Joint Radar-Communications Resource Management

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***Abstract*—This paper describes a joint radar-communications resource management framework and modeling approach for a synergistic concept that integrates the radar and communications functionality into a single shared-spectrum system. Such systems share a single transmission - communicating with mobile radios and illuminating the target simultaneously. The results are presented as a function of system exclusivity, i.e., how performance varies as the system is tuned between communications optimized and radar optimized. A joint figure of merit is proposed and used to show how a synergistic shared-spectrum system provides more radar and communications capacity than either a stand-alone communications system or a stand-alone radar system.**

Keywords—radar resource management, spectrum sharing.

I. INTRODUCTION

The ever increasing strain on limited spectrum resources has driven the recent development of radar and communications systems into near and long-term design paradigms: coexistence and co-design [1]. The coexistence paradigm takes a short-term view where existing and emerging radar and communications systems are redesigned to operate in the same spectrum on a noninterfering basis through low-level cooperation and/or spectrum sensing.

The co-design paradigm takes a long-term view where a joint radar and communication system is designed from the ground up. In this paradigm the separation between the radar and communications systems is not necessarily well-defined because the joint system can be highly coupled. It is this coupling that presents potential synergistic improvements along with design and analysis challenges.

In [2] a joint radar and communications system co-design concept was introduced that shares a single transmitter and transmit antenna and uses a joint waveform to simultaneously transmit data to users and illuminate the target. This system is suitable for forward operating bases, small naval vessels and some civil applications such as air traffic control.

In such a system the high degree of synergy between radar and communications poses many design and analysis challenges. One particular challenge is the development and analysis of efficient joint radar and communications resource management and scheduling schemes. As a first step in developing efficient resource management and scheduling schemes this paper focuses on the development of a joint resource management framework and modeling approach. The analytic models will be used for estimating the joint radar and communications performance in order to benchmark potential resource management and scheduling schemes.

In Section II we introduce a framework for understanding resource management and scheduling as a process that uses the system state, available resources and mission requirements to produce a schedule for distributing resources. In Section III we develop an analytic system model and derive formulas for estimating performance. In Section IV we quantify joint radar and communications system performance and define a joint performance metric. In Section V we show results of the model for a specific scenario and set of requirements.

II. RESOURCE MANAGEMENT AND SCHEDULING FRAMEWORK

The high degree of synergy between radar and communications requires a process for managing and scheduling resources. At the highest level in the framework the Resource Management and Scheduling (RMS) process is responsible for allocating system resources to best meet the joint radar and communications mission requirements (Fig. 1).

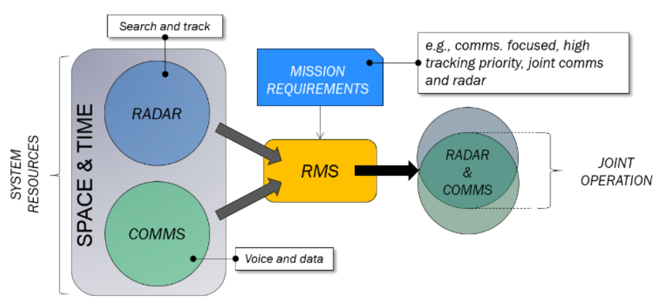

Fig. 1. Role of the resource manager and scheduler.

The RMS uses its knowledge of the system state, available system resources and mission requirements to generate an optimal scan schedule for execution. Fig. 2 depicts the RMS process flow that is used to allocate the system's resources. The system state is represented by the current and near-future states of the communications and radar activity. The system's state depends upon both the communications state (communications node registry and associated geo-registration of the nodes, the radio capability of each node, available energy resources, total number of users, number of active users and the arriving/departing users) and the radar state (radar search timeline, active tracks and potential tracks).

