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Coordinated radar resource management for networked phased array radars

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Abstract

A phased array radar has the ability to rapidly and adaptively position beams and adjust dwell times, thus enabling a single radar to perform multiple functions, such as surveillance, tracking and fire control. A radar resource manager prioritises and schedules tasks from the various functions to best use available resources. For networked phased array radars that are connected by a communication channel, this document considers whether coordinated radar resource management (RRM), which exploits the sharing of tracking and detection data between radars, enhances performance compared to Independent RRM. Two distinct architectures for Coordinated RRM are proposed, centralised management and distributed management, and characteristics of each architecture are specified. It is shown that different types of distributed management are possible, with each type characterised by varying amounts of coordination between the radars. A two-radar network and 30-target scenario are modeled in the simulation tool Adapt_MFR, to analyse the performance of Independent RRM and two types of Coordinated RRM. Results indicate that the Coordinated RRM techniques achieve the same track completeness as Independent RRM, while decreasing track occupancy and frame time. Therefore, Coordinated RRM can improve reaction time against threats, at the expense of sending data across a communication channel.

Résumé

Un radar à balayage électronique peut positionner les faisceaux et régler les temps de tenue rapidement et de manière adaptative, permettant ainsi à un seul radar de remplir de multiples fonctions, comme la surveillance, la poursuite et la conduite de tir. En outre, la gestion des ressources radar attribue aux tâches des diverses fonctions une priorité et les ordonnance pour permettre une utilisation optimale des ressources disponibles. Pour les radars à balayage électronique réseautés raccordés par un canal de communication, le présent document examine si la gestion des ressources radar (GRR) coordonnée, qui exploite le partage des données de poursuite et de détection entre les radars, améliore la performance par rapport à la GRR indépendante. Deux architectures distinctes pour la GRR coordonnée sont proposées (gestion centralisée et gestion répartie), et leurs caractéristiques sont précisées. On constate que divers types de gestion répartie sont possibles, et que chaque type est caractérisé par une coordination plus ou moins importante entre les radars. De plus, un réseau à deux radars et un scénario à trente cibles sont modélisés dans l'outil de simulation Adapt_MFR en vue d'analyser la performance de la GRR indépendante et deux types de GRR coordonnée. Selon les résultats, les techniques de GRR coordonnée produisent le même taux de complétude de poursuite que la GRR indépendante, tout en réduisant le taux d'occupation de la poursuite et la durée de trame. Par conséquent, la GRR coordonnée peut améliorer le temps de réaction par rapport aux menaces, au prix de la transmission de données sur un canal de communication.

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Executive summary

Coordinated radar resource management for networked phased array radars

Peter W. Moo, Zhen Ding; DRDC Ottawa TM 2013-124; Defence Research and Development Canada – Ottawa; November 2013.

Background: A phased array radar has the ability to rapidly and adaptively position beams and adjust dwell times, thus enabling a single radar to perform multiple functions, such as surveillance, tracking and fire control. A key aspect of phased array radar operation is radar resource management (RRM), which considers how best to schedule tasks associated with the multiple functions. Previous work has focused on optimal methods for assigning relative priorities to various tasks and using the priority values to scheduling tasks appropriately for a single phased array radar. This work considers a network of phased array radars that are connected by a communication channel. The purpose of this work is to determine whether Coordinated RRM, which exploits the sharing of tracking and detection data among radars in the network, can enhance radar performance.

Principal results: Two distinct architectures for Coordinated RRM are formulated, centralised management and distributed management. It is shown that different types of distributed management are possible, with each type characterised by varying amounts of coordination between the radar nodes. A two-radar network and 30-target scenario are modeled in the simulation tool Adapt_MFR, to analyse the performance of Independent RRM and two types of Coordinated RRM. All RRM techniques utilise adaptive task prioritisation, track update intervals, and radar scheduling. It is shown that the two types of Coordinated RRM achieve the same track completeness as Independent RRM, while decreasing track occupancy and frame time.

Significance of results: Results show that Coordinated RRM can enhance radar performance compared to Independent RRM. This indicates that a radar network using Coordinated RRM can improve reaction time against new threats. To achieve this enhanced performance, the radars must send data across a communication channel. The data to be transmitted includes the position, velocity, and orientation of each radar platform, detections associated with overlapping tasks, and the estimated position of targets at track confirmation.

Future work: The use of Coordinated RRM offers the potential for significant performance improvements, but also requires further study. In this work, it is assumed that the communication channel is error-free and that data is transmitted with zero latency. Future work should examine the effect on channel errors and data latency on the performance of

Coordinated RRM techniques. The example considered utilises RRM techniques based on fuzzy logic prioritisation and the time-balancing scheduler. Independent RRM and Coordinated RRM based on other techniques should also be considered.

Sommaire

Coordinated radar resource management for networked phased array radars

Peter W. Moo, Zhen Ding ; DRDC Ottawa TM 2013-124 ; Recherche et développement pour la défense Canada – Ottawa ; novembre 2013.

Introduction : Un radar à balayage électronique peut positionner les faisceaux et régler les temps de tenue rapidement et de manière adaptative, permettant ainsi à un seul radar d'effectuer de multiples fonctions, comme la surveillance, la poursuite et la conduite de tir. Un aspect clé du fonctionnement du radar à balayage électronique est la gestion des ressources radar (GRR), qui examine la meilleure faon de programmer des tâches associées à des fonctions multiples. De plus, des travaux antérieurs ont porté sur les méthodes optimales pour assigner des priorités relatives à diverses tâches et utiliser les valeurs prioritaires pour programmer les tâches de manière appropriée pour un seul radar à éléments de phase. La présente étude porte sur un réseau de radars à balayage électronique connectés par un canal de communication. Elle vise à déterminer si la GRR coordonnée, qui exploite le partage des données de poursuite et de détection entre les radars dans le réseau, permet d'améliorer la performance du radar.

Résultats : Deux architectures distinctes pour la GRR coordonnée sont formulées, soit la gestion centralisée et la gestion répartie. De plus, divers types de gestion répartie sont possibles, et chaque type est caractérisé par une coordination plus ou moins importante entre les noeuds radar. En outre, un réseau à deux radars et un scénario à trente cibles sont modélisés dans l'outil de simulation Adapt_MFR en vue d'analyser la performance de la GRR indépendante et deux types de GRR coordonnée. Par ailleurs, les techniques de GRR utilisent le classement adaptatif des tâches par ordre de priorité, les intervalles de mise à jour des pistes et l'ordonnancement radar. On constate que les deux types de GRR coordonnée produisent le même taux de complétude de poursuite que la GRR indépendante, tout en réduisant le taux d'occupation de la poursuite et la durée de trame.

Portée : Selon les résultats, la GRR coordonnée peut améliorer la performance du radar par rapport à celle de la GRR indépendante. Cela indique qu'un réseau de radars qui utilise la GRR coordonnée peut améliorer le temps de réaction contre les nouvelles menaces. Pour obtenir cette performance améliorée, les radars doivent transmettre les données sur un canal de communication. Les données à émettre comprennent la position, la vitesse, l'orientation de chaque plateforme radar, les détections associées aux tâches qui se chevauchent et la position évaluée des cibles au moment de la confirmation de la poursuite.

