Cognitive Radar Information Networks for Security along Canada/U.S Border

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Executive Summary

The events of 9/11 have made it necessary for officials to protect their citizens by affordably monitoring potential threats on or alongside vast waterways, such as the 3,700 km long Great Lakes St. Lawrence Seaway System, which is occupied by large numbers of non-cooperative recreational and commercial vessels, snowmobiles (in winter), and low-flying aircraft.

21st century, wide-area radar information networks (RINs) have been developed to address these threats and are being deployed on the Canada/US Border. This paper demonstrates the dramatic, additional force multiplication achievable by building the operator’s cognitive abilities of attention and intelligence into these networks. We refer to the resulting systems as cognitive radar information networks (CRINs).

CRINs learn from the environment and past operator decisions in order to address operator overload and risk management principles. In particular, they can automatically focus system resources (i.e. apply attention) on areas of heightened interest, while maintaining acceptable system performance elsewhere (i.e. attention is applied intelligently). For example, attention can be applied to particular areas when (a) INTEL indicates an illegal activity is going to take place there; (b) a covert operation is underway there; (c) an accident or incident has occurred there; (d) the system detects suspicious activity there; or (e) when a high-risk event could result such as during VIP events or LNG tanker transits.

This white paper provides an accessible understanding of CRINs to law enforcement officials, operators, policy makers, program managers, radar system developers and research scientists and hence is a must read.
Introduction to Radar Information Networks

Background

The events of September 11, 2001 focused the efforts of various public and private stakeholders on homeland security. Identified threats include terrorist or criminal activities, accidents or natural disasters. As described below, threats occurring on or alongside water are particularly challenging as waterways are vast in extent with large numbers of recreational and commercial vessels [1,2].

Terrorist or criminal activities can be carried out using low-flying general aviation aircraft, and vessels of all sizes from large container ships down to zodiacs and jet-skis. When the water is frozen over, snowmobiles and vehicles add to the target mix. Awareness of what these uncooperative targets are doing at any given time and understanding whether particular target behaviour is suspicious and requires closer examination is what we mean by situational awareness. Protecting people and property from such threats requires situational awareness that provides authorities and citizens with timely information to prevent, respond to, and mitigate them.

From a temporal standpoint, threats can occur at any time, day or night, and are infrequent; therefore situational awareness is needed 24/7/365. Furthermore, because threats can unfold in just seconds (e.g. a vessel crosses a narrow waterway such as the St. Lawrence River and lands on the shoreline of another country violating an international border, or a vessel enters a marine exclusion zone on the waterside of a nuclear power plant on Lake Ontario), persistent surveillance is needed to provide adequate situational awareness.

From a spatial perspective, threats can occur anywhere across our vast waterways. Canada's coastline spans over 200,000 km and the world's coastlines total 356,000 km (CIA World Factbook). Worldwide, commercially navigated waterways are estimated at over 670,000 km. North American international borders along waterways exceed 6,000 km (US Congressional Research Service, Library of Congress, Report RS21729) and there are over 20,000 km of actively maintained commercial inland and intra-coastal waterways (US Army Corps of Engineers). The Great Lakes St. Lawrence Seaway System alone spans 3,700 km in length bringing goods to/from dozens of ports with an international border running through it, and serving an area of North American that is home to about two-thirds of Canada’s population and industries, and one-quarter of the United States’.

With this background, manufacturers have responded with the development of affordable, wide-area surveillance radar information networks which are in the early stages of deployment to provide the required situational awareness to stakeholders [3].

Characteristics of wide-area radar information networks are described next, leading to some new operator issues not encountered before. These challenges, referred to herein as the operator overload problem, arise from the vastness of the areas covered, the large number of friendly targets present, and the large number of radars to be controlled. Examination of this problem leads to the recognition that these 21st century radar networks would benefit significantly if the operator's cognitive abilities of attention and intelligence could
be built into them. In this white paper, the authors lay the vision and groundwork for such cognitive radar networks.

**Radar Information Network Overview**

The wide-area radar information networks we have in mind, typically, consist of a number of inexpensive ground-based radar sensors mounted on structures around the large waterways they intend to provide surveillance coverage for. The structures include towers, roof-tops, tripods on the ground, tethered aerostats, and even mobile structures such as trucks on land or vessels on the water. Such a network is illustrated in Figure 1 and described in detail in [3].

Target data typically include an estimate (also referred to as a measurement) of target

![Figure 1: Model of wide-area radar information network for the Great Lakes with pre-defined attention cells.](image)

The arrangement of radar nodes and the coverage afforded by each are designed to overlap so that seamless coverage is available across the wide area of interest. In this way, targets moving anywhere throughout the entire area will be picked up by at least one radar sensor node. At each sensor node, the radar typically scans 360°, and uses its transmitter to interrogate the environment with a selected waveform. Its receiver picks up reflections or echoes from targets and clutter in the environment, and processes them, using a particular receiver processing mode, to automatically extract information from each target in the environment. The extracted information is referred to herein as target data, and typically consists of both detections and tracks.
parameters updated every couple of seconds. These parameters include {latitude, longitude, altitude, speed, heading, size}. At any instant in time, the current target data represent the locations, dynamics and sizes of all targets seen by the radar network. Over time, complete trajectories are extracted or formed for each target indicative of target behaviour. Target data are typically sent over standard computer or cellular network links (wired or wireless) to an information system or repository that stores forever, organizes, and relays desired target data to operators/users in real-time. For the purpose of this paper, the information system will be considered centralized without loss of generality, recognizing that by simple network routing, distributed information systems, processors, and servers can be viewed as being similar to centralized for most practical purposes.

Remote users (located anywhere there is network access to the radar network in general, or its information system in particular) are also typically provided with a number of applications (software) which query the information system for both real-time or historical target data, including post-processed target data. A host of target data processors can access the information system over the network, generate a variety of information products (e.g. traffic patterns, border-crossing statistics, suspicious behaviour alerts, marine exclusion zone violations around critical infrastructure, etc.), and make these available to users as well. Information sent to users support a variety of user missions including surveillance, automated alerting of suspicious activity or activity of interest, interdiction, intelligence, investigations, analysis, prosecution and research.

Radar networks, in accordance with the architecture described in [3], allow owners of radar nodes to share any subset of their target data with others, creating virtual radar networks that span political boundaries, for example. Standardized, open interfaces allow authorized users the ability to access shared target data and generate their own information products behind their own respective firewalls for information privacy and policy purposes. Such radar networks have been shown to be particularly valuable in joint law enforcement operations [4].

The modular nature of the radar information network includes flexibility in selection of platforms, transceivers, and antennas to address coverage and performance requirements; and software definable radar processing algorithms suitable for target extraction of surface and air targets of interest. Typical radar sensors are X or S-band marine radars with a rotation rate typically in the 24-48 RPM range. Conventional magnetron radars typically include three waveforms: a short-pulse (SP), high-range resolution waveform (e.g. 10 m), a medium-pulse (MP), medium range resolution waveform (e.g. 50 m), and a long-pulse, low-resolution waveform (e.g. 150 m). Solid-state, Doppler marine radars are also available. A SP waveform is typically available; and rain and sea clutter suppression is afforded by Doppler processing. Radar remote controllers are available which allow transmitter illumination and receiver processing mode to be changed under remote software control [3].

The COTS marine radars all come with non-agile array antennas that provide a horizontal beam width typically between 0.3° to 3° and a vertical beam width typically 20° wide and oriented as +/- 10°. These 2D radars can not provide altitude information in their target data. Marine radar transceivers coupled with custom-
developed, agile pencil-beam antennas are available from manufacturers such as Accipiter [3], provide altitude information for airborne targets, and can be commanded under software control to follow an airborne target such as a low-flying aircraft.

Specialized, military or coherent, 3D radars are also available in some cases and can integrate with the radar networks considered here. In such cases, phase information may be available in the target data as well.

In summary, the wide-area radar information networks of the 21st century will involve a heterogeneous mixture of radars, mostly marine radars, which are not synchronous, but operate independently as described above and form a virtual radar information network (VRIN). They will provide target information in a common format to a target information system so that integrated situational awareness can be provided. New radar technologies will build upon such radar information networks to provide new capabilities.

