IET Radar, Sonar & Navigation

Research Article

Coordinated radar resource management for networked phased array radars

ISSN 1751-8784
Received on 14th November 2013
Revised on 3rd October 2014
Accepted on 23rd October 2014
doi: 10.1049/iet-rsn.2013.0368
www.ietdl.org

Peter W. Moo ✉, Zhen Ding

Radar Sensing and Exploitation Section, Defence Research and Development Canada, Ottawa, Canada, K1A 0Z4
✉ *E-mail: Peter.Moo@drdc-rddc.gc.ca*

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. Networked phased array radars that are connected by a communication channel are studied. This study considers whether coordinated radar resource management (RRM), which exploits the sharing of tracking and detection data between radars, enhances performance compared with independent RRM. Two types of distributed management techniques for coordinated RRM are proposed, with each type characterised by varying amounts of coordination between the radars. A two-radar network and 30-target scenario are modelled in the simulation tool Adapt_MFR, to analyse the performance of the two coordinated RRM techniques against the baseline case of independent 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. The performance of coordinated RRM for a communication channel with errors is also modelled and analysed.

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. Since 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. Although 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 with another. Adaptive tracking, including adaptive track update intervals, were considered in [5–10]. ‘Task scheduling’ involves deciding which look requests should be scheduled and specifying the starting time of each scheduled look [11–16]. Scheduling algorithms typically make use of relative task priorities in formulating the radar schedule, and may incorporate adaptive track update intervals.

Track scheduling for networked radars has been considered by He and Chong [17, 18], who model the sensor scheduling problem as a partial observable Markov decision process and formulate a scheduling solution based on particle filtering. In [19], track scheduling is carried out using a modified quality-of-service resource allocation model. Track scheduling methods have also been proposed to minimise sensor loading [20, 21]. By contrast, this paper considers the scheduling of both tracking and surveillance tasks for networked radars, and quantifies both tracking and surveillance performance. In addition, the techniques presented here adaptively schedule tasks based on the characteristics of the targets within the coverage areas of the radars.

This paper considers a network of phased array radars which are connected by a communication channel [22]. The purpose of this paper 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 paper, the term ‘resource management’ will refer to RRM, 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 are 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 two distributed management techniques for coordinated RRM, and Section 4 presents a model for communication channel availability. Section 5 presents an overview of the simulation tool Adapt_MFR, which will be used to demonstrate and analyse coordinated RRM performance. In Section 6, coordinated RRM for a two-radar network is analysed in modelling and simulation, and compared with the baseline case of independent RRM. Finally, conclusions are presented in Section 7.

2 Preliminaries

Fig. 1 illustrates the role of a resource manager for a single radar. In this paper, the radar functions considered are surveillance and tracking. Each function consists of one or more tasks. For the target

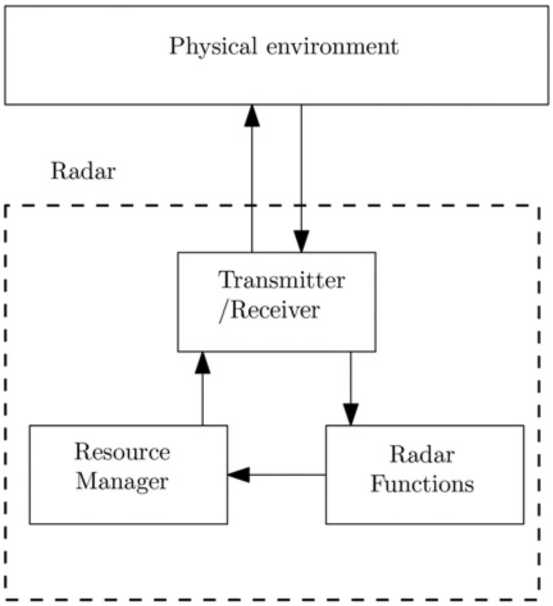

Fig. 1 *Resource management for a single radar*

tracking function, a task involves the tracking of an individual target, whereas 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. 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.

This paper presents the formulation of coordinated RRM for networked radars, where detection and tracking data from other radars are used in radar scheduling. 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 paper considers the resource management of a network of N monostatic radars. The portion of the network that is colocated with a radar antenna will be referred to as a node. 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 ‘distributed management’ techniques, which will be specified later in this paper. ‘Centralised management’ techniques are not considered here.

An element common to the radar networks is a communication channel. The channel capacity, or maximum throughput, is a key element of networked radar and may vary with time.

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 Fig. 2. Coverage area is defined in range and angle. Each coverage area may have different range and angular extents, so that any overlapping regions will vary with range and angle. For a tracked target or surveillance region that is located in the overlapping region, the resource manager must

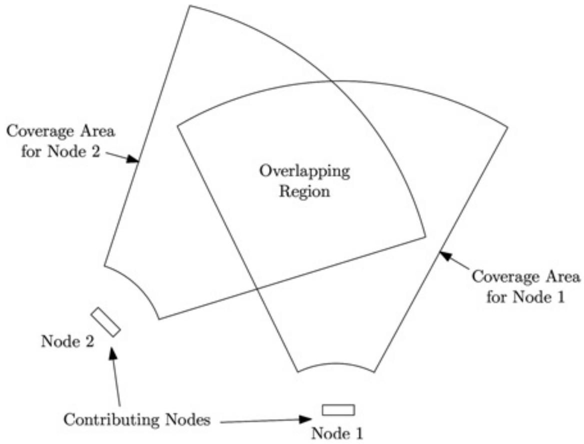

Fig. 2 *Two nodes with overlapping coverage areas*

decide which contributing node should carry out the associated surveillance or tracking task.

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 radar to a radar with 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 hypothesis tracking, tracking performance was analysed when a subset of hypotheses and tracks are communicated between the sensors [23]. When joint probabilistic data association (JPDA) is used in a distributed sensor network, Chang *et al.* [24] 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 [25]. A technique was presented for increasing the effective update rate while maintaining a reasonable communications bandwidth.

Two types of distributed tracking [26] are considered in this paper. For independent RRM, each radar conducts tracking independently of the other radars in the network, and the tracks are initiated and maintained separately. For coordinated RRM, a single track is created for each target, and detection-to-track data association is conducted for detections from all radars in the network.