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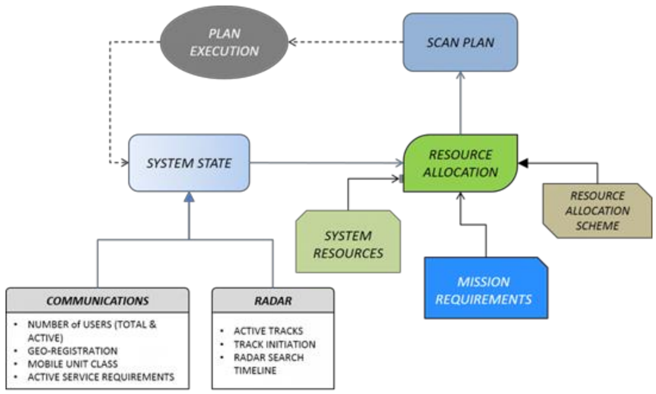

Fig. 2. RMS process flow.

Not all missions will be the same and some may rely more heavily on communications while others on radar and tracking. To keep the RMS framework as general as possible it is necessary to include mission requirements as an input and guide for resource allocation. This generalization will also be useful when testing and evaluating an RMS process since performance will be mission specific.

In the RMS process flow the resource allocation process is governed by the Resource Allocation (and Scheduling) Scheme (RAS). The RAS is an abstraction for the implementation details of the resource allocation process, which consists of a collection of subroutines (joint optimization functions, rules and heuristics) that take as input, the system state, available resources and mission requirements and return a realizable scan schedule.

To further the framework we can think of the RMS as providing a set of services to a notional set of consumers or users (e.g., radar search user, voice communications user) with the mission requirements acting as a mediator. In this framework we assign each service a set of resource requirements and priority levels, that when combined are equivalent to a quality of service (QoS). In the most general case, the QoS for communications and radar services will be set by the mission requirements, although realistically some services will need a minimum level of QoS to even be considered services. Example communications and radar service classes and their associated service requirements are described in Table I and Table II respectively.

TABLE I. COMMUNICATIONS SERVICE CLASSES

Type of Data	**Throughput**	**Maximum Latency**	**Nominal Priority**
Voice	10 kbps	200 ms	1
Low. rate data	50 kbps	1 s	2-4
Med. rate data	300 kbps	3 s	2-4
High rate data	1 Mbps	5 s	2-4

TABLE II. RADAR SERVICE CLASSES

Radar Mode	**Dwell**	**Revisit Interval**	**Nominal Priority**
Low Elevation Search	16 ms	2 s	1
Medium Elevation Search	10 ms	4 s	2
High Elevation Search	10 ms	4 s	3
High Update Rate Track	10 ms	250 ms	1

To gain additional insight into the problem of joint resource management it is useful to abstract the service requirements back to their basic time and space resources. Table III shows how system service requirements are mapped to radar system resources.

TABLE III. RESOURCE MAPPING

System Resource		**System Service**	
		Radar	***Communications***
Space	***Beam Positions***	Volume Coverage	User Coverage
Time	***Beam Revisit Rate***	Coverage Rate	Latency
	Beam Dwell	Detection Range	Throughput

III. SYSTEM MODEL

In this section we derive the basis of an analytic model for computing communication system user capacity and QoS supportable by a given radar timeline. In this paper we make the assumption that the radar operates at full duty cycle in search/track mode to simplify the computations. The communications uplink from the user to the system is assumed to take place in a different band so the focus of the model is on downlink only.

We begin with a basic model of a radar timeline (see Fig. 3) consisting of three parameters: beam dwell duration τ, number of beam positions per scan interval N and beam revisit interval T, where $T \geq N\tau$. We define the scan occupancy as $\rho = \frac{N\tau}{T}$. Note that in general the revisit interval may not be fully occupied with radar activity i.e., $T > N\tau \rightarrow \rho < 1$.

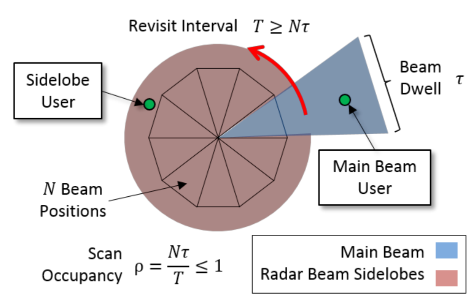

Fig. 3. Basic model of a radar timeline.