Recherches futures : L’utilisation de la GRR coordonnée permettrait d’améliorer considérablement la performance, mais elle doit aussi faire l’objet d’études supplémentaires. Dans le cadre de la présente étude, on suppose que le canal de communication est sans erreur et que les données sont émises avec un temps d’attente nul. D’autres études devraient porter sur l’effet des erreurs de canal et des latences de données sur la performance des techniques de GRR coordonnée. L’exemple porte sur l’utilisation des techniques de GRR en fonction du classement de l’ordre de priorité par logique floue et d’un ordonnanceur à équilibrage du temps. Finalement, il faudrait aussi étudier la GRR indépendante et la GRR coordonnée axées sur d’autres techniques.

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1 Introduction

Military systems are increasingly considering task force operation, where multiple platforms are deployed to an area of interest. This focus has resulted in research activity in sensor resource management, which optimises the assignment of multiple sensors to multiple tasks [1]. Sensor resource management takes place at the Command and Control (C2) level and attempts to answer the question of what tasks should be assigned to various sensors. For a complex sensor such as a phased array radar, an equally important question considers how the sensor should schedule each of its assigned tasks. Because a phased array radar has the ability to rapidly and adaptively position beams and adjust dwell times, a single radar can perform multiple functions, such as surveillance, tracking and fire control. A radar resource manager prioritises and schedules tasks from the various functions. While sensor resource management operates among many sensors on one or more platforms at the C2 level, radar resource management (RRM) operates on a single platform at the single sensor (radar) level to make the best use of the flexibility of a phased array radar [2].

Previous work on RRM has considered adaptive techniques which vary with the number and type of tasks to be executed by the radar. **Task prioritisation** quantifies the relative importance of tracking and surveillance tasks that must be carried out by the radar [3], [4]. In prioritising target tracks, the estimated characteristics of the target and the environment are used to compute relative priorities. For surveillance tasks, a priori information about threats and the recent history of detections and tracks can be used to compute the relative priority of a sub-region compared to another. Update intervals for tracking tasks can be varied adaptively based on task priority or target dynamics [5–7]. **Task scheduling** involves deciding which look requests should be scheduled and specifying the starting time of each scheduled look [8–13]. Scheduling algorithms typically make use of relative task priorities in formulating the radar schedule, and may incorporate adaptive track update intervals.

This document considers a network of phased array radars which are connected by a communication channel [14]. The purpose of this work is to determine how the sharing of tracking and detection data among radars in the network can be used to enhance RRM performance. For the remainder of this document, the term “resource management” will refer to radar resource management, as opposed to the C2 concept of sensor resource management. The networked concepts developed will be referred to as **Coordinated RRM**, since the data from other radars is exploited in carrying out RRM. High-level concepts for Coordinated RRM will be formulated. In addition, results from the simulation of a two-radar network will illustrate the performance gains that are possible with Coordinated RRM.

Section 2 discusses radar network terminology, previous work in distributed tracking and performance metrics. Section 3 formulates and characterises high-level management architectures for Coordinated RRM. Section 4 presents an overview of the simulation tool Adapt_MFR, which will be used to demonstrate Coordinated RRM performance. In Section 5, Coordinated RRM for a two-radar network is analysed in modeling and simulation. Finally conclusions are presented in Section 6.

2 Preliminaries

Figure 1 illustrates the role of a resource manager for a single radar. The radar functions include surveillance and tracking. Each function consists of one or more tasks. For the target tracking function, a task involves the tracking of an individual target, while for the surveillance function, a task involves the monitoring of a specified region of interest. Each task consists of several looks, where a look requires one continuous time interval of finite duration to be completed. For a tracking task, a look is an attempt to update a track by steering the radar in the direction of the expected location of the target. For a surveillance task, a look consists of one or more beam positions of the radar.

Each task sends look requests to the radar scheduler. For a target tracking task, a look request may consist of an attempt to update a track at a specified time. The specified time will depend on the time of the track update, the estimated target dynamics and the tracking model. Each task makes look requests independently, based only on its own requirements. The radar scheduler receives all look requests and formulates a schedule for the radar, under the constraint that at any given time, the radar only executes one look. The radar scheduler must decide whether or not to schedule the look request. For example, if two look requests which start at the same time are received, the scheduler must decide whether to alter the start times of one or both looks or to not schedule one of the looks.

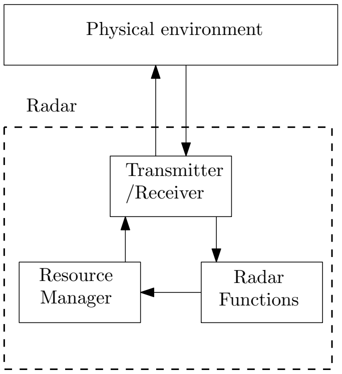


Figure 1: Resource management for a single radar.

This document presents the the formulation of Coordinated RRM for networked radars, where detection and tracking data from other radars is used in radar scheduling. In order to develop these Coordinated RRM techniques, a number of preliminary concepts are discussed in this section, including radar network terminology, distributed tracking, and performance metrics.

2.1 Radar networks

This document considers the resource management of a network of N monostatic radars. Although attention is restricted to monostatic radars, it is possible to extend the resource management problem to include multistatic radars. Due to the large number of possible combinations of transmitters and receivers, a multistatic network will be even more complex than a monostatic network.

Different types of resource management architectures for radar networks can be formulated, and each may lead to different solutions for the resource management problem. This work considers two types of resource management architecture: **centralised management** and **distributed management**. These concepts will be specified later in this document. In both cases, the portion of the network that is colocated with a radar antenna will be referred to as a node.

An element common to the radar networks is a communication channel. The channel capacity, or maximum throughput, is a key element of networked radar. If the channel is wireless, the capacity will likely change over time. Resource management algorithms must therefore be able to cope with the potential of time-varying channel capacity. For this work, it will be assumed that all data is received without error on the channel. In future work, the modeling of communication errors will need to be accounted for to accurately assess resource management performance.

The relationship between the coverage areas of the radar nodes is an important characteristic of the network. Consider the case when two or more nodes have coverage areas that overlap. Define the nodes with overlapping coverage areas as contributing nodes. The common coverage area will be called the overlapping region, as shown for the two node case in Figure 2. For a tracked target or surveillance region that is located in the overlapping region, the resource manager must decide which contributing node should carry out the associated surveillance or tracking task. This assignment may vary with task and as a function of time. This adds complexity to the scheduling task for the resource manager.

If the coverage areas of each node do not overlap, then each node would be managed as in the single-radar case. If coverage areas are adjacent to each other, then tracks could be handed off from one coverage area to an adjacent coverage area.