2.3 Performance metrics

RRM performance can be quantified using a number of metrics, including the single integrated air picture metrics for tracking [27]. In this paper, RRM performance will be measured by evaluating track completeness, track occupancy and frame time. Track completeness C is given by

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

so that $0 \le C \le 1$. The coverage area is defined as the region where the signal-to-interference ratio exceeds a specified threshold. The signal-to-interference ratio is computed based on the highest energy waveform that is possible to transmit. In this paper, interference will

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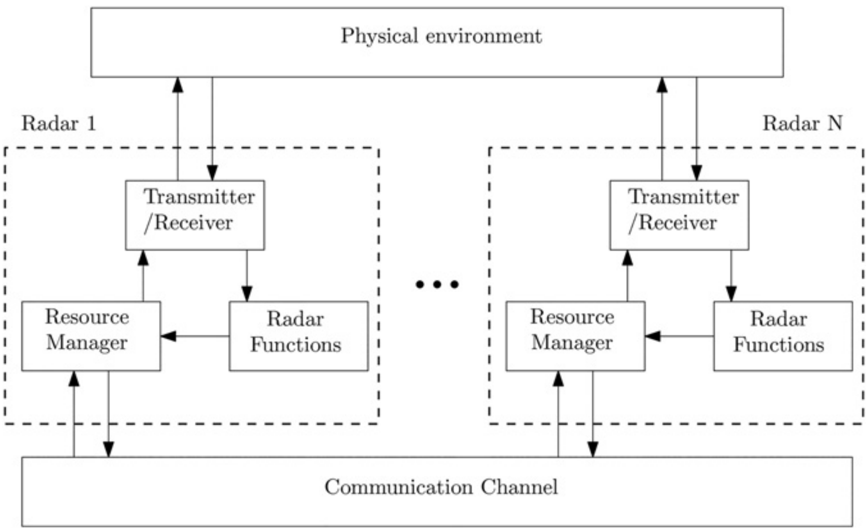

Fig. 3 *Radar network with distributed management architecture*

only include noise. In a real system, interference may include clutter and could be affected by environmental effects such as ducting. Such interference would affect the maximum detection range, and therefore the defined coverage area, of the radar.

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 paper is to develop coordinated RRM techniques that demonstrate enhanced performance compared with independent RRM techniques. Performance will be measured by computing track completeness, track occupancy and frame time.

3 Distributed techniques for coordinated RRM

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. This section formulates two coordinated RRM techniques employing a 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 Fig. 3. The resource managers communicate with each other through the communication channel. Note that tracking and detection data are shared via the resource managers. The information transmitted on the communication channel will vary depending on the resource management method that is employed. With distributed management, each node is autonomous and can operate independently in the absence of communication from all other nodes.

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 will 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 be 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 the last update and detection rates for a surveillance task. The position and orientation information of other nodes allow 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 and the channel capacity.

Specific scheduling techniques for a two-radar network are formulated below. For these techniques, RRM is coordinated for tracking tasks only. Surveillance tasks are conducted independently for the two radars. Errors on the communication channel may cause the channel to not be available for certain durations of time. This will be modelled in Section 4. For coordinated RRM techniques, the data to be communicated between the radars will be specified.

3.1 Independent RRM

In this case, each radar carries out independent RRM for all tasks. This was referred to as Type 0 management in Table 1 and is the baseline case against which coordinated RRM will be assessed. No data are communicated between the radars. Each radar utilises an independent tracker and employs independent RRM that includes three aspects of adaptivity:

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

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

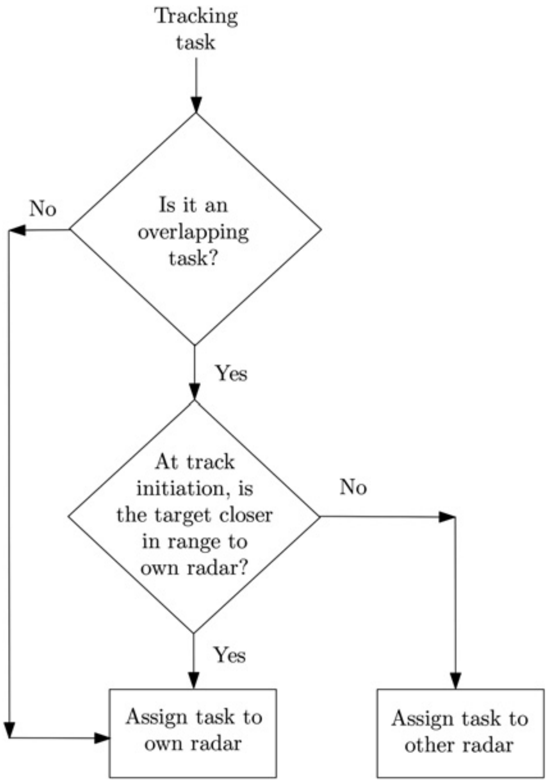

Fig. 4 *Task assignment algorithm for Type 1 Management*

The fuzzy logic prioritisation technique [3] is 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

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

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 $\geq$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 [11, 28]. 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.

3.2 Type 1 Management

When the channel is available, Type 1 Management assigns overlapping tracking tasks 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 Fig. 4. Each radar conducts surveillance over its entire coverage area. Each radar also conducts tracking of its exclusive tracking tasks.

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, including 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 data sent across the communication channel is specified in Table 2. The position, velocity and orientation of each radar platform are sent to the other platform, so that both radars can compute coverage areas and the overlapping region, if any. This data also allow 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 task has been assigned to a particular radar, only detections in the overlapping region are sent across the channel.

In Type 1 Management overlapping tasks are not assigned to both radars, which reduce the time required for tracking tasks compared with independent RRM. In particular, the radar that is not assigned to a particular track does not assign looks to update that track, which frees up the radar to carry out other tasks. The benefit gained from the coordinated scheduling of overlapping tasks will be quantified in Section 6.

Table 2 Data sent across the communication channel for Type 1 Management

Platform	Overlapping tasks
position	detections
velocity	estimated position at track confirmation
orientation	

3.3 Type 2 Management

When the channel is available, Type 2 Management assigns overlapping tracking tasks 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 Fig. 5. Note that Type 2 Management is computationally more intensive than Type 1 Management, because a comparison of the target ranges to each radar is carried out for each look associated with a tracking task. Each radar carries out surveillance of its entire coverage area and conducts tracking of its exclusive tracking tasks.