In the system under consideration the communications waveform is the same as the radar waveform so that when communications is overlaid on top of the radar model above it gives rise to a comms. user's achievable throughput model (see Fig. 4). In this user throughput model we assume that a user has only two achievable instantaneous data throughput rates q_0 and q_1 ($q_0 \leq q_1$) corresponding to the beam sidelobe and main lobe channel rates respectively. Although the inactive part of the scan period is illustrated as contiguous, in general it will not be and moving forward we will assume that it is evenly distributed over the scan period. Using this model we focus on three cases where we formulate a user's supportable QoS.

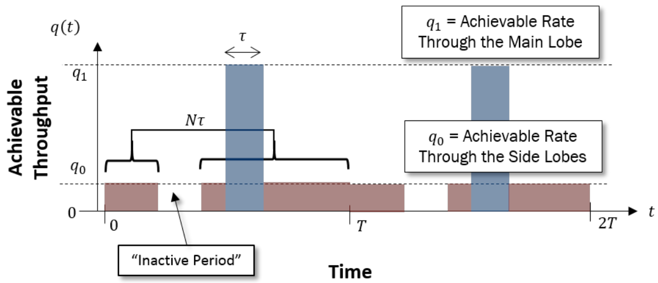

Fig. 4. A user's achievable throughput model.

A. Case 1

The first case (see Fig. 5) is when a comms. user utilizes the link exclusively during the period of illumination by the main beam (highest rate q_1). In this case the user's data buffer $B(t)$ increases during the period the link is not available to the user. The supported QoS is tabulated in Table IV. The supported user throughput is denoted by Q and is bounded above by $Q_{max} = \frac{q_1\tau}{T}$. The supported latency L is defined as $L = \frac{\max(B(t))}{Q}$, the maximum buffer size reached over the user's timeline divided by the user's supported throughput. L is bounded below by $L_{min} = T - \tau$. The link efficiency is defined as $\frac{Q_{max}}{q_1\rho}$ and is a measure of how efficient the available radar timeline is at supporting the maximum achievable user throughput. In this case the link efficiency is 1.

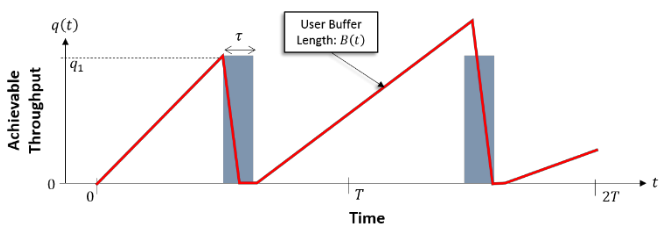

Fig. 5. Case 1 – Comms. user utilizes main beam capacity exclisively.

TABLE IV. CASE 1 – COMMS. USER SUPPORTED QOS

Supported Throughput	Supported Latency	Link Efficiency
$Q \leq \frac{q_1\tau}{T} = Q_{max}$	$L \geq T - \tau = L_{min}$	1

B. Case 2

The second case (see Fig. 6) is when a user utilizes the link during the entire scan interval (period of illumination by the main beam followed by sidelobe illumination). Computing the supported QoS can be broken down into three sub cases based on achievable sidelobe rate as shown in Table V.

Note that when latency is represented with square brackets $[A, B]$ A is the best-case latency and B is the worst-case latency (shows the potential range of supported latencies). Additionally, we can justify that the worst-case latency is unlikely under the assumption that the scan schedule is evenly distributed over the scan period (the worst-case occurs when the inactive period of the scan is contiguous). We also point out that Case 1 is a special instance of Case 2 where $q_0 = 0$.

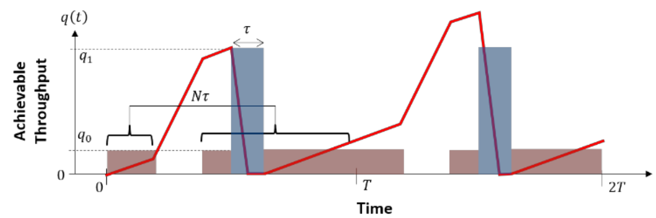

Fig. 6. Case 2 – Comms. user utilizes the main beam and sidelobe capacity.