2.2 Distributed tracking

The extension of RRM to networked radars will build on previous results from distributed tracking in distributed sensor networks. Data association, which is the association of measurements from one or more sensors to the same target, is a key problem in multiple target tracking. When multiple sensors are connected by a communication channel, the information to be communicated on the channel must be determined. For the case of multiple

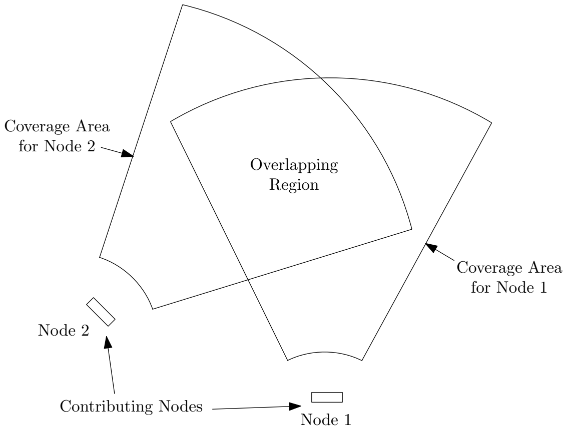


Figure 2: Two nodes with overlapping coverage areas.

hypothesis tracking, tracking performance was analysed when a subset of hypotheses and tracks are communicated between the sensors [15]. When joint probabilistic data association (JPDA) is used in a distributed sensor network, [16] showed that a global tracking estimate is formed by communicating the local estimates of each target along with the feasible events and their probabilities. Increasing the effective tracking update rate with a large network of track-while-scan radars was considered in [17]. A technique was presented for increasing the effective update rate while maintaining a reasonable communications bandwidth.

In general three types of distributed tracking can be considered [18], as follows

1. Independent tracking
2. Distributed track fusion (track-to-track data association)
3. Distributed track maintenance (measurement-to-track data association)

In independent tracking, each radar conducts tracking independently of the other radars in the network, and the tracks are initiated and maintained separately. If a target is in the coverage area of multiple radars, it is likely that each radar will create a track of that target. With distributed track fusion, each radar conducts tracking independently, and track fusion is carried out via track-to-track data association to remove redundant tracks. With distributed track maintenance, a single track is created for each target, and measurement-to-track data association is conducted for measurements from all radars in the network.

2.3 Performance metrics

RRM performance can be quantified using a number of metrics, including the SIAP metrics for tracking [19]. In this work, RRM performance will be measured by evaluating track completeness, track occupancy and frame time. Track completeness C is given by

$$C = \frac{\text{total time interval over which any track number is assigned to target}}{\text{total time that target is in the defined coverage area of radar}} \tag{1}$$

so that $0 \leq C \leq 1$. The coverage area is defined as the region where the signal-to-noise ratio exceeds a specified threshold. Track occupancy is the fraction of available radar time that the radar is either transmitting waveforms or receiving the returns from transmissions related to tracking functions. Surveillance frame time is the time between surveillance looks in a given region of space. For a specified region, either average frame time or maximum frame time can be measured. In an ideal case, track completeness is large, and track occupancy and frame time are small.

The goal of this work is to develop Coordinated RRM techniques that demonstrate enhanced performance compared to Independent RRM techniques. Performance will be measured by computing track completeness, track occupancy and frame time.

3 Architecture concepts for coordinated radar resource management

Coordinated RRM includes the scheduling of tracking and surveillance tasks, the processing of tracking and detection data from other radars, and the specification of techniques for distributed tracking. As such, it addresses a time-varying multidimensional optimisation problem. Since Coordinated RRM is a new area of study, this section formulates two distinct management architectures: centralised management and distributed management. Specific Coordinated RRM techniques will be implemented and analysed in Section 5.

3.1 Centralised management architecture

In a network with centralised management, a single resource manager formulates the schedule for all radar nodes. The resource management platform may be colocated with any one of the radar nodes or may be located separately. This architecture is shown in Figure 3, which illustrates the case when the resource management platform is located separately from the radar nodes. The resource manager receives on the communication channel tracking and detection data from each of the nodes and sends over the communication channel a resource schedule to each of the radar transmitters. The advantage of centralised management is the ability of the resource manager to utilise and control all of the available radar resources. A resource manager in a network with centralised management fully exploits the multiple radar nodes that are available. The disadvantages of centralised management include the vulnerability of varying throughput on the communication channel and the potential for data latency. If communication to any of the nodes is not available, then that radar cannot be adaptively scheduled. Each radar node could have a default resource allocation scheme that may be used in the event of failure of the communication channel.

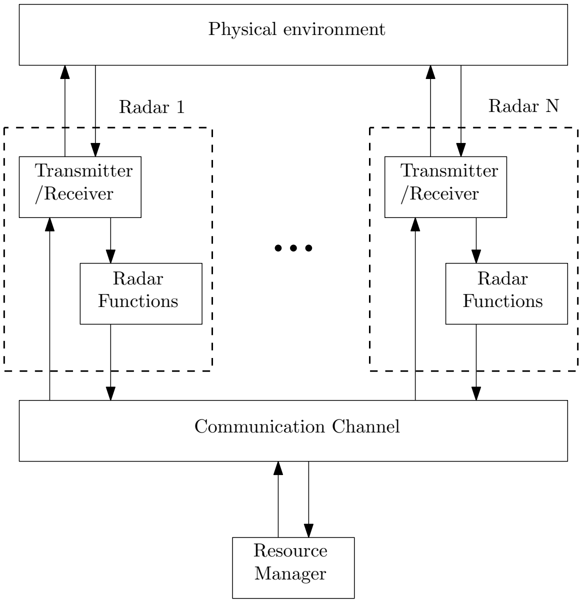


Figure 3: Radar network with centralised management architecture.

For networks with centralised management, the resource manager must decide how to schedule *N* antennas at any given time. The relationship between the coverage areas of the radar nodes will affect how the antennas are scheduled. Because there is full communication between the resource manager and all of the nodes, the coverage areas of the nodes will be known at all times by the resource manager.

When overlapping regions exist and communication with one of the contributing nodes is not available, the centralised resource manager can assign one of the other contributing nodes to carry out surveillance and tracking in the overlapping region. This redundancy protects against communication failure.

3.2 Distributed management architecture

In a network with distributed management, each node is a radar that operates autonomously and has a dedicated resource manager, as shown in Figure 4. The resource managers communicate with each other through the communication channel. The information transmitted on the communication channel will vary depending on the resource management method that is employed. An advantage of distributed management is the reduced reliance on the communication channel, as compared to centralised management. Although the nodes are linked by the communication channel, each node is autonomous and can operate independently in the absence of communication from all other nodes. The disadvantage of distributed management is the distributed nature of the scheduling optimatisation. It is generally easier to optimise the performance of a network with centralised management.

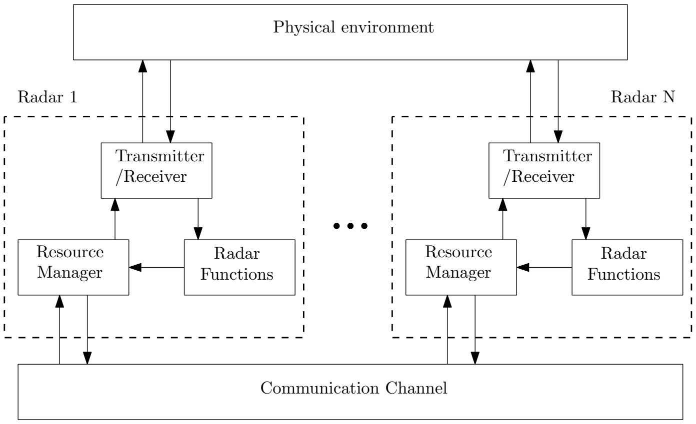


Figure 4: Radar network with distributed management architecture.