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 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, including tracks assigned to the other radar.

For Type 2 Management, the data sent across the communication channel is specified in Table 3. The position, velocity and orientation of each radar platform are 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 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 scheduled track update looks or detections from surveillance looks that are gated with the track.

3.4 Target prioritisation for radar networks

Target prioritisation techniques allow a radar resource manager to prioritise multiple tasks in order to develop a more effective radar

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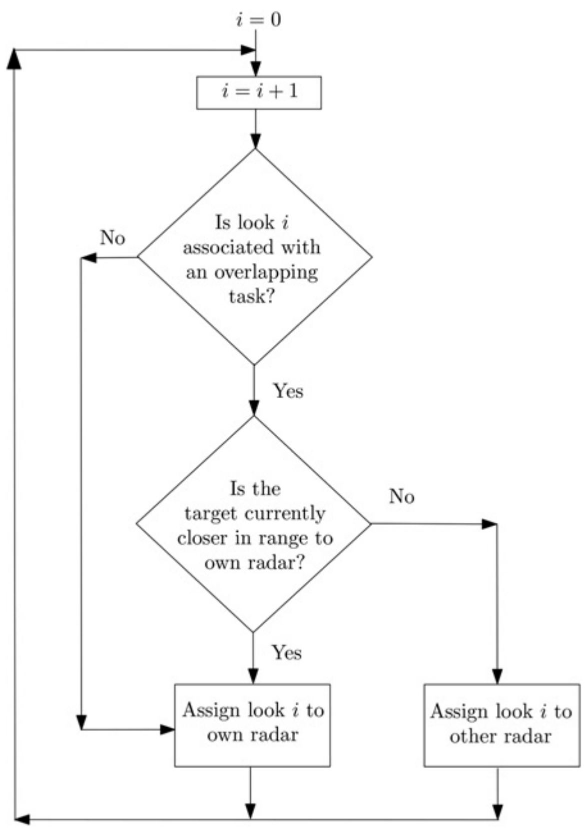

Fig. 5 *Look assignment algorithm for Type 2 Management, for looks i = 1, 2, … of a given tracking task*

Table 3 Data sent across the communication channel for Type 2 Management

Platform	Overlapping tasks
position velocity orientation	detections tracks

schedule. To date, target prioritisation has been considered for resource management of a single radar. This section 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. Furthermore, 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, because of differing clutter or noise levels, differing relative target velocities or unfavourable aspect angles with respect to radar cross-section (RCS).

4 Model for communication channel availability

To implement coordinated RRM techniques, the radar network relies on a communication channel between radars to transmit and receive data related to target detections and tracks. It is assumed that the radar network employs a digital communication system with forward error correction (FEC) channel coding [29]. If the bit error rate (BER) of the channel is less than or equal to the maximum BER of the FEC code, then the data are received without error. However, if the BER of the channel is greater than the maximum BER of the FEC code, then the data are not received reliably.

This paper models the effects of errors on the communication channel, together with error control coding employed by the communication system. When the BER of the channel is less than or equal to the maximum BER of the FEC code, then the channel is available. When the BER of the channel is greater than the maximum BER of the FEC code, then the channel is not available. Over time, the channel is available with probability p. This realistic model for channel availability accounts for errors that may occur because of interference on the channel, together with error control coding that would be employed by the communication system.

5 Adapt MFR simulation tool

Adapt_MFR is a full radar simulation package that was designed and developed at Defence Research and Development Canada Ottawa to analyse the performance of RRM techniques for naval radars operating in a littoral environment. Adapt_MFR runs causally, producing detection output results for one beam at a time.

An illustration of the high-level Adapt_MFR simulation architecture is presented in Fig. 6. 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 a interacting multiple model (IMM) 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 [30].

To analyse the performance of RRM techniques, Adapt_MFR is operated in a simulation mode with an IMM tracker. An overview of this mode is shown in Fig. 6. To 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 in a loop, with time incremented in each pass by the dwell time of the radar beam, until the simulation time ends. Surveillance continues until a detection occurs and a confirmation is scheduled for that detection. Target detection modelling is based on the radar range equation. Signal-to-noise ratio and detection probabilities are computed, and the detection of a target is determined based on a Monte Carlo test. 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. On the basis of the radar scheduling algorithm being modelled, future surveillance and tracking beams are assigned at specific times. Adapt_MFR is capable of modelling networked radars with an arbitrary number of radars. Multiple-radar tracking is also enabled.