C. Case 3

The third case is when a comms. user is sufficiently close to the transmitter and has reached the maximum possible data rate available with sidelobe communications, thus the minimum and maximum achievable rates are the same. The supported QoS for this case is tabulated in Table VI. Note that this is also just a special instance of Case 2 where $q_0 = q_1$.

TABLE VI. CASE 3 – COMMS. USER SUPPORTED QOS

Supported Throughput	Supported Latency	Link Efficiency
$Q \leq \frac{q_1 N\tau}{T}$	$L \geq \left[\frac{T}{N} - \tau, T - N\tau\right]$	1

D. Number of Supportable Comms. Users

It is straightforward to apply the above results to compute the number of supportable comms. users M for each case given q_0, q_1, and the required throughput Q_{req} assuming the required latency L_{req} is supportable. For example, in Case 1 if $L_{req} \geq T - \tau$ we have:

$$M \leq \left\lfloor \frac{Q_{max}}{Q_{req}} \right\rfloor = \left\lfloor \frac{q_1\tau}{Q_{req}T} \right\rfloor \quad (1)$$

Where $\lfloor\cdot\rfloor$ is the floor function (so that M is a non-negative integer).

TABLE V. CASE 2 – COMMS. USER SUPPORTED QOS

Supported Throughput	Sidelobe Rate	Supported Latency	Link Efficiency
$Q \leq \frac{(q_0(N-1) + q_1)\tau}{T}$	$q_0 \leq Q$	$L \geq T - \left(1 + \frac{q_0}{Q}(N-1)\right)\tau$	$\frac{q_0(N-1) + q_1}{Nq_1} \leq 1$
	$Q < q_0 < \frac{T}{N\tau}Q$	$L \geq \left[T - \left(1 + \frac{q_0}{Q}(N-1)\right)\tau, T - N\tau\right]$	
	$\frac{T}{N\tau}Q \leq q_0$	$L \geq \left[\frac{T}{N} - \tau, T - N\tau\right]$	

TABLE VII. NUMBER OF SUPPORTABLE USERS FOR A GIVEN QOS

Case		Supported Users				Sidelobe Rate Constraint	Supported Latency
1	***All Comms Through Main Beam***	Users per Beam Position	$M \le \left\lfloor \frac{q_1 \tau}{Q_{req} T} \right\rfloor$	Users per Scan Interval	$M \le \left\lfloor \frac{q_1 \tau}{Q_{req} T} \right\rfloor N$	None	$L_{req} \ge T - \tau$
2	***All Comms Spread over Scan Interval***	Users per Scan Interval	$M \le \left\lfloor \frac{(q_0(N-1) + q_1)\tau}{Q_{req} T} \right\rfloor$			$q_0 \le M Q_{req}$	$L_{req} \ge T - \left(1 + \frac{q_0}{Q_{req}}(N-1)\right)\tau$
						$M Q_{req} < q_0 < M Q_{req} \frac{T}{N\tau}$	$L_{req} \ge \left[T - \left(1 + \frac{q_0}{Q_{req}}(N-1)\right)\tau, T - N\tau\right]$
						$M Q_{req} \frac{T}{N\tau} \le q_0$	$L_{req} \ge \left[\frac{T}{N} - \tau, T - N\tau\right]$
3	$q_0 = q_1$	Users per Scan Interval	$M \le \left\lfloor \frac{q_1 N \tau}{Q_{req} T} \right\rfloor$			None	$L_{req} \ge \left[\frac{T}{N} - \tau, T - N\tau\right]$

It is clear that if a service requires a latency $L_{req} < T - \tau$ then using the main beam exclusive approach (Case 1) is not viable and communications must be spread over the entire scan period (Case 2). Table VII shows the summary of the formulas for computing the number of supportable users for the three cases. It is important to point out that the latency in Case 2 is dependent on the number of supported users which is reflected in the generally sub-optimal link efficiency in Table V.