**Why Cognitive Radar Information Networks?**

With conventional military or air traffic control (ATC) radars, operator overload is mitigated by employing dedicated and highly-trained radar operators, and making targets of interest (TOIs) cooperative so that they can be assigned and managed. In military scenarios, identify friend or foe (IFF) transponders installed on friendly targets allow operators to automatically distinguish friendly radar target tracks from enemy tracks or false tracks caused by clutter. Civil aircraft carry transponders allow air traffic controllers to do the same. The air space or maritime operating areas are also controlled so that targets that should not be there stay out. Dedicated radar operators ensure their respective radars are optimally tuned for detecting and tracking their respective TOIs under different environmental conditions.

This is not the case for 21st century radar information networks. It is the uncooperative targets (that do not carry transponders to make them identifiable) that are of most interest, and especially the small ones which are most difficult to detect and track with radar at further distances. Furthermore the area of interest is not controlled, so thousands of commercial and recreational targets are present. Finding suspicious targets is like looking for a needle in the haystack. In addition, the vastness of the area covered by the radar information network, and the number of (dissimilar) radars involved make optimizing radar sensitivity to specific developing situations particularly challenging. It is no longer a simple task of a dedicated operator adjusting the gain-control dial on one radar in order to increase its sensitivity. Now, a network of remote radars needs to be intelligently adjusted to focus attention in a particular localized area where it is needed at a particular time. If ignored, the above issues will lead to either operator overload or result in a limit in system performance that is otherwise achievable. By addressing these issues, we can significantly enhance the price/performance/complexity advantages of radar information networks; and help operators to be more productive by focusing on tasks best suited to their skills.

No one today would deny the informational, communication, and joint / common situational awareness that the Internet brings to people around the world, including law enforcement personnel. This wide-area computer information network, while
organizing information on a scale never before imagined, brings with it a major information overload problem. How do different users find the information they are interested in when they need it? The answer lies in algorithms that continually crawl the web, identifying new content and network behaviour, indexing and organizing the information so that it is searchable, and providing search engine tools and an ecosystem of applications to help users quickly get what they need when they need it. The same is true for radar information networks, albeit on a much smaller scale. To maximize situational awareness and situation understanding, the information content (including targets and disturbances such as clutter) of the environment must be continuously analysed and indexed to automatically learn from the environment, with tools provided to assist operators in exploring, discovering and finding what they need when they need it.

If we had enough of them, and if they had the time, experienced and dedicated radar operators have the cognitive abilities to focus attention where it is needed, and the intelligence to learn from the environment and trade-off how best to keep the radar network optimized for changing security situations. These innate capabilities of the human brain lead us to examine the potential of cognitive dynamic systems to further improve the performance of radar information networks.

The human brain is the most powerful, highly distributed information-processing machine, particularly so when the requirement is to deal with complex cognitive tasks, exemplified by visualization and control. In this context, there is much that we can learn from the visual brain in designing a new generation of cognitive radar networks [5–8].

A cognitive radar information network may be viewed as a significant “force multiplier”. In other words, the cognitive radar information network would make it possible for the operator to be more efficient and effective by drawing attention to different localized areas of interest across and around border regions, for example.

Radar information networks would typically be deployed and tuned to baseline operating conditions. If conditions never changed, there would be reduced need (for an operator) to change radar network settings. However, in practice, changes in the environment occur which are referred to herein as unexpected or uncertain events. The events drive our need to focus the radar information network’s attention to localized areas, intelligently, i.e. without compromising the overall performance of the radar network.

*Unexpected or Uncertain Events which can benefit from Cognitive Radar Information Networks*

Two classes of events are described below, which motivate the case for investing in the development of cognitive radar information networks (CRIN). The provided examples illustrate the points and are not intended to be limiting in any way.

The first class of events leads to an automatic CRIN response not requiring operator intervention, thereby mitigating operator overload. Based on the location and nature of the event and past experience gained by the CRIN, the operator is alerted to the event and appropriate radar sensor nodes are automatically adjusted (e.g. a particular transmitter waveform and/or associated receiver processing mode is
selected for use) to robustly focus system attention or optimize performance where needed. Suspicious targets as well as environmental disturbances fall into this first class of events. The second class of events is operator driven. Both classes of events are described further below.

First Class: Suspicious Targets

The CRIN will automatically detect suspicious targets around particular areas of interest such as border crossings, or marine exclusion zones (MEZ) around critical infrastructure such as a nuclear power plant. A rendezvous, as well as other abnormal behaviour such as deviation from regulated routes, will be detected by the CRIN; then the operator will be alerted, and the CRIN will automatically adapt itself to bring attention to such areas to reduce operator overload and/or enhance performance. Detecting such suspicious behaviours is particularly difficult for operators, especially as they occur within dense traffic environments, and may take considerable time and concentration to observe.

For example, consider the typical traffic pattern shown in Figure 2 for a summer day on the west end of Lake Ontario, over a six hour period. Many target tracks are evident over this period of time. Tracks are colour-coded, with each colour indicating the particular radar which generated the track. Six radars contributed to the traffic history shown in Figure 2. A suspicious target buried in this sea of targets is difficult for an

![Figure 2: Radar tracks from six radars over a period of six hours on west end of Lake Ontario. The tracks for each radar are shown in the same colour. The Canada/U.S. border is also shown in yellow emanating from the Niagara River. Numerous border crossings are observed over this period. East-west and north-south laneways of commercial traffic are also visible if one looks closely.](image-url)
operator to recognize.

In Figure 3, several vessel tracks from Figure 2 are extracted. The vessel trajectory highlighted in red leaves the Port of Hamilton, heads east and crosses the border into the United States, does a turn around and heads back into Canadian waters, and then heads south into the Welland Canal. Within the same four-hour time period, another large vessel leaves the Port of Hamilton, heads east towards the border, then loops back and returns to the Port of Hamilton. The two vessels did not rendezvous, but they did behave suspiciously. It would be extremely difficult for the operator to pick this out in real-time, and make adjustments to the configuration of the radars in the network, if required, in order to draw more attention. In this case, or more radar nodes, and/or increasing resolution by using a different transmitter illumination for one or more radars, to see for example, whether the larger vessel came very close to a smaller one. This is an example where cognition can help to assist the operator and reduce information overload.

**First Class: Environmental Disturbance**

Environmental disturbances include weather (e.g. precipitation) which can lead to the appearance of “false” targets in localized areas, and sea/lake clutter variations which result in reduced radar sensitivity and/or increased probability of false alarm (PFA).

Such disturbances are typically isolated to relatively small areas in comparison to the total coverage area; and they typically move or change with the predominant winds, which for Lake Ontario are westerly.
An example of precipitation on Lake Ontario is shown in Figure 4. The green, localized areas that appear like clouds are precipitation cells picked up by the same radars used for Figure 2 and Figure 3. If one watches these precipitation cells in time, they will move from west to east in response to the local winds patterns. The CRIN is able to detect the presence and location of such disturbance areas and alert the operator that performance is affected there. Then the CRIN could reduce attention in those areas if requested to reduce operator overload, or alternatively, enhance performance there by switching waveforms or changing receiver processing mode while keeping the operator informed. In addition, the CRIN can manage the system optimizations in a dynamic manner (i.e. in synchrony with the movement of the disturbance) to reduce operator overload while maintaining operator awareness.

**Second Class: Operator Driven Events**

The second class of events is operator driven. In this case, the operator has knowledge of an unfolding situation and wants the CRIN to robustly focus attention in a designated area or areas for some period of time. The following are examples of operator-driven events:

- Intelligence indicates that an illegal transaction is likely to take place in a certain area and extra sensitivity is need for evidence and prosecution;

- Law enforcement personnel are conducting a covert surveillance operation in an area and want increased...
sensitivity;

- there has been an accident on the water with a small vessel and search and rescue personnel require focused attention to find the drifting vessel or wreckage; and

- a particular target, e.g. an LNG tanker, is moving through the wide-area and a high-sensitivity region or protective bubble-zone around the target is desired throughout its journey.

For both classes of events, the CRIN must continue operating robustly in its primary surveillance mission, notwithstanding the fact that it is making changes to the baseline operating state of the network, by changing in a localized manner, the transmitter illumination and receiver operating mode of one or more radars. Operators will be able to define global and regional performance figures of merit (FOMs) that are to be maintained during the application of attention to designated areas of interest. Areas or cells available for increased attention can be pre-defined as illustrated in Figure 1, allowing the CRIN to gain experience by learning from its environment. The FOMs might be based on a multi-target tracking continuity measure applied to a given attention cell, for example. The FOMs ensure that global target sensitivity does not degrade below some specified level, while particular regional areas may have different performance thresholds that must be maintained. It is all about exploiting the available system resources associated with the network of radars in the best manner possible to meet mission requirements. For suspicious targets or disturbances that move over large areas, the attention cells will change over time while the CRIN maintains its surveillance mission.

