period to dwell time ratio, and is shown in (2).

$$N_S = \frac{T_{obs}}{t_{dwell}} \quad (2)$$

where: N_S is the number of receiver dwells performed during the observation period, T_{obs} is the receiver observation period in seconds and t_{dwell} is the receiver dwell time in seconds. Given that the optimised chromosome pattern is unlikely to repeat, the scan time (T_{scan}) of the evolved schedules are likely to equal the observation time (i.e. $T_{scan} = T_{obs}$). In contrast, if a repeating sweep schedule is employed, there may be multiple receiver scan periods during the observation time (i.e. $T_{scan} < T_{obs}$).

For example, for a $60s$ observation period with a $10ms$ frequency dwell time, 6000 integer genes would be used to form each chromosome. We designed our GA to use a population of 50 chromosomes and found that it requires approximately 100 generations to converge to a useful degree. It is anticipated that the schedule will be optimised pre-mission and therefore although optimisation using a GA is not fast, sufficient optimisation time is available.

The range of gene values between 1 and 10 inclusive represents the ten channels within which the ten test emitters may be intercepted in. An extra channel ('channel 0') represents the other 54 receiver channels in which we do not expect to intercept an emitter from the test EPL. Our receiver search strategies are optimised to improve receiver P_I against a specific set of target emitters only; dwells upon any channels other than those where we expect to intercept target emitters will not increase P_I. If the receiver is dwelling on one of those other channels it is not searching for an emitter of interest and thus in the context of our experiments the actual channel it is dwelling on is irrelevant, hence the combination of all those other channels into a generic channel 0.

Note that a practical ES system would typically not want to totally abandon all intercept capability against emitters not in its EPL, so it is important that the receiver spends at least some time dwelling on these other channels. This need could be addressed by interleaving our optimised search strategies with a repeating sweep. An optimisation constraint can be added that ensures that some minimum proportion of each scan period was spent dwelling on channel 0; however, we have not enforced a minimum level in this work.

VI. Experiment Results

In our experiments the optimiser acts upon the strategy dwell sequence only. Dwell time is equal for all dwells and is fixed within each experiment; observation period is also fixed in each experiment. A total of six experiments were conducted, each with a different pair of dwell and observation times:

- Experiment 1: $T_{obs} = 20s$, $t_{dwell} = 100ms$;
- Experiment 2: $T_{obs} = 20s$, $t_{dwell} = 50ms$;
- Experiment 3: $T_{obs} = 20s$, $t_{dwell} = 10ms$;
- Experiment 4: $T_{obs} = 40s$, $t_{dwell} = 10ms$;

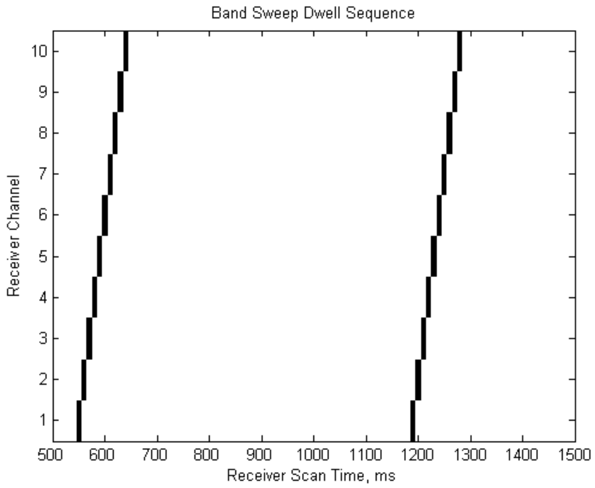

Figure 3. Fragment of band sweep reference dwell sequence for the 10 frequencies used by emitters in the test EPL. 100 dwell periods are shown, each of 10ms, giving a total 1 second section of the observation period.

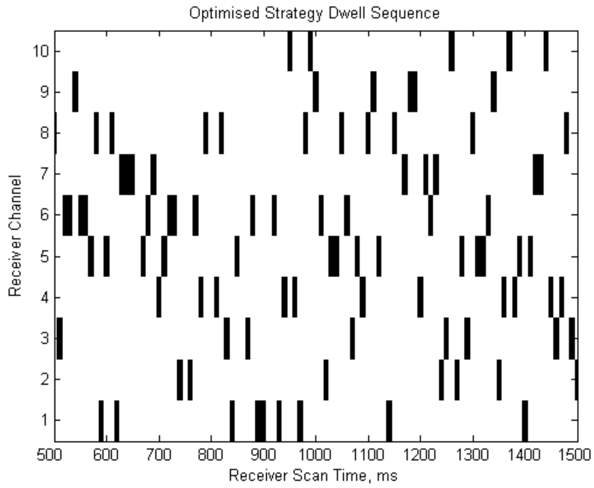

Figure 4. Fragment of an optimised dwell sequence for the 10 frequencies used by emitters in the test EPL. 100 dwell periods are shown, each of 10ms, giving a total 1 second section of the observation period.