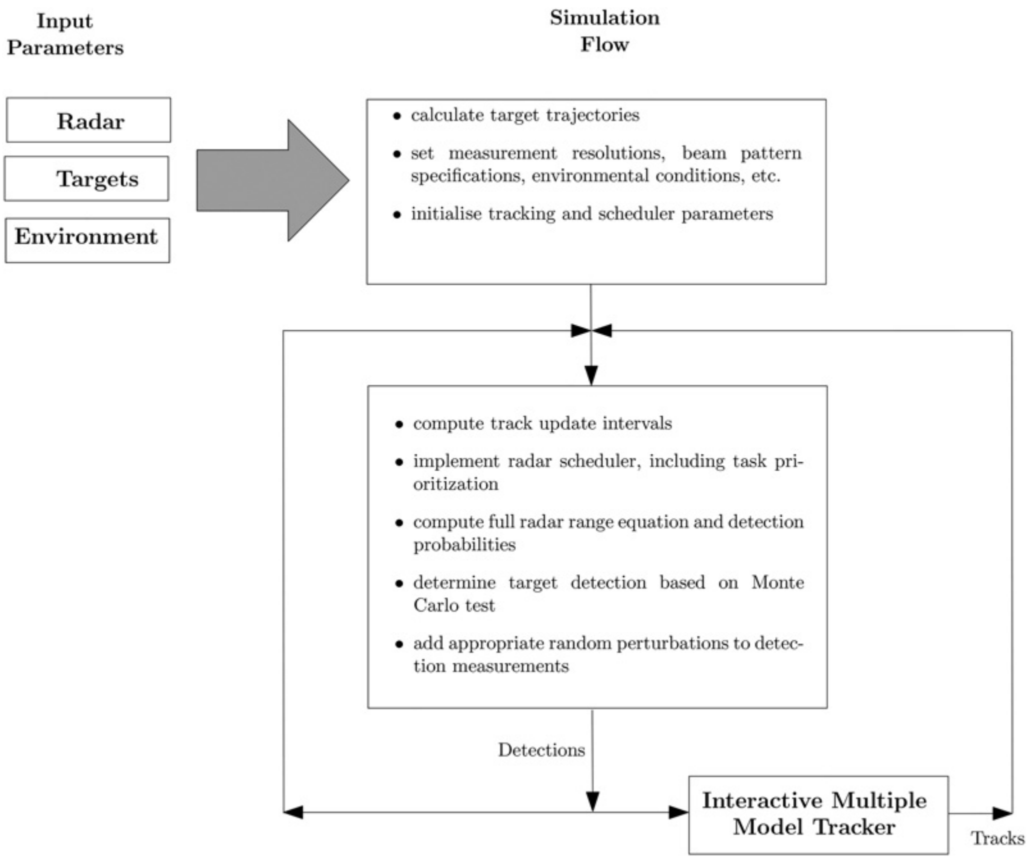

Fig. 6 *High-level overview of the simulation mode with IMM tracker in Adapt_MFR*

Adapt_MFR accurately assesses RRM performance by causally modelling 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 with ground truth data.

6 Two-radar network example

Section 3 formulated techniques for coordinated RRM. In this section, a two-radar network example is considered, and the performance of these techniques is analysed. The performance analysis utilises the Adapt_MFR simulation tool, which was described in Section 5.

The scenario is shown in Fig. 7 and is specified 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° in azimuth.

The scenario consists of 30 targets with trajectories defined over a time interval of 200 s. Each target has a fixed altitude, RCS and velocity. In addition, each target follows one of three trajectory types. 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.

Two sets of targets are considered: Target Set A and Target Set B. The parameter values for the target sets are listed in Table 4. It is seen that Target Set B has targets with smaller RCS and larger velocity values. Fig. 7 shows a top-down view of the radar locations and target trajectories for Target Set A.

Adapt_MFR simulations were run for the scenario with Target Set A. The following five cases were considered, where p is the probability of channel availability, as described in Section 4.

1. Independent RRM.
2. Type 1 Management with $p = 1$.
3. Type 2 Management with $p = 1$.
4. Type 1 Management with $p = 0.5$.
5. Type 2 Management with $p = 0.5$.

An IMM tracker with NN-JPDA [30] was utilised in all cases. The track initiation process is as follows. After a target detection, the radar specifies a target confirmation look for that target. If the target is confirmed, then a tentative track is formed. After a tentative track has been updated two times in three attempts, the tentative track becomes a confirmed track. For the purposes of computing track occupancy, track confirmation looks are associated with target detection, whereas update looks for tentative tracks or confirmed tracks are associated with target tracking.

For the case of Type 1 Management with $p = 1$, Fig. 8 shows the number of tracks with priority ≥0.75, and the number of tracks with priority <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 at certain brief periods of time during the simulation, there may be untracked targets or false tracks.

For $p = 1$, the communication channel was available during the entire simulation. For $p = 0.5$, the simulation time interval of 200 s was divided into subintervals of 10 s. For each subinterval, the channel was randomly chosen as either being available or not available, with equal probability. For Type 1 Management with $p = 0.5$, a transition from the channel being available to not available resulted in the two radars initiating new tracks independently. When the channel transitioned from being not available to available, multiple tracks of the same target were fused into a single track. For Type 2 Management with $p = 0.5$, a transition from the channel being available to not available required that existing tracks be assigned to one of the radars. Each

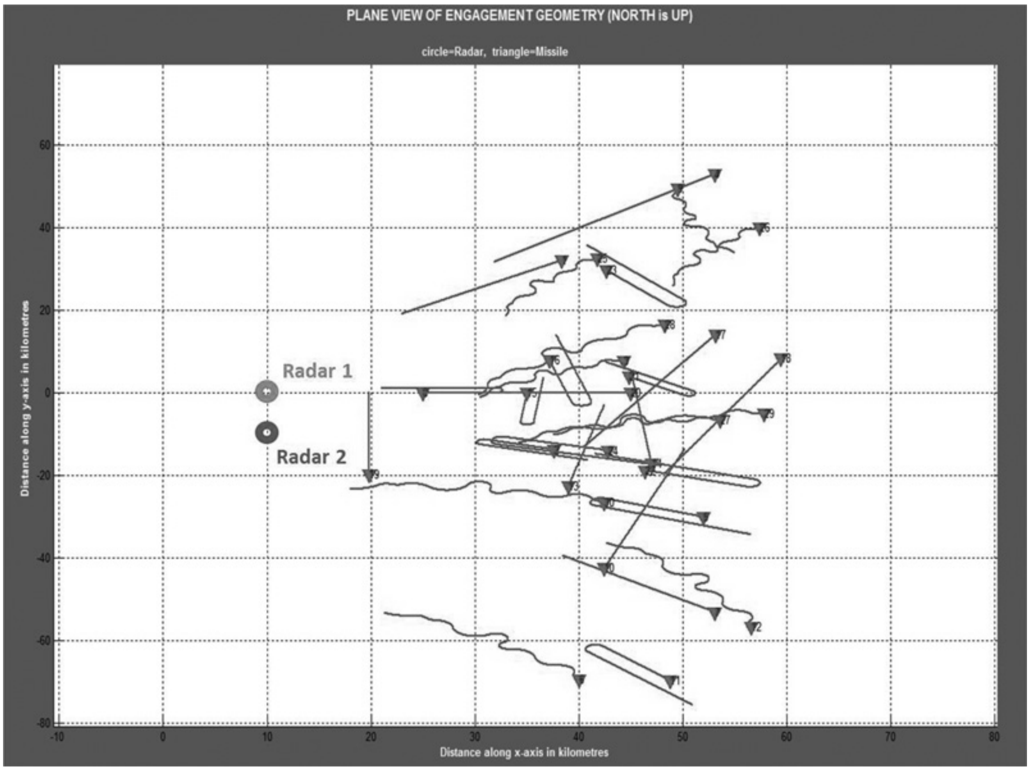

Fig. 7 *Top-down view of radar positions and target trajectories for the scenario with Target Set A*

Triangles indicate target position at the start of its trajectory

track was assigned to the radar that most recently updated the track. As was the case with Type 1 Management, when the channel transitioned from not available to available, multiple tracks of the same target were fused into a single track. Track-to-track association was carried out using target ground truth to associate multiple tracks with each target. Track-to-track fusion was then performed using an averaging scheme, which resulted in only one track being associated with each target. In a real-world environment, track-to-track association and fusion could be carried out statistically [26, pp. 195–197].