For CRINs that include agile radar sensors as discussed earlier, the CRIN could also be tasked with locking onto a designated, high-risk TOI such as a low-flying aircraft headed towards an urban area, and sacrificing surveillance for a short period of time to maintain target lock.

**The Accipiter CRIN Concept**

The concept of operation and architecture of cognitive radar information networks as envisioned here are discussed next. This is followed in the subsequent section by a detailed treatment of the relevant theory of cognitive dynamic systems as well as technical issues and supporting R&D needed to make CRINs a reality.

**Concept of Operation**

The wide-area covered by the CRIN is divided up into a number of virtual, geographical, **attention cells** as illustrated in Figure 1. The CRIN operates with a baseline radar configuration and performance (which may change with season). Attention is applied to one or more requested cells while intelligence ensures that surveillance in the remaining cells continues to function robustly. Robustness includes both global and local cell metrics – i.e. global performance is controlled so that it will not degrade below a certain threshold; and individual local cells are controlled so as not to degrade below respective performance thresholds.

**Calling for Attention**

A cell may be designated for added attention by: (1) the operator, or (2) automatically by the CRIN’s **cognitive controller**. Both the cognitive controller and the operator provide intelligent feedback to the system. In one case, the operator may see a situation first
that requires attention; in another, the cognitive controller may deduce a situation (e.g. due to a disturbance such as weather or a potentially suspicious behaviour detected) that results in attention being designated for one or more cells.

Using pre-defined attention cells allow the CRIN to build up knowledge and experience in relation to each cell so that the cognitive controller can act quickly and robustly, on-the-fly, when attention is needed in a certain area.

An area of focused interest may move with a target as the target journeys (like a protective bubble), causing cells needing attention to change automatically in time. Even weather cells move – hence, the cognitive controller can use its intelligence to automatically adjust the cognitive radar information network on-the-fly in response to such TOIs or weather disturbances.

Cognition may also be applied to the problem of detecting suspicious target behaviour, in order to assist the operator and reduce information overload, especially in dense target environments.

The system could also automatically propose new scenarios not described previously by the operator, but determined by the CRIN to be anomalous, through its gained experience. For example, the CRIN could learn from past behaviour that a particular type of target has never been observed in a cell or area where it is now detected.

**Behavioural Geometries**

Even a single target of interest will occupy a region over a period of time (because it moves). Furthermore, situations of interest such as border crossings, loitering in a marine exclusion zone, or a target deviating from a regulated laneway all occur in geometric regions. These regions have physical extent and shape in space. We call them geometries. Hence, activity around such a geometry can be emphasized by applying attention to the cell or cells containing it.

**Agile Radars**

If an agile radar node provides coverage in a region of interest (e.g. a radar with a dual-axis scanner [3]), then the cognitive controller could also cause the agile radar to adjust its elevation scan pattern to lock on and stay with a target of interest such as a low flying aircraft, especially if the target is behaving suspiciously.

**Divide and Conquer Strategies**

Dividing up the area into cells where attention can be applied fits the surveillance nature of the radar information network, and represents a divide and conquer approach to computational efficiency.

Various divide and conquer strategies similar to those used in the brain can automatically assist in the target information processing. For example, automatic deduction could be applied using target subspaces developed by grouping targets with similar attributes (e.g. RCS or speed, acceleration, location, radar node number, ...) and then looking for suspicious behaviour against a number of operator-described scenarios. Each scenario could be described using geometries (e.g. a border crossing zone, an MEZ, etc.) and behavioural criteria (e.g. loitering, rendezvous, departure from expected routes, AIS turned off, etc.).
**Cognitive Radar Basics**

Figure 5 illustrates the first step towards a cognitive radar with a single Transmitter and Receiver that incorporates a *perception-action cycle* similar to that used in the brain. 

During each cycle of the perception-action cycle, the Transmitter transmits a waveform to illuminate the environment, the Receiver receives measurements from the environment, and provides feedback information about the environment back to the Transmitter, which is used by the Transmitter’s Cognitive Controller to adaptively (based on learning) select a new (potentially different) illumination for the next perception-action-cycle. Traditional radar (without cognition) does not have the feedback path between the Receiver and Transmitter and does not learn from experience how to best select a new illumination.

![Figure 5: Perception-Action cycle for a single radar](image)

The radar environment or world includes two sources: unknown targets and disturbances such as clutter (e.g. precipitation, sea/lake clutter) and thermal noise. Targets are deterministic in the following sense. There is a certain number of them, and each one has a particular location, speed, heading and RCS at each time instant. What we have described here are unknown. Though targets are deterministic, since they are unknown, they represent a source of uncertainty. On the other hand, disturbances are stochastic in nature. Disturbances and uncertainties are responsible for state estimation errors.

The Receiver extracts information from the measurements it receives about the world. In particular, it computes or estimates two states associated with the world at each particular time update $t$: (1) the *target state* of the world represents its knowledge of the multiple targets present at time $t$, and the *entropic state* of the world which represents the disturbances in the world, along with the imperfections associated with its target knowledge (as represented by the target state). The entropic state is associated with the target state estimation error. Entropy is a metric for assessing the quantity of information we are lacking – hence the name entropic state. The Receiver is assumed to have memory to store the target state and entropic state forever, or alternatively, sends this information to a central location or repository for storage.

The Transmitter does not see (i.e. sense) the environment directly; rather, it illuminates the environment. As a result, if it is to learn from the environment in order to select an appropriate illumination in an intelligent manner, it must see the environment through the Receiver’s eyes. This *seeing* is implemented through the feedback path from the Receiver to the Transmitter, which is a key characteristic of cognitive radar systems.

Humans learn how to make good, robust decisions from past experience; also they remember their consequences. The Transmitter (or some central computer where the Transmitter’s Cognitive Controller lives) is afforded with memory so that it can learn from its past illumination-
selection decisions and their impact on each attention cell. The Feedback Information is based on the current Receiver measurements (typically predicted forward to the next time step) and/or the entropic state which the Cognitive Controller uses in its algorithms to make a robust illumination selection.

With the basic cognitive radar structures defined in Figure 5, it is appropriate to summarize key operating principles of cognitive dynamic systems and identify those structures which are largely responsible for such capabilities.

1. The principle of information preservation recognizes that measurements contain important information about the world that should be preserved for present and future exploitation. The Receiver which produces these measurements will retain this information in a local store, and/or send it to a central repository.

2. Like human memory, the task of cognitive memory is to predict the consequences of action taken by the Transmitter in the most reliable manner through a continuous learning process from one cognitive cycle to the next. Cognitive memory can be supported in the Receiver and Transmitter or via a central repository with linkages to both the Receiver and Transmitter decisions.

3. Attention is that cognitive algorithmic capability which allows a cognitive radar to focus its resources (illumination, sensing, and information processing) on a situation of interest involving a subgroup of targets. This capability helps operators manage or ease the information overload which results from surveillance in wide-area, dense target environments.

4. Intelligence is that cognitive algorithmic capability that enables the Transmitter to select both a particular illumination and Receiver operating mode in a robust manner in the face of environmental disturbances and uncertainties. (Note: setting of Receiver operating mode is not shown in figures.) Robustness means that system performance will not degrade below a certain level in areas not subjected to increased attention.

Implementation Details

The single cognitive radar can be expanded and extended into a cognitive radar information network (CRIN) as illustrated in Figure 6. The perception-action-cycle feedback paths for each radar node are explicitly shown. However, if one takes advantage of the ability of modern RINs to organize their Receiver information in a central repository (by having each Receiver send its information in real-time there), then...
The CRIN block diagram in Figure 7 shows Receiver and Transmitter memory organized in a Central Repository which attempts to isolate the cognitive elements so they can be spiraled into existing radar networks that do not presently have cognition. This is essential to manage cost and risk. Furthermore, cognition can be introduced incrementally, in one or more nodes at a time, with increasing levels of cognition added as software upgrades once the underlying R&D and implementations mature. Receiver information from the collection of radars is organized in the Central Repository providing direct access (or feedback) to the Transmitter via the Cognitive Controller.