- Experiment 5: $T_{obs} = 60s$, $t_{dwell} = 10ms$; and
- Experiment 6: $T_{obs} = 120s$, $t_{dwell} = 10ms$.

In each experiment the EA was used to optimise a strategy dwell sequence to maximise P_I against the ten test emitters. Twenty independent trials of the optimiser were run for each experiment and the results were averaged over all trials to produce a single mean value of P_I for analysis.

In each experiment the optimised strategies were compared against two baselines: a repeating sweep of the microwave band and a repeating sweep of only those 10 channels in which we expect to intercept emitters. Both sweeps use the dwell time and observation period specified for the optimiser for each experiment however for the band sweep, $T_{scan} = 640$ms and for the channel sweep, $T_{scan} = 100$ms. The former (the 'band sweep') represents the realistic default behaviour of a SSH receiver, but is a poor comparison baseline in isolation as we expect its P_I to be inherently low as it only spends 10 out of every 64 dwells tuned to a channel in which it can intercept an emitter. We expect the latter (the 'channel sweep') to have an inherently higher P_I as it spends all its dwells tuned to channels in which emitters may be intercepted; the channel sweep is effectively a non-optimised strategy and is a useful baseline to which we can compare our optimised strategies.

The first three experiments test dwell time variation for a constant scan period. The three values of dwell time which we test are $100ms$, $50ms$ and $10ms$. Observation time is held constant at $20s$. The last three experiments are for variable observation period and constant dwell time. We test three values of observation period: $40s$, $60s$ and $120s$. Dwell time is constant at $10ms$.

Figure 3 shows a 1 second fragment of a receiver scan performing a band sweep (the 500ms to 1500ms section). Only the 10 channels that correspond to the emitters in the test EPL are shown and it is apparent that the receiver is tuned to other channels during most of its dwells. Figure 4 shows the equivalent fragment for a receiver using a dwell sequence that has resulted from our optimisation process. It is clear that the schedule is far more complex than a repeating sweep.

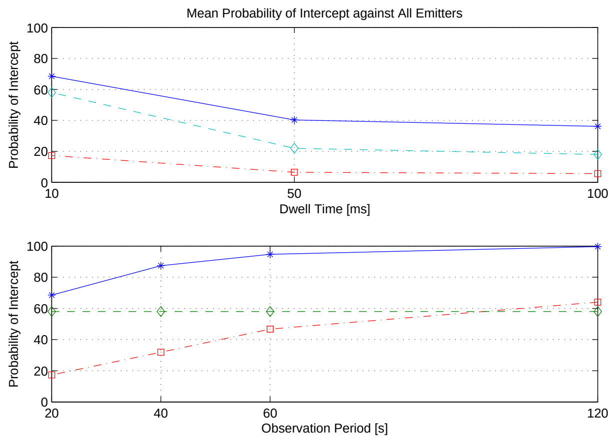

Figure 5. Overall P_I Against All Test Emitters. These two plots illustrate the mean P_I achieved against all the emitters in the test EPL by the GA-optimised strategies (solid '*') compared to the reference band sweep (dot-dash '□') and channel sweep (dashed '◇') sequences.

Figure 5 shows the P_I results for each of the experiments. The figure comprises two plots of receiver performance versus an optimiser input parameter. The upper plot shows P_I versus variable t_{dwell} for fixed $T_{obs} = 20s$. The lower plot shows P_I versus variable T_{obs} for fixed $t_{dwell} = 10ms$.

A. GA-Optimised Strategy Performance

Figure 5 shows the GA-optimised strategy achieved the highest overall P_I in all six experiments. For dwell times of $50ms$ and $100ms$ the GA results were very similar with P_I having fallen from a peak at $10ms$. We expected this relationship between dwell time and P_I as a short dwell time allows the receiver to cover the frequency band faster and the link between fast frequency scans and high P_I has been proposed previously [2].

As the observation period (and therefore GA chromosome length) was extended, the lower section of Figure 5 shows the P_I achieved by the GA increased. We expected this relationship between observation period and P_I as a long observation period inherently allows for more intercept opportunities. The P_I improvement demonstrated diminishing returns over successive observation period extensions, with P_I eventually reaching saturation close to 100%. Consider that P_I is calculated from the number of emitter/receiver window function phase shifts which result in at least one intercept: as the observation period increases, more intercept opportunities become available but it also becomes more likely that an intercept has already occurred during that scan. Only the first intercept of each scan contributes to P_I so any subsequent intercepts will not further improve P_I. Therefore, the P_I improvement gained by increasing observation period demonstrates diminishing returns.