A degenerate case of distributed management is the case where no communication channel exists. This case will be called Independent RRM and serves as a baseline against which Coordinated RRM techniques can be compared.

For networks with distributed management, each node communicates its coverage area to the other nodes in the network. If none of the nodes overlap, then each node operates independently. If nodes have adjacent coverage areas, then it may possible to hand off tracks between the nodes.

Consider the case where overlapping regions exist. The surveillance and tracking tasks can be partitioned into overlapping tasks and exclusive tasks. Overlapping tasks are those where the associated target or surveillance region is located in an overlapping region. All other tasks are then exclusive tasks. When overlapping regions exist, a contributing node can coordinate its schedule with other contributing nodes.

For overlapping tasks, all nodes have the current estimate and relevant track information for a tracking task, and the time of last update and detection rates for a surveillance task. The position and orientation information of other nodes allows a local node to map the received tracking and surveillance data into the local coordinate frame.

When overlapping regions exist, various types of distributed management for the contributing nodes can be specified. These are detailed in this section and are summarised in Table 1. The type of distributed management employed by a radar node can change with time, depending on factors including the number of contributing nodes, the size of the overlapping region, the number of overlapping tasks, or the channel capacity.

In Type 0 distributed management, each node carries out independent management. There

Table 1: Types of distributed management.

Name	*Description*
Type 0	Independent management.
Type 1	Autonomous management with assignment of overlapping tasks.
Type 2	Autonomous management with assignment of overlapping looks.
Type 3	Temporary centralised management.

is no communication between nodes. This type of distributed management will be necessary when the channel capacity is zero. Furthermore, Type 0 may be desirable when the size of the overlapping region is small relative to the individual coverage areas of the contributing nodes or when the number of overlapping tasks is small.

In Type 1 distributed management, each overlapping task is assigned to a contributing node, and all looks for that task are carried out by the assigned node. In this case, a task assignment algorithm must be developed to assign tasks to nodes. For an individual node, assigned tasks would include exclusive tasks and overlapping tasks that are assigned by the task assignment algorithm. Task assignments could change if a task ceases to be an overlapping task. It is expected that task assignment would depend on task priorities and the relative loading of the contributing nodes.

In Type 2 distributed management, individual looks corresponding to overlapping tasks are assigned dynamically to contributing nodes, so that different looks from a given task may be carried out by different nodes. For a Type 2 distributed manager, a technique for look assignment needs to be specified. Compared to Type 1 distributed management, Type 2 distributed management has increased flexibility, at the expense of increased complexity and computational costs. Look assignments will likely vary with task priorities and the relative loading of the contributing nodes. Because looks are assigned individually, it may be possible to obtain better overall performance by taking advantage of time-varying task priorities and look geometries.

In Type 3 distributed management, one of the contributing nodes is selected as the centralised manager. The manager then formulates the radar schedule for all contributing nodes. As discussed in Subsection 3.1, centralised management fully controls the resources of all contributing nodes but is vulnerable to data latency and fluctuating channel capacity. In Subsection 3.1, centralised management was a system architecture where a single resource manager is used to control the radar network at all times. In Type 3 distributed management, the network has a distributed management architecture but temporarily allows one resource manager to carry out centralised management.

For looks associated with overlapping tasks, consider a technique for dynamically assigning individual looks to a contributing node. Type 2 Distributed Management and Type 3 Distributed Management provide distinct implementations of the technique, with a corresponding tradeoff in computational complexity and required channel throughput. For Type 2 management, look assignments are computed at all contributing nodes. The surveillance and tracking data that is distributed among all contributing nodes is sufficient to allow all nodes to perform the same calculations which determine look assignments. For Type 3 management, the looks assignments are computed at the centralised manager. In this case, surveillance and tracking data is distributed among all contributing nodes, and the centralised manager must also send look assignments across the channel. Compared to Type 2 management, Type 3 management requires less overall computational complexity but increased overall channel throughput.

3.3 Target prioritisation for radar networks

Target prioritisation is a key element of RRM. In developing techniques for Coordinated RRM, the concept of target prioritisation will need to be generalized to networked radars. Here, some considerations for prioritisation are presented.

Target prioritisation techniques allow a radar resource manager to prioritise multiple tasks in order to develop a more effective radar schedule. To date, target prioritisation has been considered for resource management of a single radar. This subsection considers the prioritisation of targets that are in the coverage area of multiple radar nodes.

Fuzzy logic prioritisation [3] considers a number of variables in computing a priority value for tracking tasks and surveillance tasks. For tracked targets, five variables are considered: track quality, hostility, degree of threat, weapon system capabilities, and relative position of the target.

For a given target and in the absence of communication between the nodes, the priority computed by each radar will likely vary. For example, the relative position of the target to each radar will likely be different. Further, if the radars are significantly separated in space, the heading and range rate, which help determine the degree of hostility, will be different for each radar. This case results in a target having a different priority relative to each radar.

An alternative approach is to compute an absolute priority for each target. The input variables for fuzzy logic prioritisation can then be defined in a way that is uniform across the network. For example, the relative position could be computed relative to the radar that is closest to the target. In this case, either all radars could compute the priority using knowledge of the other radars in the network, or one radar could compute the priority and communicate the result to the other radars.

For the prioritisation of surveillance sectors, four variables are considered: new targets rate (over time), number of threatening targets, threatening targets rate (over time), and original priority. For sectors that fall within the coverage area of multiple radars, it may be that the detection rate differs for each radar, due to differing clutter or noise levels, differing relative target velocities, or unfavourable aspect angles with respect to radar cross section.

4 Adapt MFR simulation tool

Adapt_MFR is a full radar simulation package that was designed to model naval radars operating in a littoral environment. Support for both rotating and non-rotating phased array multifunction radars, as well as conventional rotating dishes such as volume search radars, is included. It incorporates models for land, sea, chaff, and rain clutter, as well as jammers. Adapt_MFR runs causally, producing detection output results for one beam at a time. Multiple waveforms and radar operational modes are available, including the dynamic and adaptive switching of waveforms. Adapt_MFR also includes the ability to models of anomalous propagation, and to incorporate real terrain features through the importation of Digital Terrain Elevation Data (DTED) files.

An illustration of the high-level Adapt_MFR simulation architecture is presented in Figure 5. The framework consists of a series of modules (left hand side) that describe the radar(s), target scenario, and environment which are required to provide input to the simulation. The simulation flow located in the centre section of the figure represents the running code, which makes use of the data and associated functionality (algorithms, models, etc.). Adapt_MFR uses a tracker which employs an Interacting Multiple Model algorithm with a constant velocity model and a Singer manoeuvring model for estimating target dynamics. The measurement models include range, range rate, bearing and elevation. Detection-to-track data association is carried out using Nearest Neighbour (NN) JPDA [20].