While shown centralized, it should be understood that the Cognitive Controller can provide local cognitive control to individual
Transmitters in the network based on respective Receiver feedback, or alternatively, cognitive control could make use of feedback from multiple Receivers or globally from the entire network. Computer network interfaces are assumed to exist between all system components allowing information to be easily shared.

Requests for attention come directly from the Operator, or automatically through the Automatic Behaviour Analysis and Detection (ABAD) processor illustrated in Figure 7. It should be noted that the ABAD processor can generate on the fly post-processed Receiver information that can help characterize the environment for future rapid use by the Cognitive Controller.

Transmitter modes are defined for each radar node. A transmitter mode is a particular set of transmitter illumination parameters which include waveform (e.g. SP, MP, LP), each of which affect range and resolution performance; RPM and elevation beam in some cases (e.g. surface beam and air beam with particular elevation angle).

The Cognitive Controller controls each Receiver by changing the Receiver (processing) mode in combination with the selected and associated Transmitter mode. Receiver mode parameters include threshold for sensitivity (PD, PFA), masking for areas of processing interest, tracking filters for air versus surface targets, etc.

The Cognitive Controller also balances system constraints in its decisions, such as target data rate limits due to bandwidth constraints, and computational loading.

We introduce a new environmental information quantity, referred to as adaptive target maps. Adaptive target maps can be generated based on targets of opportunity observed over short-term and seasonal time frames in each attention cell, and versus each radar node’s available Transmitter modes and Receiver modes. In this way, the CRIN can learn from targets of opportunity (i.e. the environment) target behaviour, as well as the CRIN’s own performance in terms of localized, cellular coverage maps for each target type. Adaptive target maps can be further organized by their attributes (e.g. small or large RCS, slow or fast speed, acceleration, etc.) into subgroups for efficient cognitive processing. These post-processed data characterize the knowledge learned from the environment over time; and they can be organized in the Central Repository for permanent storage and exploitation by the system and the operator.

These new adaptive target maps (analogous in a loose sense to adaptive clutter maps), provide meaningful surveillance performance information as a function of all Transmitter/Receiver modes and all attention cells for all radars in the network, allowing the Cognitive Controller to manage system robustness when selecting new Transmitter modes for illumination and associated Receiver modes in response to attention requests.

CRIN Details and Theory
In this section, a detailed treatment of the relevant theory of cognitive dynamic systems needed to make CRINs a reality is provided.

The visual brain is a powerful, parallelized information processing machine with a built-in ability to perform certain tasks such as focusing attention on subjects of interest and pattern recognition at speeds far beyond the capability of traditional radar systems in existence today. With wide area radar information networks being deployed in the
21st century, we need such capabilities more than ever to manage the operator overload problem. We turn to cognition as the answer to this challenge, and lay in this section the theoretical foundation for the novel cognitive radar information networks described earlier. Indeed, there is much R&D work to be done. Fortunately, with the architectures proposed in this white paper new capabilities can be spiraled into deployed RINs incrementally over time.

**Fuster’s Paradigm for Cognition**

Much has been written on human cognition in the neuroscience literature but, unfortunately, with no unique definition for cognition to be found. This state of affairs may not be surprising because the study of human cognition has been of a conceptual nature, supported by detailed experimental work.

Building on the pioneering works of Vernon Mountcastle [9], David Marr [10] and many others on the neocerbral cortex, Joakuin Fuster proposed an “abstract model” for human cognition, made up of five functional building blocks, namely perception, memory, attention, intelligence, and language [11].

Hereafter, we refer to this abstract model as Fuster’s paradigm for cognition. From an engineering perspective, Fuster’s paradigm provides an “orderly conceived structure”, with memory building on perception, memory-driven attention building on perception, and intelligence building on all three preceding functional blocks. We will not elaborate on language as it is outside the scope of this paper. In functional terms, we may briefly describe in the context of a single radar, without loss of generality, the four building blocks of specific interest to the study of cognitive radar as follows, [12,5]. We will then broaden the discussion in subsequent sections to multiple targets and multiple radars as needed by the CRINs proposed here.

1. Perception-action cycle, the function of which is to improve information gained about the environment on a (cognition) cycle-by-cycle basis. For this cyclic

![Figure 8: Block diagram of cognitive radar with multi-scale memory.](image)
operation to be realized, there has to be a feedback link connecting the receiver to the transmitter, thereby establishing a global feedback loop embracing both the transmitter and the receiver; and, above all, including the environment inside its feedback loop.

2. Multi-scale memory, which is distributed throughout the radar system; the function of memory is to learn from the environment, so as to continually improve the model of the environment perceived by the receiver and the decision-making capability of the transmitter through the control action taken on the receiver via the environment.

3. Attention, which is memory driven, and whose function is to consolidate the perceptual processing power of the receiver and decision-making power of the transmitter through the appropriate allocation of system resources. System resources, for our purposes, include the controllable illumination parameters of the transmitter, processing modes of the receiver, and the computational and bandwidth abilities of the CRIN system.

4. Intelligence, which is the most profound of all the principles of cognition. Its function is to provide the means for a decision-making strategy that is optimal in the face of environmental uncertainties. The cognitive power of intelligence exploits the use of local as well as global feedback loops distributed around the entire radar system.

**Perception-action cycle**

To elaborate on the first defining process of cognitive radar, namely the perception-action cycle, we may, without loss of generality, consider a simplified, single target tracking problem. In this context, the primary function of the environmental scene analyzer; constituting a functional block in the receiver shown in Figure 8, is to provide an estimate of the state of the radar environment by processing the measurements. The term radar environment is used here to refer to the electromagnetic medium in which a target of interest is embedded. The observables (i.e. measurements) refer to the complex baseband form of the radar returns produced by reflections from the target due to illumination of the radar environment by a signal radiated from the transmitter. In effect, state estimation serves as “perception” of the environment in the perception-action cycle in Figure 8.

Insofar as the cycle is concerned, another function of the receiver is to compute feedback information that provides a compressed measure of information contained in the measurements about the unknown target.

Typically, the transmitter and receiver of the radar are collocated, in which case delivery of the feedback information to the transmitter by the receiver is accomplished simply through a direct linkage, thereby simplifying the radar system design.

Turning next to the environmental scene actuator, constituting a functional block in the transmitter in Figure 8, its primary function is to minimize a cost-to-go function based on feedback information from the receiver, so as to act in the radar environment optimally in some statistical sense. This optimization manifests itself in the selection of a transmitted signal whose waveform controls the measurements at the receiver input. The selection of a new transmitted signal or waveform is made on a cycle-by-cycle basis. In this sense, we may therefore look to the environmental scene actuator as a cognitive controller.
With emphasis on the term “information” in what we have just discussed here, the perception-action cycle in Figure 8 provides the basis for cyclic directed information flow across the entire radar system, inclusive of the environment; it is a cardinal characteristic of cognitive radar.

**Synchrony:** A master clock is available to the entire CRIN. Each radar is permitted to operate independently. The perception-action-cycle is carried out in a time ordered manner with respect to the master clock. Thereby, the network operates in a synchronous-like manner. From a practical, implementation point of view, the network allows for the arbitrary selection of the PAC time-step to suit the particular condition of the environment and the capabilities of the independent radars. In so doing, flexibility is available to the CRIN.

**Memory**
Before proceeding to discuss the important role of memory in cognitive radar, it is instructive that we make a distinction between knowledge and memory:

- Knowledge is a memory of certain facts and relationships that exist between them, none of which changes with time. In other words, knowledge is static in its contents.
- Memory is dynamic in that its contents continually change over the course of time in accordance with changes in the environment. Stated in another way: the contents of memory are subject to time constraints, whereas knowledge is timeless and therefore, free of time constraints.

With a cognitive radar consisting of a receiver and transmitter, conventionally, it has been logical to split the memory into two parts, one residing in the receiver and the other residing in the transmitter. These two parts of memory are respectively called perceptual memory and executive memory. It is in the memory of cognitive radar where most of the learning from interactions with the environment is performed.

**Perceptual Memory:** As the name implies, perceptual memory is an integral part of how, in an overall sense, the receiver perceives the environment. To be more specific, perceptual memory provides the ability for the receiver to interpret the incoming measurements so as to recognize their distinctive features and categorize the features accordingly.