Fig. 9 shows track completeness for the six cases of independent RRM – Radar 1, independent RRM – Radar 2, Type 1 Management with $p = 1$, Type 2 Management with $p = 1$, Type 1 Management with $p = 0.5$ and Type 2 Management with $p = 0.5$. 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 include 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 Fig. 5. The results indicate that targets are tracked with track completeness of 0.95 or greater, with the exception of Target 4, whose trajectory is shown in Fig. 10. Target 4 starts at a longer range and travels towards Radars 1 and 2. With independent RRM, Target 4 is not tracked by Radar 2 until later in the scenario, because of 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.

Table 4 Set of parameter values for 30 targets

Parameter	Values: target set A	Values: target set B
altitude, m	500, 600, 750	500, 600, 750
velocity, m/s	100, 150	200, 250
RCS, m^2	50, 75	5, 10
trajectory	straight line, U-turn, weave	straight line, U-turn, weave

Track occupancy results for both radars are presented in Fig. 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 when the communication channel is available. For independent RRM, such tracks are updated by both radars, which increase track occupancy for both radars. For fixed $p = 1$ or 0.5, Type 1 Management and Type 2 Management have similar track occupancy values. Type 1 Management carries out task assignment for overlapping tasks, whereas 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. The tooth-like structure of the track occupancy plots is caused by slight variations in the number of track updates in consecutive fixed intervals. During intervals when the channel is not available, the track occupancies of Type 1 with $p = 0.5$ and Type 2 with $p = 0.5$ increase to that of the independent RRM case, as expected. This can be seen during the intervals from 50 to 70 s and from 130 to 160 s.

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 Fig. 12. Compared with independent RRM, the frame times for Type 1 Management, $p = 1$ and Type 2 Management, $p = 1$ are decreased by ∼2 s. As a result, the reaction time against new threats is improved. As expected, the frame time for Type 1 Management, $p = 0.5$ and Type 2 Management, $p = 0.5$ increase to that of independent RRM when the channel is not available. 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.

Fig. 13 plots the difference in position error between Type 2 Management with $p = 1$ and Type 1 Management with $p = 1$, for all 30 targets in Target Set A. Positive difference corresponds with

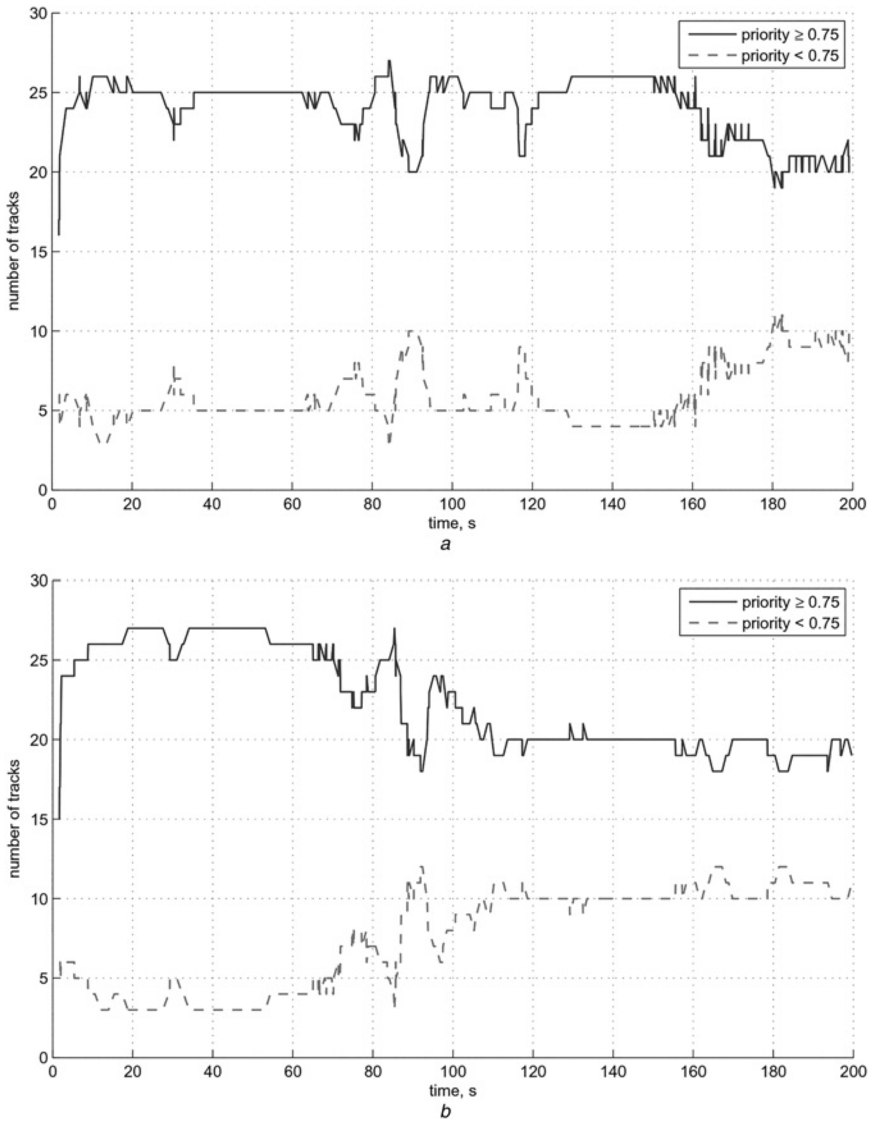

Fig. 8 *Number of high-priority and low-priority tracks for Type 1 Management for Target Set A*