As a result of the large parameter set, and general versatility of the tool, there are many and varied modes in which it may be operated. There are, however, three basic modes of operation for Adapt_MFR, which are:

- calculator mode
- simulation mode without tracker
- simulation mode with IMM tracker

The calculator mode allows the user to compute preliminary detection results in a non-causal mode. The simulation modes are causal in nature and provide a complete simulation run, making the functionality of Adapt_MFR available to the user.

In order to analyse the performance of RRM techniques, Adapt_MFR is operated in the simulation mode with IMM tracker. An overview of this mode is shown in Figure 5. To

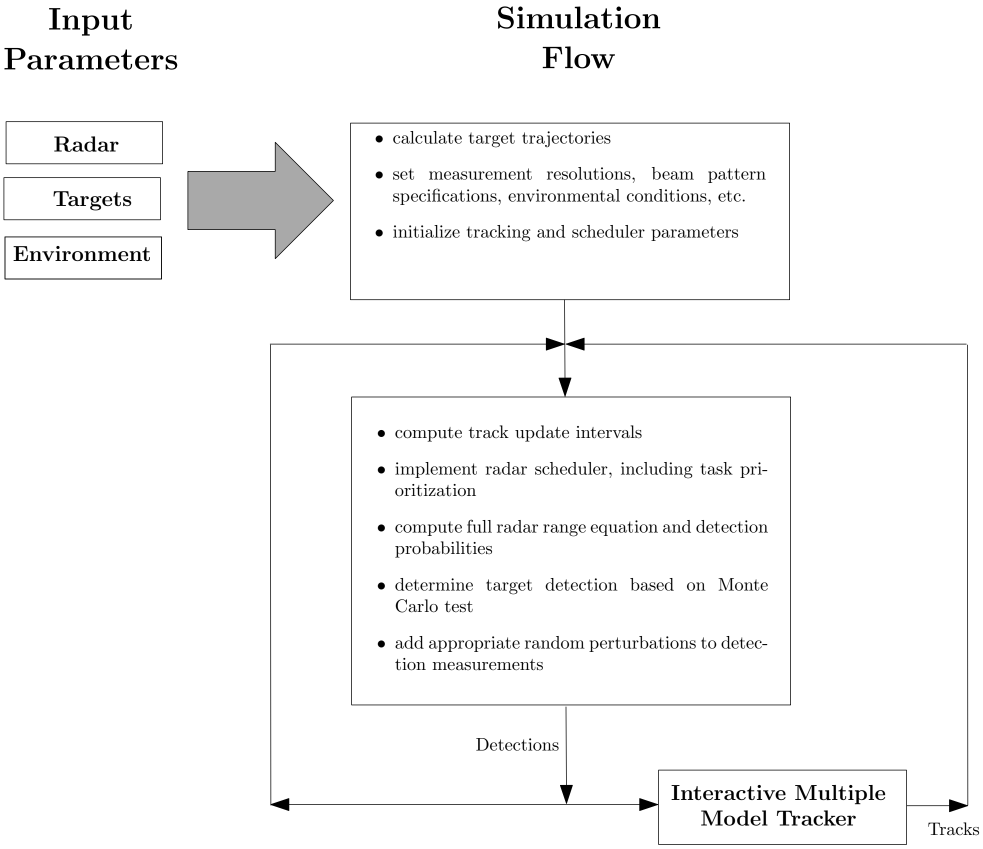


Figure 5: High-level overview of the simulation mode with IMM tracker in Adapt_MFR.

operate in this mode, user inputs are accepted through a graphical user interface and stored into corresponding radar, scheduling, environmental, and other data structures. Target initial positions and trajectories are set by the user. The simulator runs a loop, with time incremented in each pass by the dwell time of the radar beam, until the simulation time ends. Surveillance continues until detection occurs and a confirmation is scheduled for that detection. For each successful target confirmation, a measurement report is sent to the tracker. Predictions are requested at specific scheduled times based on user-defined rules to determine track update intervals. Based on the radar scheduling algorithm being modeled, future surveillance and tracking beams are assigned at specific times. Adapt_MFR is capable of modeling networked radars with an arbitrary number of radars. Multiple-radar tracking is also enabled.

Adapt_MFR accurately assesses RRM performance by causally modeling radar operation on a beam-by-beam basis. Radar detections are input to an IMM tracker. The tracker is then capable of sending track update requests to the radar scheduler. Tracking performance is analysed by comparing tracker outputs to ground truth data.

5 Two-radar network example

Section 3 formulated concepts for coordinated radar resource management, and described architectures for centralised and distributed management. In this section, a two-radar network example is considered, specific Coordinated RRM techniques are formulated, and the performance of these techniques is analysed. The performance analysis utilizes the Adapt_MFR simulation tool, which was described in Section 4.

The radar and target scenario is as follows. The two radars are stationary and are separated by 10 km, with the second radar located directly south of the first radar. The boresites of both radars point directly east. Each radar is capable of scanning ±60 degrees in azimuth.

The scenario consists of 30 targets with trajectories defined over a time interval of 200 seconds. Each target follows a trajectory at a constant altitude and has an altitude, radar cross section (RCS), velocity and trajectory type chosen from the set of parameter values listed in Table 2. The targets have varying values of initial position and initial heading, which are chosen so that each target trajectory is within the azimuthal coverage extent of one or both radars for the entire time interval. A top-down view of the scenario is given in Figure 6.

5.1 Coordinated RRM techniques

For the two-radar network scenario described above, a performance analysis will be carried out for the three cases of Independent (or Type 0) RRM, Type 1 Distributed Management,

Table 2: Set of parameter values for 30 targets.

Parameter	Set of values
Altitude (m)	500, 600, 750
Velocity (m/s)	100, 150
Radar cross section (m^2)	50, 75
Trajectory	Straight line, U-turn, Weave

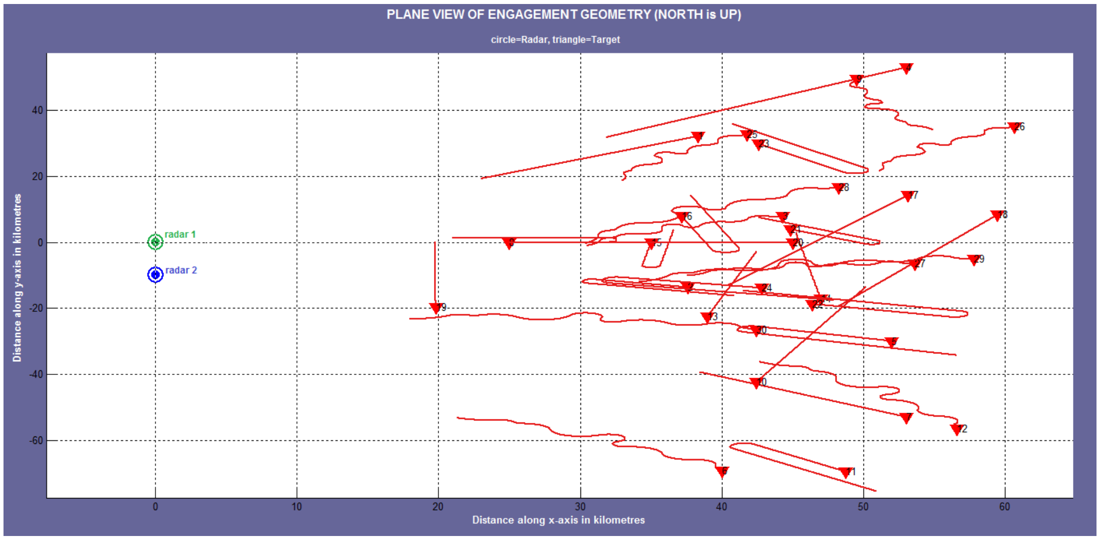


Figure 6: Top-down view of 30 target scenario.

and Type 2 Distributed Management. The specific techniques utilized for each case are detailed as follows. Note that RRM is coordinated for tracking tasks only. Surveillance tasks are conducted independently for the two radars.