We may thus offer the following definition:

*Perceptual memory is the experiential knowledge that is gained by the receiver through a process of learning from the environment, such that the contents of the memory continually change with time in accordance with changes in the environment; the experiential knowledge so gained through learning becomes an inextricable part of the perceptual memory.*

To satisfy the cognitive functional integration-across-time property, another cardinal characteristic of cognitive, we require that the perceptual memory be reciprocally coupled to the environmental scene analyzer. This reciprocal coupling implies the use of two links:

- **Feedforward (up) link** from a compartment within the environmental scene analyzer to the perceptual memory, which is intended to make it possible for the memory to update its contents in light of the new measurements.
- **Feedback (down) link** from the perceptual memory to the environmental scene analyzer, the purpose of which is to enable the analyzer to retrieve
information stored in memory; the retrieved information is naturally relevant to the particular categorical interpretation of the incoming measurements that is the focus of the attentional mechanism.

In effect, the perceptual memory adds sophistication in the form of bottom-up and top-down learning to the perception-action cycle, making it that much more powerful in terms of learning about the environment.

**Executive Memory:** Just as perceptual memory relates to perception of the environment in the receiver, executive memory relates to the corresponding transmitter’s action in the environment. To be more precise, contents of the executive memory are acquired through the transmitter’s actions in response to information about the environment that is supplied to it by the receiver via feedback; hence, the need for the feedback link included in Figure 8; we may thus offer the following definition:

*Executive memory is the experiential knowledge gained by the transmitter through the lessons learned from the actions taken to control the receiver via the environment, with contents of the memory changing with time in accordance with how the receiver perceives the environment.*

Here again, the knowledge so gained through experience becomes an inextricable part of the executive memory. Executive memory plays a key role of its own by learning how any new action taken by the transmitter in the environment benefits from the experiential knowledge gained from previous actions.

Here again, in order to satisfy the cognitive functional integration across-time property, the executive memory needs to be reciprocally coupled to the environmental scene actuator, as depicted in Figure 8. The need for this second reciprocal coupling in a cognitive radar is justified as follows:

1. The feedforward (up) link from the environmental scene actuator to the executive memory enables the executive memory to update its contents in light of new feedback information supplied to the actuator by the environmental scene analyzer.
2. The feedback (down) link from the executive memory to the environmental scene actuator enables the actuator to retrieve information stored in the memory.

**Working Memory:** Thus far, we have justified the needs for perceptual memory in the receiver and executive memory in the transmitter. Naturally, we cannot expect these two memories to function independently from each other. To be more precise, these two memories have to be also reciprocally coupled, as indicated in Figure 8. The transmitter and receiver of the cognitive radar are thereby enabled to operate in a synchronous manner through each cycle of the perception-action-cycle.

To be more precise, reciprocal coupling of the executive memory to the perceptual memory is required to address the issue of having to fully account for the cognitive functional integration across-time property. In so doing, the two memories are enabled to interact with each other so as to select the best action that can be taken by the transmitter to control the environment in light of the feedback information passed onto it by the receiver. As depicted in Figure 8, the cross-coupling between the perceptual memory and executive memory is made through the working memory, whose function is to coordinate sensory
perception in the receiver with the corresponding action by the transmitter in an orderly and timely manner. Specifically, if the wrong action is taken by the radar at one particular cycle, it is corrected on the next cycle.

**Attention**

In a fundamental sense, the purpose of attention is to selectively allocate the available system resources to realize the execution of a goal-directed action by the transmitter. We may therefore think of attention as a mechanism for prioritizing resource allocation in terms of practical importance, which makes a great deal of intuitive sense for the following reason. The system resources of cognitive radar are naturally limited, hence the following definition:

*Attention is a mechanism that protects both the perceptual-processing power of the receiver and the decision-making power of the transmitter from the information-overload problem through prioritization of how these system resources are allocated.*

In the context of cognitive radar, the term “information overload” refers to the difficulty experienced by the system when the receiver’s task of sensing the environment and the transmitter’s task of decision-making are compromised by having to handle too much information contained in the incoming measurements.

To elaborate, from the perspective of the receiver of cognitive radar, perceptive attention involves focusing the computational processing power of the receiver on a specific target situation that is of special interest. With perception consisting essentially of parallel processing and adaptive matching of characterizing “features” of the measurements to a particular “grid point” in the state-model library in the right-hand side of Figure 8, the desired mathematical model describing evolution of the hidden state across time is computed. In turn, that adaptive matching process leads to “top-down feedback”, whereby the computed state-model is made available to the environmental scene analyzer, and with it, state estimation of the target is carried out. What we have just described here is a localized perception-action cycle going on in the receiver with computation of the state-model as the object of interest.

Turning next to executive attention, the objective here is to focus the transmitter illumination capabilities in the transmitter through the use of an “explore-exploit strategy” [8]. The exploration phase of the strategy is based on two points:

1. The transmit-waveform parameter vector used in the preceding perception-action cycle is treated in the current cycle as the “centre point” of a cluster defined under point (2).
2. The grid points in the “transmit-waveform library” the left-hand side of Figure 8 that lie in the immediate neighbourhood of the centre point complete the rest of the cluster for the current cycle.

The complete cluster of grid points so obtained is down-loaded to the environmental scene actuator for action in the environment.

We may summarize the roles of attention in cognition as follows:

1. Based on the perceptual memory and executive memory built into cognitive radar, the attentional mechanism of the system allocates the available system resources, including prior knowledge; the two internal libraries of cognitive radar constitute prior knowledge.
2. In addition to these two memories, the attentional mechanism looks to the working memory for information on the consequences of actions taken by the system, with this provision being made on a short-time basis.

**Intelligence**

Previously, we identified the perception-action cycle, memory, attention and intelligence as the four functional building blocks of cognitive radar. Among this four, intelligence stands out as the most complex process and the hardest one to define. We say so, because the perception-action cycle, memory and attention, in their own individual ways and varying degrees, make contributions to intelligence, hence the difficulty in defining intelligence.

Nevertheless, we may offer the following statement on intelligence in the context of cognitive radar:

*Intelligence is the ability of cognitive radar to continually adjust itself in a robust manner through an adaptive process by making the receiver respond to new changes in the environment so as to create new forms of action and behaviour in the transmitter.*

Given the (i) localized cluster of transmit-waveforms selected from the internal library of the transmitter by the executive attentional mechanism, and (ii) feedback information about the environment supplied to the transmitter by the receiver, the decision making mechanism in the environmental-scene actuator is designed to pick the particular transmitter waveform within the cluster, for which a prescribed cost function is minimized. This optimization completes the exploit phase of the explore-exploit strategy. A unique feature of this decision-making process is the “smooth” manner in which selection of the transmit-waveform parameter is made from one perception-action cycle to the next; this feature is unique to a cognitive radar with multi-scale memory [8].

Intuitively, we may therefore say that at each perception-action cycle, the intelligent capability of the environmental scene actuator in the transmitter building on attention, memory and perception, picks the particular transmit-waveform that is adaptively matched to the environment in an optional manner, and its optionality is maintained from one cycle to the next.

**Efficiency of Processing Information:** For intelligence to stand for the processing of cognitive information toward the achievement of behavioural goals, the degree of intelligence is measured in terms of the efficiency with which that information is being processed. The key question is: How do we measure the efficiency of intelligence?

As observed earlier, the objective of the transmitter in cognitive radar is optimal action in the environment in light of feedback information sent to the environmental scene actuator in the transmitter by the environmental scene analyzer in the receiver; the optimization is done in the transmitter in some statistical sense. On this basis, we may therefore respond to the question just raised above as follows. Through the use of an optimal control algorithm in the transmitter, the cognitive radar becomes increasingly more intelligent whereby a prescribed cost-to-go function is progressively minimized on every perception-action cycle and with it, information about the environment is more efficiently utilized from one cycle to the next.
In saying so however, we should not overlook the issue of overall computational complexity of the system.

**Synchronized Cognitive Information Processing:** Looking at the perception-action cycle of Figure 8, we now see that we have a highly complex closed-loop feedback control system, nested within numerous local feedback loops positioned alongside global feedback loops. Accordingly, the receiver and transmitter of cognitive radar process information about the environment in a self-organized, synchronized manner and on a time-ordered basis.