Our results indicate that dwell time should be as short as feasible to maximise P_I, and that a compromise between high P_I and long observation period must be found. It should be noted that our technique for P_I evaluation does not allow us to determine at what time within the observation period an emitter is intercepted; remember the assertion in [8] that intercept time can only be estimated for scenarios where the initial emitter antenna orientation is known to the receiver. There is therefore a degree of uncertainty in intercept time equal to the duration of the receiver observation period; in designing a search strategy we must balance P_I with intercept time uncertainty and set the observation period accordingly. For our experiments the best compromise choice of observation period appears to be $60s$ where P_I is 94.7%.

B. Repeating Sweep Performance

The two types of repeating sweep we compared in our experiments, the band sweep and channel sweep, produced significantly different results, but both achieved lower P_I than the optimised strategies. However, for very long observation periods the band sweep did show signs of approaching a similar P_I to the optimised strategies.

Both sweeps demonstrated a similar relationship between P_I and dwell time to each other and the optimised strategies; P_I was similar for the $50ms$ and $100ms$ dwells but increased significantly when the dwell time was reduced to $10ms$. Our results therefore support the hypothesis of [2] that a SSH receiver achieves a higher P_I when its dwell time is short.

The P_I achieved by the channel sweep appears to be independent of observation period. We believe this interesting result is evidence of the synchronisation limit on receiver intercept capability proposed in [6]. Note that the synchronisation limit on the P_I of the channel sweep occurred because the observation periods used in our experiments were integer multiples of the sweep period of some emitters. If the dwell time or observation period were varied to avoid this condition then we would expect the channel sweep to demonstrate increasing P_I for increasing observation period in the same way as the band sweep. The avoidance of synchronisation by the variation of dwell time and/or observation period forms the original basis of receiver search strategy optimisation [8]. Our optimised strategies are inherently immune to the synchronisation limit on P_I due to the internal aperiodicity of their dwell sequences.

C. Discussion

In our experiments the channel sweep outperforms the band sweep in terms of overall P_I for all values of dwell time and all values of observation period except $120s$. This result is to be expected given that the channel sweep uses all its dwells to search for the emitters of interest while the band sweep spends a large proportion of its dwells tuned to channels within which we do not expect to intercept any emitters of interest.

The P_I achieved by the channel sweep was always inferior to that of the optimised strategies for each individual emitter of interest. However, the band sweep achieved comparable P_I to the optimised strategies for some specific emitters when the observation period was 120 seconds. The result suggests that a band sweep can be an effective search strategy over very long observation periods.

For a practical condition of $10ms$ receiver dwell and $60s$ observation period, the optimal strategy achieved $P_I = 94.7\%$ while the channel sweep obtained $P_I = 58.0\%$ and band sweep obtained $P_I = 46.7\%$. Thus the optimal strategy is significantly superior to the sweeping approaches and P_R is now dominated by P_D, which for a SSH, is very high.

VII. Conclusion

The results of our experiments demonstrated that the receiver search strategies produced by EA optimisers can significantly improve the intercept capabilities of a step-tuned SSH receiver. Our hypothesis that such a receiver using an optimised search strategy could achieve P_I far superior to that expected from a repeating sweep is supported by our experimental results. We have thus demonstrated how a SSH receiver with inherently high P_D can achieve a similarly high P_I, therefore overcoming the historic compromise between these two factors of receiver P_R. As a result of our work it should be possible to design future ES systems capable of achieving high P_R with a single receiver, thus avoiding the hardware costs associated with the cascaded or channelised architectures normally required to achieve high P_R in a radar ES system.

As part of our work on receiver search strategy optimisation we have developed a novel technique for the quantitative evaluation of P_I that builds on the established method of modelling radar signal intercept using the coincidence of window functions. Our approach uses the cross-correlation of window functions to determine the phase-independent aggregate P_I of a scanning receiver against a set of scanning emitters. Our technique provides an alternative to the hitherto published approaches which rely upon strict periodicity in the emitter and receiver scan behaviour and *a priori* knowledge of realistically unknown intercept scenario initial conditions.

APPENDIX

The following test EPL was used to represent the ten emitters of interest for which we optimised receiver search strategies in our experiments.

Table I
TEST EPL

Emitter	RF (channel no.)	Beam Width (deg)	Scan Rate (rpm)
1	1	1.5	12
2	2	2	6
3	3	0.8	3
4	4	1	4
5	5	0.9	6
6	6	1.7	6
7	7	1.55	15
8	8	0.55	3
9	9	1.7	3
10	10	0.55	6

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