For Coordinated RRM, communication between radars is assumed to take place without error and with zero latency. In the cases specified below, the data to be communicated between the radars will be described.

5.1.1 Independent RRM

In this case, each radar carries out Independent RRM for all tasks. This was referred to as Type 0 management in Section 3 and is the baseline case against which Coordinated RRM will be assessed. No data is communicated between the radars. Each radar utilizes an independent IMM tracker with NN-JPDA [20]. Each radar employs independent RRM that includes three aspects of adaptivity:

1. Fuzzy logic prioritisation
2. Adaptive track update intervals
3. Time-balancing scheduling

The fuzzy logic prioritisation technique [3] was implemented for tracking tasks. For each tracked target, characteristics such as heading, range, range rate, height and manoeuvre history are used to compute a target priority value between zero and one. In this way, the relative priority of each tracked target is assessed, so that more radar resources can be assigned to higher priority targets.

The tracker requests an update interval for each tracked target, and this request is sent to the scheduler. The requested track update interval depends on the target priority as follows,

$$\text{Requested track update interval} = \begin{cases} 1.5 \text{ s}, & \text{if target priority} \geq 0.75 \\ 3 \text{ s}, & \text{if target priority} < 0.75 \end{cases}, \tag{2}$$

where the target priority is a value between zero and one. If the track updates are scheduled at their requested intervals, then targets with a priority greater than 0.75 are updated twice as frequently as lower-priority targets.

The scheduling of tracking and surveillance tasks is conducted using the time-balancing scheduler [8], [21]. Each task has an associated time balance. If a look associated with that task is not scheduled, then the task time balance increases linearly with time. If a look is scheduled, the time balance decreases. At any given time, the task with the highest time balance is scheduled next.

5.1.2 Type 1 Management

For Type 1 Management, each radar conducts surveillance over its entire coverage area. Each radar also conducts tracking of its exclusive tracking tasks. Overlapping tracking tasks are assigned to the radar that has the smaller range to the tracked target. Once the overlapping task has been assigned to a radar, that radar carries out all track updates until the track ends. An overview of the assignment rules for tracking tasks is shown in Figure 7.

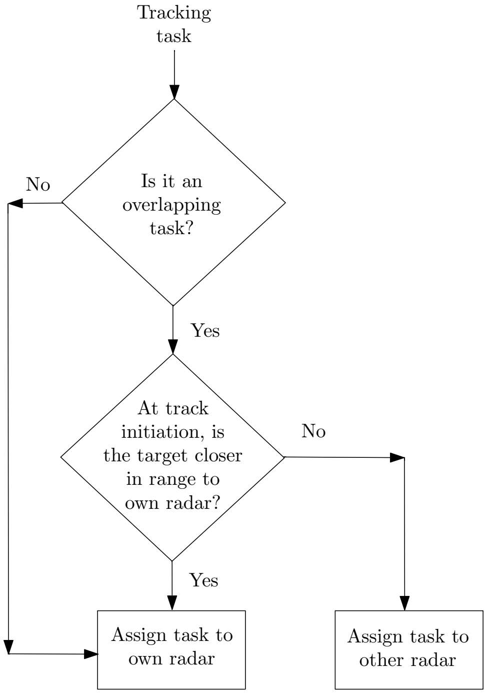


Figure 7: Task assignment algorithm for Type 1 Management.

For assigned tracking tasks, the fuzzy logic algorithm is used to compute the relative priorities of each tracked target. Adaptive track update intervals are computed using (2). Surveillance looks and tracking looks are then scheduled using the time-balancing scheduler.

Detection-to-track association is carried out for all tracks, include tracks assigned to the other radar. For example, assume that track y is assigned to Radar 1. In the course of conducting surveillance, a detection by Radar 2 will be gated against all tracks, include that of track y. If the detection is gated to track y, then the detection will be used to update track y. If the detection is not gated to track y, then Radar 1 schedules a track confirmation look.

For Type 1 Management, the following data is sent across the communication channel.

- Position, velocity, and orientation of each radar platform
- Detections associated with overlapping tasks
- Estimated position of targets at track confirmation

In general, the position, velocity and orientation of each radar platform must be sent to the other platform, so that both radars can compute coverage areas and the overlapping region, if any. For this specific example, both radars have zero velocity. This data also allows detections from the other radar to be mapped into the local coordinate frame. The estimated position of targets at track confirmation is required to compute the task assignment algorithm. Once an overlapping tracking tasks has been assigned to a particular radar, only detections in the overlapping region need to be sent across the channel.

In Type 1 Management overlapping tasks are not assigned to both radars, which reduces the time required for tracking tasks compared to Independent RRM. The benefit gained from the coordinated scheduling of overlapping tasks will be quantified when performance results are presented.

5.1.3 Type 2 Management

With Type 2 Management, each radar carries out surveillance of its entire coverage area and conducts tracking of its exclusive tracking tasks. Overlapping tracking tasks are assigned to a radar on a look-by-look basis. Each look is assigned to the radar that has the smaller range to the tracked target. An overview of the assignment rules for tracking looks is shown in Figure 8. Note that Type 2 Management is computationally more intensive than Type 1 Management, because the range calculations are carried out for each look associated with a tracking task.

After each tracking look has been scheduled, the next look is assigned to a radar based on minimum range. The fuzzy logic priority (relative to the assigned radar) and the adaptive track update interval are computed. Surveillance looks and assigned tracking looks are the scheduled for each radar using the time-balancing scheduler. As was the case with Type 1 Management, detection-to-track association is carried out for all tracks, include tracks assigned to the other radar.

For Type 2 Management, the following data is sent across the communication channel.