**The Role of Intelligence in Cognition:** In summary, the cognitive role of the transmitter is that of decision-making, in the context of which probabilistic inference plays a key role. The term inference or reasoning refers to a process by means of which conclusions to a problem of interest are reached. Inference may well be the outstanding characteristic of intelligence. We may therefore sum up the role of intelligence in cognition as follows:

The decision-making mechanism in the transmitter of cognitive radar uses probabilistic inference to pick intelligent choices in the face of unavoidable uncertainties and disturbances in the environment.

The uncertainties are attributed to certain physical characteristics of the environment that have been overlooked or they are difficult to account for in modeling the environment; as for disturbances, they arise due to stochastic phenomena beyond our control.

Indeed, it may be justifiably argued that the task of decision-making in the face of environmental uncertainties and disturbances is the very essence of building a reliable radar system, which is where intelligence plays the key role.

**Experimental Support for CRINs**

There is considerable support in the literature for the emergence of CRINs as envisioned in this white paper. One need only look back six years ago to Haykin’s forecast of a new integrative field called cognitive dynamic systems [13], from which flowed a wealth of growing research and development with respect to cognitive radio [14]. The ideas embodied in cognitive radio are now being embraced by wireless network providers through the use of femtocells [15]. Haykin’s paper on “Cognitive radio: brain-empowered wireless communications” [14] has already been cited several thousand times, far in excess of the work of other researchers and developers on cognitive radio. These same cognitive principles, innovatively adapted and applied in this white paper, provide theoretical and experimental support for cognitive radar information networks.

Similar performance benefits have already been demonstrated through experimental simulation of a simple, single cognitive radar with a perception-action-cycle focused on improved single-target tracking of a maneuvering aircraft [8]. Performance comparisons among four different radar configurations are provided there:

- Traditional active radar (TAR), which operates in a feed forward manner (i.e., with no feedback from the receiver to the transmitter).
- Fore-active radar (FAR) also referred to as a fully adaptive radar in the radar literature, which distinguishes itself from the traditional active radar in having a feedback link from the receiver to the transmitter.
Cognitive radar with one level of memory (CR1) added to the fore-active radar.

Cognitive radar with multiple levels of memory (CRm)

Examination of the results presented in [8] illustrate that better and better tracking performance is realized as memory and the perception-action-cycle are added. In particular, as more elements of cognition are added, the estimation errors are progressively reduced. This, in effect, means that the radar is progressively becoming “risk free” in the presence of environmental uncertainties and disturbance.

While experimental models need to be expanded to multiple target tracking and multiple radars to support CRIN research and development, this earlier work in cognitive radio and cognitive radar provides confidence that cognitive radar information networks will pay significant performance dividends over conventional approaches.

Two-State Model of Cognitive Radar

Traditionally, in a state-estimation procedure for target-tracking applications, we start with a state-space model, the formulation of which is based on understanding the physical underpinnings of the radar environment. This model consists of a pair of equations:

(i) System equation, which describes, in mathematical terms, evolution of the state across time with the additive system noise acting as the driving force. The state is defined as the minimal set of physical parameters that describe the target at a particular instant of time and particular location in space.

(ii) Measurement equation, which mathematically describes the dependence of measurements on the hidden state as the receiver input, corrupted by additive measurement noise.

Thus, traditionally, we only think of the target state, to be estimated using the measurements. However, a cognitive radar is radically different from its traditional active radar counterpart in the following sense:

The state-space model of the environment lies inside a closed feedback loop, in which the receiver is linked to the transmitter.

In other words, we have feedback information supplied to the transmitter by the receiver. The key question is, how do we describe this feedback information that could provide the basis for a secondary state that supplements the target state?

To address this question, we first recognize that the source of the secondary state resides in the “estimation error vector”, defined as the difference between the so-called “actual” state of the target and its estimate. Recall that the “actual” state is extracted from the state-model library through an adaptive matching process governed by perceptive attention, which was discussed previously. Since the state-estimation error vector is random, we may quantify it by appealing to Shannon’s information theory. Specifically, entropy provides the “metric” for measuring the information content of the state-estimation error vector. Now, we are ready to answer the question just raised by introducing the notion of entropic state, representing the secondary state that supplements the target state.

For us to fully describe the environment, we therefore need to think of a two-state model,
which embodies two entirely different notions [16]:

1. Target state, which is of a deterministic physical kind. Ignoring the system noise, evolution of the target state over time is described by a deterministic continuous differential equation, which is often nonlinear.

2. Entropic state, which is of an information-theoretic kind.

As radically different as these two states are from each other, they do share a common feature. The target and entropic states of the environment change over time as the cognitive radar progresses from one perception-action-cycle to the next. To elaborate, the entropic state accounts for the following uncontrollable realities:

- Uncertainties, which are attributed to the fact that the target state is unknown.
- System noise, which is of stochastic nature, attributes to physical disturbances in the environment.
- Measurement noise, the sources of which include thermal noise generated at the amplifier input in the receiver as well as quantization noise that arises from using an analog-to-digital converter for digital processing of the complex baseband measurements, representing the radar returns. Then there is lake/sea clutter, weather clutter and other interference that would also have to be accounted for.

Recognizing that a cardinal characteristic of cognitive radar is the “control” exercised indirectly by the transmitter over the measurement noise in the receiver, the entropic state provides the mathematical premise for facilitating the feedback link from the receiver to the transmitter. In so doing, the entropic state – representing the feedback information in Figure 8 – is responsible for improving the information – processing power of cognitive radar, which is unreachable by a traditional active radar.

The adoption of entropic state as the feedback information from the receiver to the transmitter has a profound impact on how the transmitter is designed. Specifically, it opens the door for using “reinforcement learning” as the approximate dynamic programming algorithm for designing the cognitive controller, whereby computational complexity of the transmitter is reduced dramatically [16].

To summarize, modeling of the environment in cognitive radar comprises two states, one deterministic and the other stochastic, that are respectively defined as follows:

1. Target state, which is the minimal set of deterministic parameters needed for describing the target hidden from the receiver, and therefore unknown, at any instant of time and physical location in space.

2. Entropic state, which is an information-theoretic measure of the environmental uncertainties and disturbances that are responsible for the errors made by the receiver in estimating the target state.

From these two definitions, it follows that the closer we bring the entropic state of the environment to zero, the more deterministic the cognitive radar becomes. Stated in another way, the entropic state represents the “risk” that arises from uncertainties and disturbances and the smaller it becomes through cognition, the more “reliable” the cognitive radar becomes, hence the reference to cognitive radar as a risk controller.

Application to Real-World CRINs

With the material on cognitive radar theory at hand, the stage is now set for us to build
On that theory addressing the real world of the cognitive radar information network (CRIN), aimed at security applications around large bodies of water such as the Great Lakes.

In structural terms, the CRIN is composed of three systems integrated into one that is appropriately referred to as complex system of systems; specifically, we have:
- Observation network, which consists of a network of inexpensive marine surveillance radars, each is cognitized, building on the current design through software expansion. Figure 9 shows a block diagram at the observation network.
- Mid-level information – processing system, which processes the outputs of the individual surveillance radars with the aim of solving the suspicious target-recognition problem.
- Executive-level system, which is where overall control and decision-making in the entire CRIN is centered. The primary aim here is to command subsets of surveillance radars in the observation network to focus attention on one or more areas in the environment. Such areas require enhanced performance as a result of (i) the detection of suspicious targets, (ii) the presence of environmental disturbances, or, (iii) operational priorities as determined by the operator.

Figure 9: Block diagram of the Observation Network in the CRIN
Note: Any radar can be selected for action by the executive level system to apply attention in the neighborhood of that radar.
With the observation network explained previously, we may now proceed to describe the mid-level information processing network, which involves two issues: the detection of suspicious targets and generalization of the entropic state.

**Suspicious Target Detection**

Perhaps, the most challenging problem in designing the CRIN for security is that of detecting the presence of one or more suspicious targets. As previously mentioned, this problem may be viewed as those of finding a “needle in the haystack”. Not only that, but also the solution to the problem has to be provided automatically in an on-line manner.

To appreciate the practical difficulty of the suspicious-target detection problem, consider the real-life image of Figure 2, depicting a highly congested ensemble of target tracks, representing one hour of traffic across Lake Ontario. The tracks are computed, off-line by using radar data collected from a network of six Accipiter radars distributed across Lake Ontario, all the way from Niagara-on-the-Lake to Toronto Island. The tracks shown in white are attributed to a single radar and those with multiple colours are attributed to two or more radars.