a Radar 1
b Radar 2

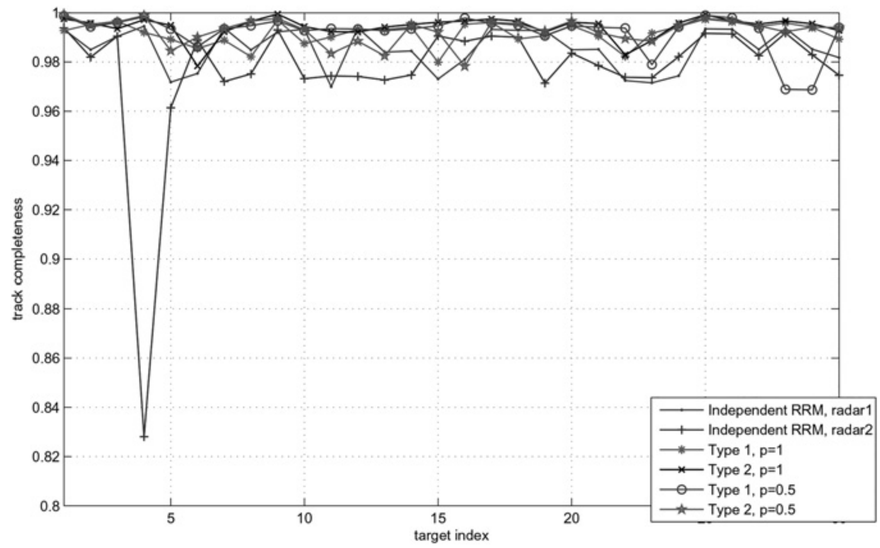

Fig. 9 *Track completeness for the scenario with Target Set A*

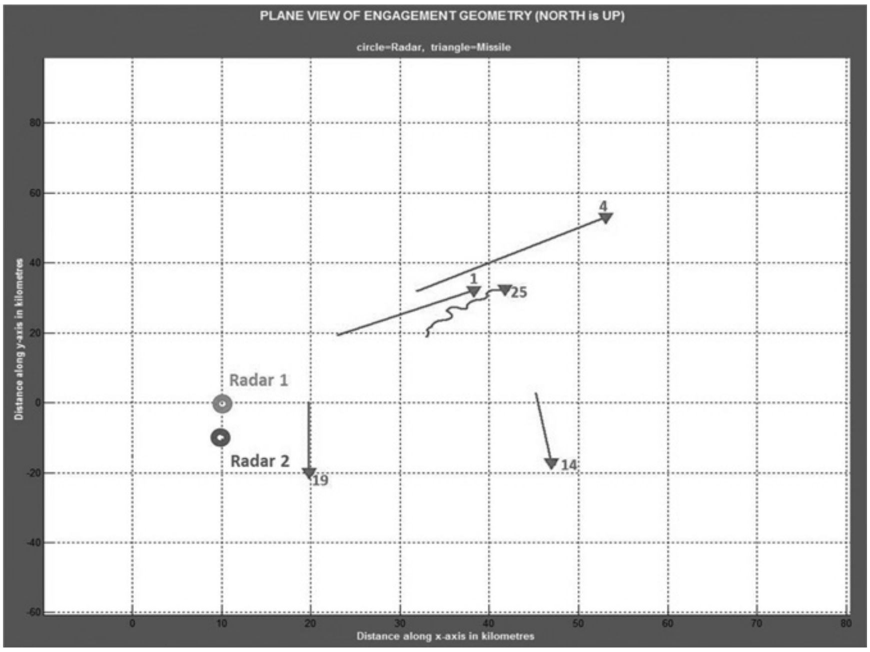

Fig. 10 *Top-down view of radar locations and select target trajectories for scenario with Target Set A*