- Position, velocity, and orientation of each radar platform
- Detections and tracks associated with overlapping tasks

The position, velocity and orientation of each radar platform must be sent to the other platform, so that both radars can compute coverage areas and the overlapping region, if any. Detections and tracks associated with overlapping tasks are required, since the estimated

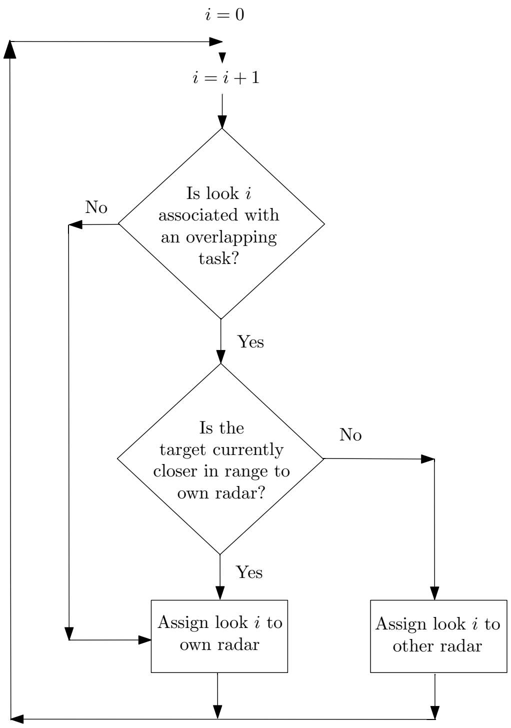
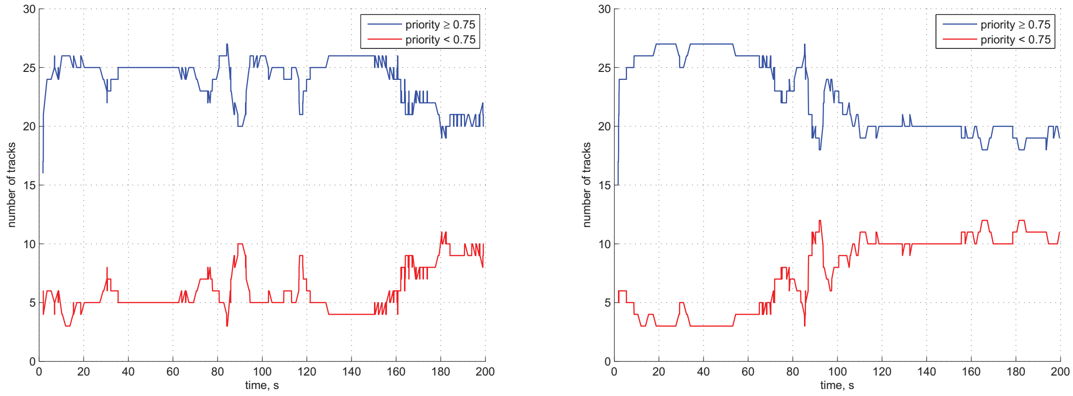


Figure 8: Look assignment algorithm for Type 2 Management, for looks $i = 1, 2, ...$ of a given tracking task.

range to each radar is used to compute the look assignment on a look-by-look basis. A given track may be updated by either radar, using scheduling track update looks or detections from surveillance looks that are gated with the track.

5.2 Performance results

An Adapt_MFR simulation was run for the 2-radar, 30-target scenario with Independent RRM, Type 1 Management, and Type 2 Management. For the case of Type 1 Management, Figure 9 shows the number of tracks with priority greater than or equal to 0.75, and the number of tracks with priority less than 0.75. Both are plotted against simulation time for each radar. The priority of a track determines the requested track update interval, as specified in (2). The total number of tracks may not always equal the number of targets, 30, because of untracked targets or false tracks.



(a) Radar 1. (b) Radar 2.

Figure 9: Number of high-priority and low-priority tracks for Type 1 Management.

Figure 10 shows track completeness for the four cases of Independent RRM - Radar 1, Independent RRM - Radar 2, Type 1 Management and Type 2 Management. Track completeness was computed as specified in (1). For Independent RRM, tracking is carried out independently for the two radars. The results for Type 1 consider any track that is associated with a given target, regardless of which radar was assigned the track. The results for Type 2 includes tracked targets where updates were carried out by a single radar and those where updates were carried out by both radars, as per the look assignment specified in Figure 8. The results indicate that in almost all cases, targets are tracked with track completeness of 0.95 or greater. Target 4, which starts at a longer range and travels towards Radars 1 and 2, is an exception to this behaviour. With Independent RRM, Radar 2 does not track Target 4 until later in the scenario, due to lower signal-to-noise ratio at the start of the scenario. This accounts for the track completeness of 0.82 for Independent RRM - Radar 2. For Type 1 Management, Target 4 is assigned to Radar 1, and for Type 2 Management, all looks associated with the tracking of Target 4 are carried out by Radar 1. For Target 23, Type 1 Management has slightly lower track completeness, because track confirmation is delayed by other track confirmations occurring at the same time.

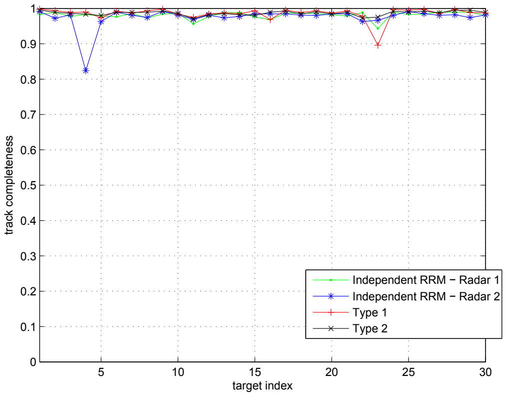
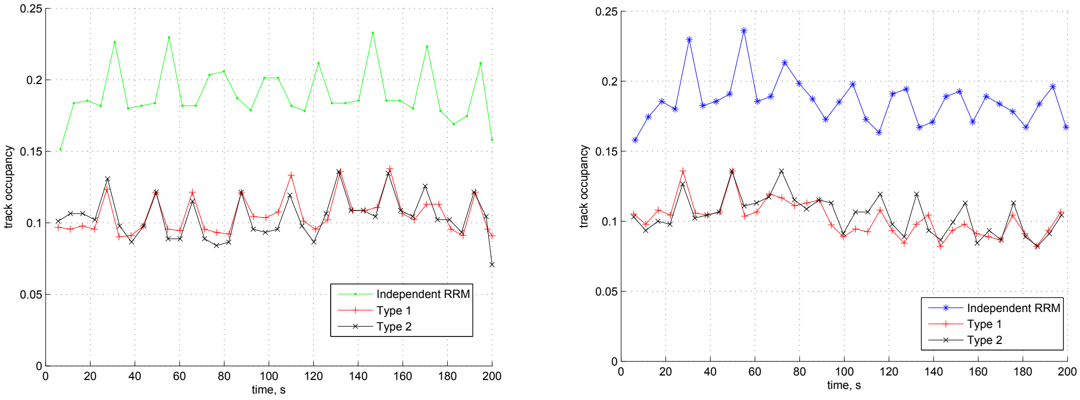


Figure 10: Track completeness for the 30-target scenario.

Track occupancy results for both radars are presented in Figure 11. For Type 1 Management and Type 2 Management, tracks associated with targets in the overlapping region are updated by only one of the two radars. For Independent RRM, such tracks are updated by both radars, which increases track occupancy for both radars. Type 1 Management and Type 2 Management have similar track occupancy values. Type 1 Management carries out task assignment for overlapping tasks, while Type 2 Management carries out look assignment for overlapping tasks. The distinction between task assignment and look assignment has a negligible effect on track occupancy.