Currently, methods for detecting a suspicious target in an environment exemplified by that shown in Figure 2, using signal/information-processing techniques automatically in an on-line manner are not known.

This statement may not be surprising for the simple fact that detection of a suspicious target in the scenario addressed herein is entirely different from the traditional target-detection problem in the presence of sea/lake clutter, where we may use a Bayesion hypothesis testing procedure. Sure, in the case of suspicious target detection, we can also postulate a hypothesis. But, in light of Figure 2, unfortunately, such a hypothesis does not lend itself to traditional detection procedures. Simply put, the nature of the new hypotheses, to be described herein, has to be behavioural and not mathematical.

To emphasize the nature of the behavioural hypotheses in the suspicious-target detection problem, we need to remind ourselves of the underlying characteristics of a suspicious-target that were described previously under the heading of Behavioural Geometries. Therein, we identified a few illustrative “discriminants” that characterize a suspicious target, namely:

- A border crossing
- A rendezvous
- Loitering in an exclusion zone (e.g. an area around a nuclear power station)
- Other abnormal target behaviour (e.g. a trajectory that deviates from a regulated laneway or seaway, turning ones AIS transponder off, a trajectory in an unusual place or at an unusual time, etc.)

Each of these discriminants is of a “behavioural” kind. We can now define two hypotheses of interest:

Hypothesis, $H_0$: The radar trajectory under test belongs to a well-behaved target because its behaviour is normal.

Hypothesis, $H_1$: The radar trajectory under test belongs to a suspicious target because its behaviour is abnormal.

Having clarified the underlying issue involved in the detection of a suspicious target, where do we find the algorithmic
mechanism to solve this new kind of target detection? The answer lies in the use of soft computing, and, in particular, fuzzy logic.

**Soft Computing**

To begin what we have in mind, we cannot do better but reproduce verbatim the statement made by Lotfi Zadeh, the father of fuzzy logic [17]:

“In traditional “hard” computing, the prime desiderata are precision, certainty, and rigor. By contrast, the point of departure in soft computing is the thesis that precision and certainty carry a cost, and that computation, reasoning and decision making should exploit – wherever possible – the tolerance for imprecision and uncertainty.”

We may therefore go on to say that the issue of detecting a suspicious target in an environment exemplified by the image depicted in Figure 2 can best be tackled through the use of fuzzy logic, neural networks [18], and soft computing.

The remarkable human ability of a radar operator. Indeed, it can be justifiably argued if it were possible for an experienced radar operator to focus attention entirely on the radar screen picturing the congested ensemble of target tracks shown in Figure 4, then at a certain point in time – that operator will have detected the suspicious target.

Figure 10 presents a block-diagrammatic depiction of a soft computing algorithm for the detection of a suspicious target. Note that unlike traditional target detection, the threshold in soft computing takes the form of a behavioural threshold, and so it should.

Note also that in Figure 10, we have used the “if-then” rule in the way in which the decision is made in favour of hypothesis $H_0$ or hypothesis $H_1$. For example if the trajectory of a target deviates from a regulated laneway, then that target is suspicious. This example illustrates the logic behind probabilistic reasoning.

![Figure 10](image)

**Figure 10:** Illustrating the soft computing algorithm for detecting suspicious targets

To expand on what we have just said, we need to remind ourselves of the fact that the exploitation of tolerance for imprecision and uncertainty underlies the remarkable human ability of a radar operator. Indeed, it can be justifiably argued if it were possible for an experienced radar operator to focus attention entirely on the radar screen picturing the congested ensemble of target tracks shown in Figure 4, then at a certain point in time – that operator will have detected the suspicious target.

The principal constituents of the soft computing are three-fold:

<table>
<thead>
<tr>
<th>Example Behavioural Thresholds</th>
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</thead>
<tbody>
<tr>
<td>(i) border crossing</td>
</tr>
<tr>
<td>(ii) rendezvous</td>
</tr>
<tr>
<td>(iii) loitering</td>
</tr>
<tr>
<td>(iv) abnormal target behaviour</td>
</tr>
</tbody>
</table>

The principal constituents of the soft computing are three-fold:
1. Fuzzy logic, which is primarily concerned with imprecision.
2. Neural networks, the role of which in soft computing is learning theory.
3. Probabilistic reasoning, which is primarily concerned with the issue of uncertainty.

The important note here is that although there exists overlaps between these three constituents, when it comes to soft computing they do indeed complement each other.

For more detailed information on these three constituents of soft computing, the reader is referred to the books listed under references [19-23].

**Entropic State of Localized Environment**

Another topic that needs to be addressed in the design of CRIN is that of environmental disturbances such as precipitation or sea/lake clutter, for which we need a reliable indicator. To this end we look to a generalization of the entropic state introduced in the part dealing with Cognitive Radar Theory.

Therein, the entropic state of an environment was introduced in the context of a single cognitive radar that tracks a single target; this scenario is somewhat idealized but, nevertheless, it could be generalized in a practical way, as discussed next.

In a real-world surveillance scenario intended to track multiple targets using a single radar (e.g. the Accipiter Radar), we have to think in terms of the entropic state of a “localized” part of the environment under surveillance, where the radar is one of the many within a CRIN. The key question is how do we define and therefore compute the entropic state of such a localized environment?

To address this fundamental question of practical importance, we make the following two observations:

1. Using the target tracking algorithm of the surveillance radar, we have access to the state-estimation error vector of each target under surveillance; accordingly, we may compute the entropic state of each of the target, being surveilled.
2. The target states are all independent of each other. From information theory, we know that given a set of statistically independent random vectors, the overall entropy of the set is equal to the sum of the entropies of the individual random vectors.

It follows therefore that in radar surveillance, the composite entropic state of the associated localized environment is equal to the sum of all the entropic states concerned.

Now, for most of the time, radar surveillance of the environment is in a steady state, which means that in a corresponding way the composite entropic state is relatively constant. It follows therefore that any noticeable increase in this relatively constant value is attributed to the unexpected occurrence of some disturbance in the localized environment. More than likely, a natural cause for such a disturbance is weather precipitation or increased surface clutter.

We may thus go on to say:

*The composite entropic state of a localized environment under surveillance provides a “barometer” for disturbances due to*
weather precipitation and or clutter in the environment.

This statement will be put to good use later on.

**The Mid-Level Information Processing System**

In Figure 11, we have assembled the functional blocks that constitute the mid-level information-processing system of the CRIN, the inputs of which consist of target trajectories and entropic states computed by the individual surveillance radars in the observation network.

The new functional block included in Figure 11, namely the sorting machine, is intended to provide a systematic mechanism for implementing the engineering paradigm: divide and conquer, which was mentioned previously. Simply put the sorting machine orders the incoming inputs from the observations network into sub-groups; for example, we may sort by radar-cross sections of the targets (e.g. small, medium, and large), as well as by target speeds (e.g. slow, moderate and fast).

![Figure 11: Block diagram of mid-level information processing system in the CRIN](image-url)
In so doing, the tasks to be performed by the soft computing algorithm for the detection of suspicious targets (using target trajectories) and the issue of precipitation alarms (using entropic states) are simplified considerably.

Note that the upper part of Figure 11 includes a suspicious target library (indicative of suspicious target behaviours) that is used by the soft computing algorithm and is reciprocally coupled to the executive memory in the executive-level system. This library consists of prior information (e.g. provided by the operator) as well as information learned from experience by the cognitive controller over the course of time.

**The Executive-Level System**

The observations network and mid-level information-processing system, described in Figure 9 and 11, respectively, provide the front ends of the third and last functional block in the CRIN, namely the executive-level system, depicted in Figure 12. The system consists of three constituents:

- Radar operator,
- Cognitive controller, and
- Memory reciprocally coupled to the cognitive controller

In a way, the cognitive controller builds on the following cognitive processes:

- The perception-action cycles performed individually by the surveillance radars through their interactions with the radar environment;
- Memories built into the surveillance radars; and
- The computations performed to produce target trajectories and entropic states pertaining to the radar environment.
Moreover, the cognitive controller looks to the mid-level information processing system for the soft-computing detection of suspicious target(s), and environmental disturbances such as precipitation and surface clutter, if and when they arise. Last but by no means least; the cognitive controller is reciprocally coupled to the radar operator, who is responsible for the final decisions made. The radar operator can call for attention to a particular area and task the cognitive controller to deliver it.