Triangles indicate target position at the start of its trajectory

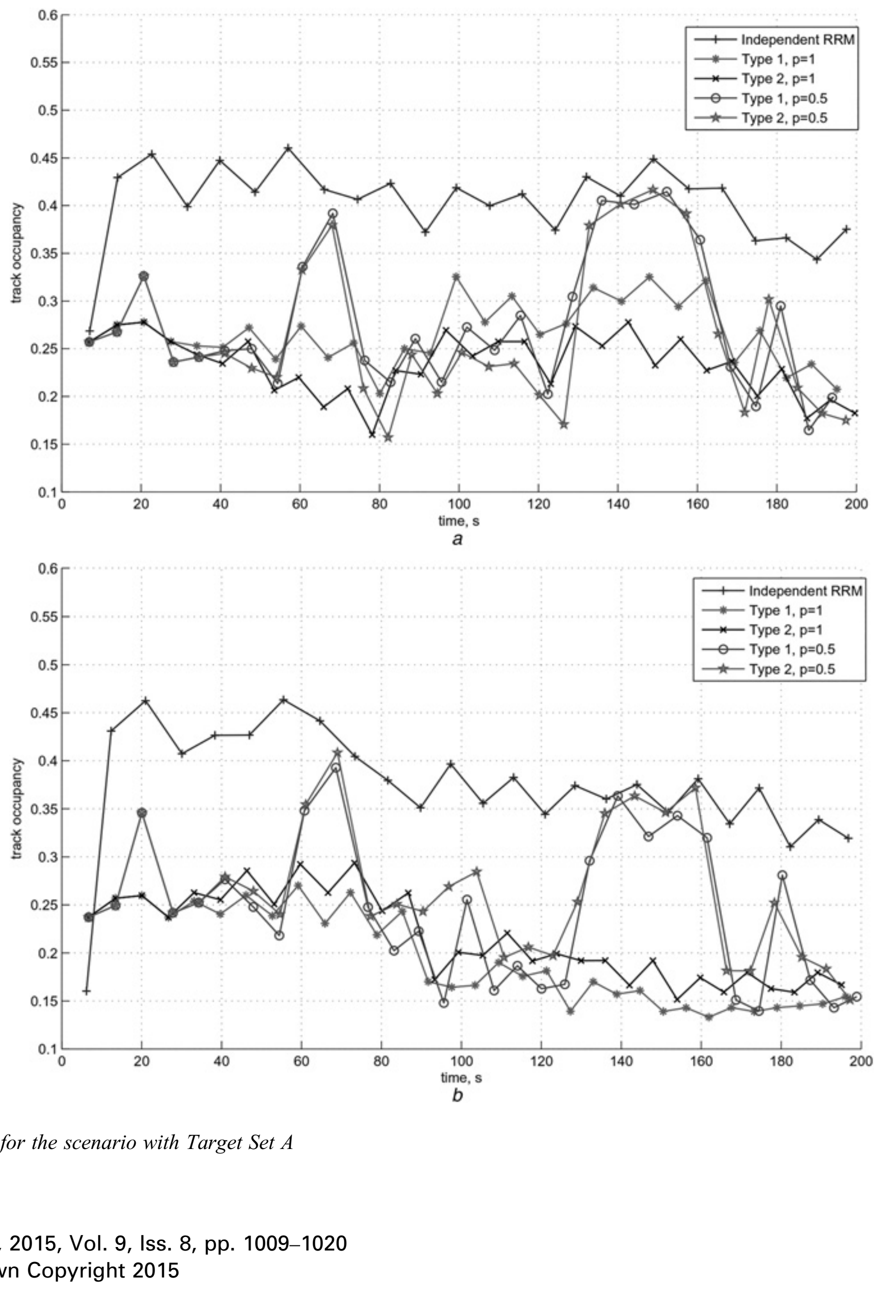

Fig. 11 *Track occupancy for the scenario with Target Set A*

a Radar 1
b Radar 2

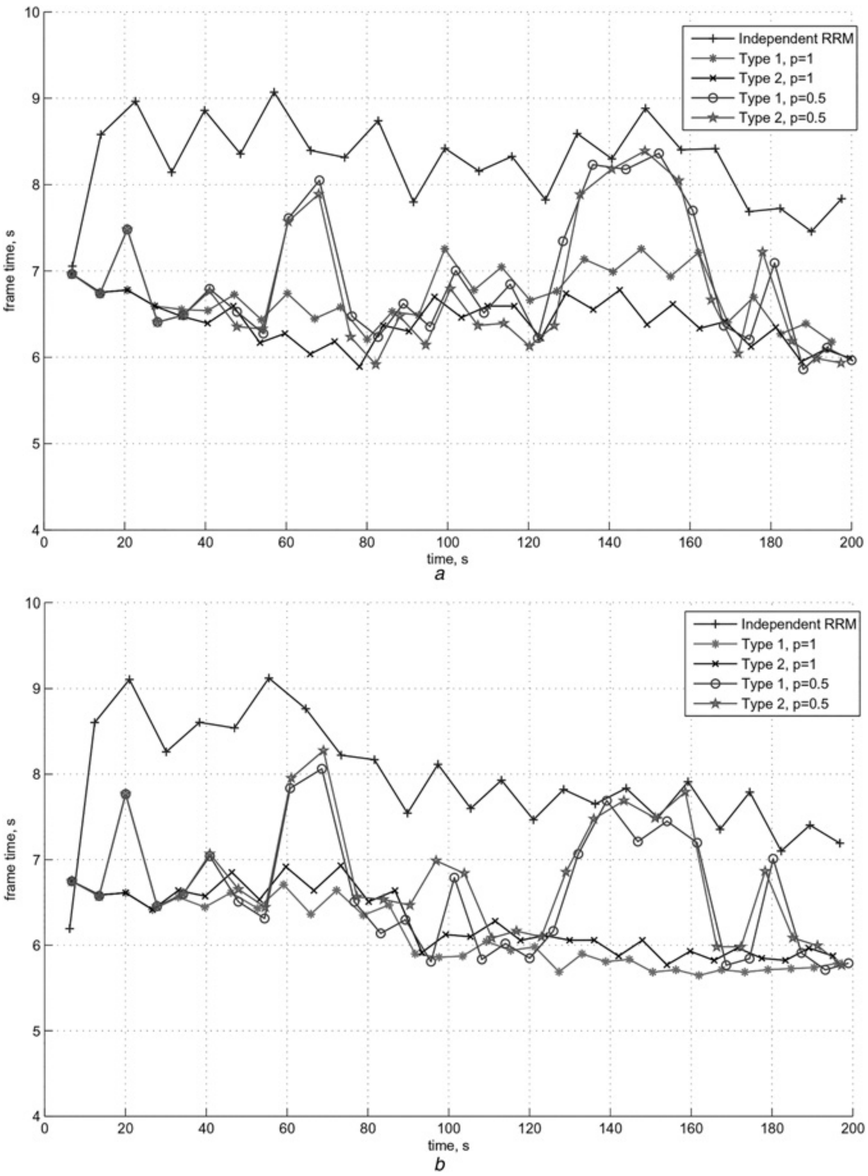

Fig. 12 *Frame time for the scenario with Target Set A*

a Radar 1
b Radar 2

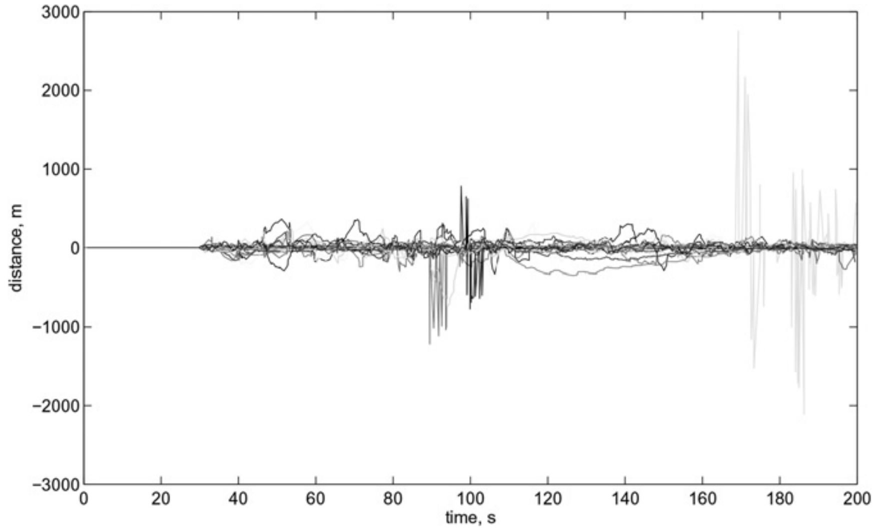

Fig. 13 *Difference between position error for Type 2 Management with p = 1 and position error for Type 1 Management with p = 1*