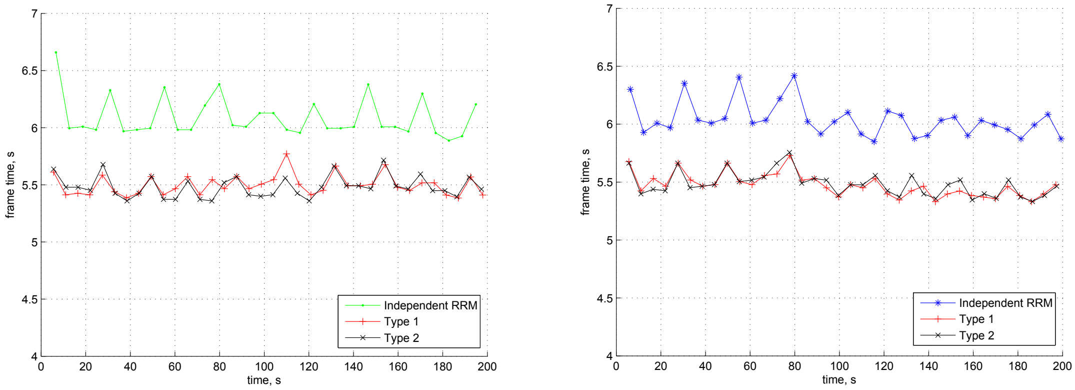


(a) Radar 1.

(b) Radar 2.

Figure 11: Track occupancy for the 30-target scenario.

The decreased track occupancy resulting from the use of Coordinated RRM increases the time available for surveillance. This results in decreased frame time for both radars, as shown in Figure 12. The frame time decreases from approximately 6 seconds for Independent RRM to approximately 5.5 seconds for Type 1 Management and Type 2 Management. As a result, the reaction time against new threats is improved. These results apply to the 30-target scenario under consideration. For a scenario with a larger number of targets in the overlapping region, the frame time for all cases would increase. However, the difference in frame time between Independent RRM and Coordinated RRM would also increase, indicating a more significant advantage for Coordinated RRM.



(a) Radar 1.

(b) Radar 2.

Figure 12: Frame time for the 30-target scenario.

Results from the 30-target scenario show that Type 1 Management and Type 2 Management achieve track completeness close to one, with similar results for Independent RRM. Furthermore, Type 1 Management and Type 2 Management have decreased track occupancy and decreased frame time compared to Independent RRM. This indicates that a radar network using Coordinated RRM can improve reaction time against new threats. To achieve this enhanced tracking performance, the radars must send data across a communication channel. The data to be transmitted includes the position, velocity, and orientation of each radar platform, detections associated with overlapping tasks, and the estimated position of targets at track confirmation. In addition, for Type 2 Management, tracks associated with overlapping tasks must be transmitted.

A radar is overloaded when not all tracking look requests can be scheduled. In this case, it is likely that track completeness will not be one for all targets. Coordinated RRM can improve track completeness compared to Independent RRM when the individual radars are overloaded. Overall, differences in track completeness and track occupancy between Type 1 and Type 2 Management will depend on the task assignment and look assignment algorithms.

6 Conclusions

This study considered whether the sharing of detection and tracking data can enhance radar resource management performance. Coordinated radar resource management exploits data that is transmitted across a communication channel. Two distinct architectures for Coordinated RRM were formulated, centralised management and distributed management. It was shown that different types of distributed management may be proposed, with each type characterised by varying amounts of coordination between the radar nodes. A two-radar network and 30-target scenario were modeled in the simulation tool Adapt_MFR, to analyse the performance of Independent RRM and Coordinated RRM. All RRM techniques utilised adaptive task prioritisation, track update intervals, and radar scheduling. It was shown that Coordinated RRM achieves the same track completeness as Independent RRM, while decreasing track occupancy and frame time. Therefore, Coordinated RRM can improve reaction time against threats, at the expense of sending data across a communication channel.

The use of Coordinated RRM offers the potential for significant performance improvements, but also requires further study. In this work, it was assumed that the communication channel is error-free and that data is transmitted with zero latency. Future work should examine the effect on channel errors and data latency on the performance of Coordinated RRM techniques. The example in Section 5 utilised RRM techniques based on fuzzy logic prioritisation and the time-balancing scheduler. Independent RRM and Coordinated RRM based on other techniques, such as those presented in [2], should also be considered.

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A phased array radar has the ability to rapidly and adaptively position beams and adjust dwell times, thus enabling a single radar to perform multiple functions, such as surveillance, tracking and fire control. A radar resource manager prioritises and schedules tasks from the various functions to best use available resources. For networked phased array radars that are connected by a communication channel, this document considers whether coordinated radar resource management (RRM), which exploits the sharing of tracking and detection data between radars, enhances performance compared to Independent RRM. Two distinct architectures for Coordinated RRM are proposed, centralised management and distributed management, and characteristics of each architecture are specified. It is shown that different types of distributed management are possible, with each type characterised by varying amounts of coordination between the radars. A two-radar network and 30-target scenario are modeled in the simulation tool Adapt_MFR, to analyse the performance of Independent RRM and two types of Coordinated RRM. Results indicate that the Coordinated RRM techniques achieve the same track completeness as Independent RRM, while decreasing track occupancy and frame time. Therefore, Coordinated RRM can improve reaction time against threats, at the expense of sending data across a communication channel.

Un radar à balayage électronique peut positionner les faisceaux et régler les temps de tenue rapidement et de maniére adaptative, permettant ainsi à un seul radar de remplir de multiples fonctions, comme la surveillance, la poursuite et la conduite de tir. En outre, la gestion des ressources radar attribue aux tâches des diverses fonctions une priorité et les ordonnance pour permettre une utilisation optimale des ressources disponibles. Pour les radars à balayage électronique réseaut´es raccordés par un canal de communication, le présent document examine si la gestion des ressources radar (GRR) coordonnée, qui exploite le partage des données de poursuite et de détection entre les radars, améliore la performance par rapport à la GRR indépendante. Deux architectures distinctes pour la GRR coordonnée sont proposées (gestion centralisée et gestion répartie), et leurs caractéristiques sont précisées. On constate que divers types de gestion répartie sont possibles, et que chaque type est caractérisé par une coordination plus ou moins importante entre les radars. De plus, un réseau a` deux radars et un scénario à trente cibles sont modélisés dans l'outil de simulation Adapt MFR en vue d'analyser la performance de la GRR indépendante et deux types de GRR coordonnée. Selon les résultats, les techniques de GRR coordonnée produisent le même taux de complétude de poursuite que la GRR indépendante, tout en réduisant le taux d'occupation de la poursuite et la durée de trame. Par conséquent, la GRR coordonnée peut améliorer le temps de réaction par rapport aux menaces, au prix de la transmission de données sur un canal de communication.

14.

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Phased array radar; networked radar; Radar resource management Tracking metrics; Distributed tracking