The cognitive controller can also be authorized to apply attention in an intelligent manner in response to environmental disturbances or a discovered suspicious target, for example, in order to keep the CRIN performance optimized automatically.

It is therefore not surprising that the cognitive controller is by far the most powerful artificial functional block in the CRIN. Its primary function is two-fold:

1. **Decision-making**, which involves identification of the localized part of the radar environment requiring attention as well as the associated surveillance radars in the CRIN that can impact performance there (for example, the radars that are closest), and
2. **The speedy focused attention on the areas of interest**, directing respective surveillance radars to apply their system resources to enhance performance in those areas, in an intelligent manner subject to system constraints.

Figure 12 shows a block diagram of the executive-level system, where the executive memory’s function is to store information relating to decisions made by the cognitive controller and continually update the stored information from one perception-action cycle to the next. In other words, the executive memory continually learns from overall interactions with the environment and every time the controller is about to act, the executive memory reminds it of past actions taken and their consequences.

One other important note is the fact that the executive memory is also reciprocally coupled to the suspicious targets library in the mid-level information processing system to learn from prior knowledge stored therein and provide it with new information gathered from the controller’s overall interactions with the environment.

Lastly, the cognitive controller looks to the disturbance barometer for information on precipitation and clutter, the occurrence of which may well be needed for decision-making.

**Focusing Attention on the Area of Interest**

How does the Cognitive Controller command the attention of the CRIN to an area of interest? The answer to this fundamentally important question will be the subject of research directed towards making CRINs a reality. Work on cognitive dynamic systems to date point to an explore-exploit strategy as a suitable approach, as further described below.

This strategy works as follows:

1. Knowledge (obtained through memory) of the available transmitter illuminations and receiver processing modes associated with each radar that has influence over the area of interest is provided.
2. A cluster of adjustable radar parameter combinations is formed for this subset of radars, with the current radar parameter vector representing the centre of the new cluster. This move constitutes the first
step in the exploration phase and the starting point of a perception-action-cycle.

3. For each radar in the subset, the entropic state of the targets in question is made available to the Cognitive Controller. Alongside this entropic state, an entropic reward function is computed, which relates to the improvement in measured performance from the previous PAC step. The algebraic sign of this entropic reward function guides the action of the Cognitive Controller in a correct manner. The sign is positive if the reward is positive; otherwise, it is negative in which case we have the equivalent of "punishment." In a loose sense, we may think of reinforcement learning as a "reward and punish" sort of algorithm.

4. The Cognitive Controller smoothly advances from the current radar parameter-vector to a new one in the cluster of possible parameter-vectors using, for example, a reinforcement learning algorithm. Each action (i.e. change) taken by the cognitive controller will result in a corresponding change in the entropic state.

5. The Q-learning algorithm [24] is one method of reinforcement learning and planning, whereby both learning and planning are integrated together. Using the algorithm, the optimal action is computed and taken by selecting that particular radar parameter vector for which the performance of each radar in the subset is optimized, and with it the exploit phase of the strategy is completed.

The Q-learning Algorithm: For our problem, the Q-factor is defined on the basis of (entropic) state-action pairs. The behavioural task of reinforcement learning positioned in the Cognitive Controller is to find an optimal policy after trying out various possible sequences of actions, observing the transition from one entropic state to another for each radar under test, and finally, the corresponding rewards resulting from the transitions. The policy used to generate such a behaviour is called the "behaviour policy." To describe the essence of the Q-learning algorithm, consider a sample consisting of a trial action, performed on an entropic state that results in transition to a new state and therefore an observed reward resulting from the transition. The Q-learning algorithm, due to Watkins [25], provides an online procedure for learning an optimal behaviour policy through experiential interactions of the Cognitive Controller with the radar environment, which is gained solely on the basis of the four-tuple sample: current entropic state, trial action, next entropic state, and transition reward. In short, the Q-learning algorithm may be viewed as a combination of value iteration algorithm and Monte Carlo simulation.

In reinforcement learning, the value function is defined as the expected value of an "infinite" sum of discounted rewards for a particular entropic state; in practice, the summation is terminated, once the value function stabilizes. As such, the value iteration is an algorithm based on iterative computation of the value iteration function.

One last comment is in order: there is microbiological evidence that reward signals resulting from interactions of an animal with the environment are processed by mid-brain neurons, known as dopamine neurons [26]. Viewing these neurons as "a retina" of the rewards system, the responses produced by dopamine neurons may be considered as teaching signals for another kind of reinforcement learning called "temporal - difference learning".
The Integrated Cognitive Radar Information Network

In Figure 13, we have integrated the three parts of the CRIN, namely the observations network, mid-level information-processing systems and the executive-level system, into a single block diagram.

Examination of Figure 13 reveals that we now have a new global perception-action cycle that embodies all three constituents’ parts of the CRIN as well as the environment. In effect, in building the CRIN, we have made the entire network into a closed-loop feedback control system that is reciprocally coupled to the radar environment.

To summarize, we may describe the CRIN as a distributed complex system of systems that operates in a self-organized and synchronous manner, with all the practical benefits attributed to cognition. Most importantly, referring to Figure 13, we see that the CRIN embodies several perception-action-cycles that include the environment. Hence, an enhanced radar information processing network is realized.

Summary and Conclusions

In this paper, we have considered 21st century, wide-area radar information networks (RINs) that have been developed and are being deployed along the Canada/US border to address threats associated with vessels, low-flying aircraft and other targets of interest. The vastness of the areas being monitored, the large numbers of dissimilar radars employed, and the rich environment of commercial and recreational targets, make suspicious activity identification quite challenging for operators.

The paper demonstrated that dramatic, additional force multiplication is achievable by building the operator’s cognitive abilities of attention and intelligence into these radar networks. The resulting cognitive radar information networks provide relief for operator overload, increasing their effectiveness significantly and cost-effectively.

The concept of operation and a practical architecture for CRINs was presented. We showed how existing radars and assets can be leveraged to incrementally build in cognition. A detailed treatment of the relevant theory of cognitive dynamic systems and related algorithms was presented, as well as technical issues and supporting R&D needed to make CRINs a reality in the future. This treatment will guide researchers and developers by providing them with a unified framework within which to work.

We illustrated how CRINs can learn from the environment and past operator decisions in order to assist operators, while respecting risk management principles that require the primary surveillance mission to be maintained. We developed the incremental structures and system elements needed to provide the needed capability to automatically focus system resources (i.e. apply attention) on areas of heightened interest, while maintaining acceptable system performance elsewhere (i.e. attention is applied intelligently).

This key, cognitive capability leverages existing surveillance assets to provide improved system sensitivity and performance when and where they are needed most. For example, attention can be
applied to particular areas when INTEL or covert operations dictate, reactively in response to accidents or incidents or the automatic detection by the system of suspicious activity, or proactively when a high-risk event could result during VIP events or LNG tanker transits.

We have also shown how CRINs can take advantage of specialized radar assets such as agile radars that can be tasked to lock onto a designated, high-risk target of interest such as a low-flying aircraft headed towards an urban area, sacrificing surveillance for the short time needed to maintain target lock.

This paper presents a vision for the 21st century. Homeland security, rather than theatre defence, will drive radar innovation. Homeland security requires situational understanding over vast areas, continuously, forever, and the areas are target rich, with mostly friendly targets, and the odd threatening one. This is in stark contrast to defence environments which are typically limited in space and time, and which there are only friends (who identify themselves) and foes who are relatively sparse.

Convergence between radar sensing, communications, and information technology during the past 20 years has lead us to spatially distributed, heterogeneous radar information networks that will grow in dominance and utility in the 21st century. From a technology stand point, we are now in striking distance of being able to introduce powerful, cognitive capabilities into our surveillance machines. The vision for cognitive radar information networks presented here will hopefully excite stakeholders into action and drive innovation across human and machine sciences during the early part of this century.

![Figure 13: Block diagram of the CRIN](image-url)

In the 20th century, radar had its genesis and major advances were made to radar engineering in response to the physics of remote sensing of the environment. A skilled operator was coupled to large, scalar radar sensors to provide interpretation and intelligence.
References