Positive difference corresponds with lower Type 2 error

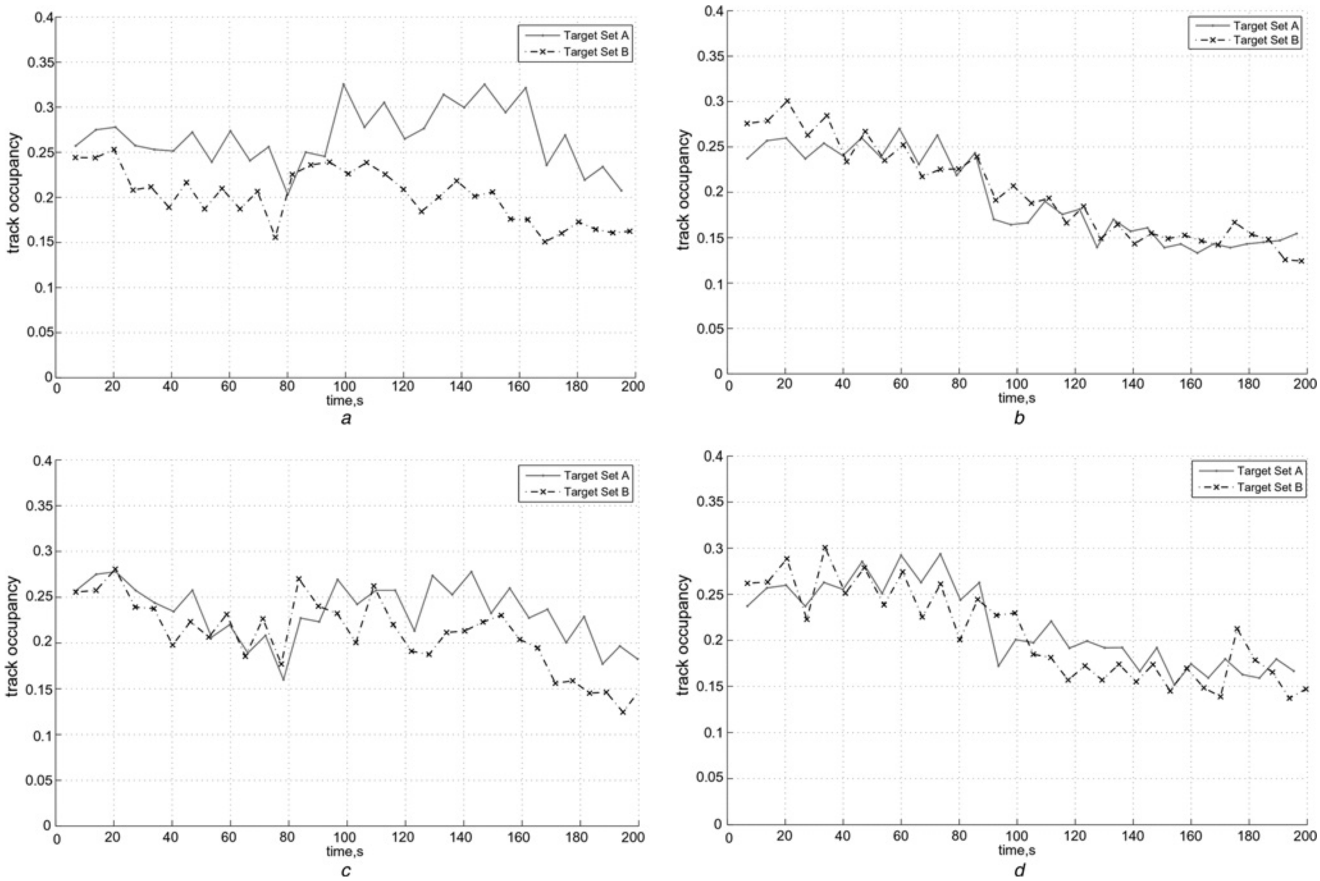

Fig. 14 *Comparison of track occupancy for Target Set A and Target Set B*

a Radar 1: Type 1 Management, $p = 1$
b Radar 2: Type 1 Management, $p = 1$
c Radar 1: Type 2 Management, $p = 1$
d Radar 2: Type 2 Management, $p = 1$

lower Type 2 error. For some targets, Type 1 Management has smaller position error, whereas Type 2 Management has smaller position error for other targets. For this target scenario, neither the use of Type 1 or Type 2 Management results in smaller estimation error. For a small number of targets, there are periods of time when the estimation error has sharp increases in value for either Type 1 or Type 2 Management, which causes a spike in the difference value plotted in Fig. 13. The increase in estimation error value occurs when two or more targets cross paths, and the tracker momentarily associates the track with a different target.

Fig. 14 compares track occupancy for Target Set A with that for Target Set B. Figs. 14*a* and *b* show track occupancy for Type 1 Management with $p = 1$ for Radars 1 and 2. Although the track occupancy is similar for Radar 2, Target Set B has somewhat lower track occupancy for Radar 1. This is because the targets in Target Set B are moving away from the radars at a higher velocity, which decreases target priority and increases track update intervals. For Type 2 Management with $p = 1$, Figs. 14*c* and *d* show track occupancy for Radars 1 and 2. Again in this case, track occupancy is similar for Radar 2, but Target Set B has slightly lower track occupancy for Radar 1. Similar to Type 1, this is caused by higher velocity targets that are moving away from the radars.

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. However, when the communication channel is available, Type 1 Management and Type 2 Management have decreased track occupancy and decreased frame time compared with 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 the 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. When the communication channel is not available, results showed that the performance of coordinated RRM is similar to that of independent RRM.

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 with independent RRM when the individual radars are overloaded. Overall, differences in track completeness and track occupancy between Type 1 and Type 2 Managements will depend on the task assignment and look assignment algorithms.

7 Conclusions

This paper considered whether the sharing of detection and tracking data can enhance RRM performance. Coordinated RRM exploits data that are transmitted across a communication channel. Two types of coordinated RRM techniques were formulated, with each type characterised by varying amounts of coordination between the radar nodes. A two-radar network and 30-target scenario were modelled 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 performance of coordinated RRM for a communication channel with errors was also modelled and analysed. For the examples considered here, there was no difference in performance between Type 1 and Type 2 Managements.

The use of coordinated RRM offers the potential for significant performance improvements; however, the analyses of further radar and target scenarios are required before definitive conclusions can be drawn about the benefits of coordinated RRM and about comparisons between Type 1 and Type 2 Managements. The example in Section 6 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.

8 Acknowledgments

The authors thank Bill Brinson, Bing Yue and Joseph Chamberland of C-CORE Ottawa for carrying out simulations in Adapt_MFR.

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