In a realistic system the inactive period depicted in Fig. 4 may be taken up by other radar modes, e.g., other elevation search and high-update rate tracking. We will also assume that any remaining unallocated radar timeline can be used exclusively for communications. In Fig. 7 we show a generalized achievable user throughput model that takes into account other radar modes and inactive periods in the radar's timeline.

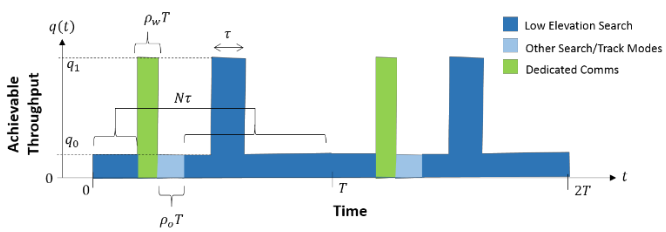

Fig. 7. Generalized achievable throughput model.

In this case the other radar modes and inactive periods are assigned a fraction of the total timeline ρ_0 and ρ_w respectively.

In order to simplify the analysis of complex radar timelines, we assume that when the system is operating in the other radar modes a user is only capable of utilizing the minimum potential throughput q_0 (sidelobe communications only). This assumption is justified if the only comms. users being supported are on the ground and illuminated exclusively by the low elevation search beams. We further assume that any unused timeline is available to a user at the maximum potential throughput q_1 (dedicated communications).

Additionally, the granularity of the link resource must be considered because it will put upper limits on the number of serviceable users. For example, in a time-division multiple access system the maximum number of users supportable will be the number of available user timeslots within a service latency interval. We take resource granularity into account in the model with the parameter ϵ. Table VIII shows a summary of the formulas derived for computing the number of supported users in this generalized radar timeline. Note that the function $\Omega(a, b)$ is defined as follows:

$$\Omega(a, b) = \left\lfloor \frac{b}{\left\lceil \frac{b}{\min(a,b)} \right\rceil} \right\rfloor \tag{2}$$

Where $\lceil\cdot\rceil$ is the ceiling function.

IV. QUANTIFYING JOINT SYSTEM PERFORMANCE

To quantify joint radar-communications system performance we introduce a perspective for analyzing the joint capability space. By viewing the system's timeline as a whole (see Fig. 8) it can be thought of as being divided into two

TABLE VIII. NUMBER OF SUPPORTABLE USERS IN A GENERALIZED RADAR TIMELINE

Service Latency	Case	Supported Users
$T - \tau \le L_{req}$	$q_1 \ge \frac{Q_{req} T}{\tau}$	$M \le \Omega\left(\left\lfloor \frac{q_1 N \tau}{Q_{req} T} + \frac{q_0 \rho_0 + q_1 \rho_w}{Q_{req}} \right\rfloor, \left\lfloor \frac{L_{req}}{\epsilon} \right\rfloor\right)$
	$q_1 < \frac{Q_{req} T}{\tau}$	$M \le \Omega\left(\left\lfloor \frac{(q_0(N-1) + q_1)\tau}{Q_{req} T} + \frac{q_0 \rho_0 + q_1 \rho_w}{Q_{req}} \right\rfloor, \left\lfloor \frac{L_{req}}{\epsilon} \right\rfloor\right)$
$L_{req} < T - \tau$	N/A	$M \le \Omega\left(\min\left(\left\lfloor \frac{q_0(N-1)\tau}{\max\left(0, Q_{req}(T - \tau - L_{req})\right)} \right\rfloor, \left\lfloor \frac{(q_0(N-1) + q_1)\tau}{Q_{req} T} \right\rfloor\right), \left\lfloor \frac{N\tau L_{req}}{T\epsilon} \right\rfloor\right) + \Omega\left(\left\lfloor \frac{q_0 \rho_0 + q_1 \rho_w}{Q_{req}} \right\rfloor, \left\lfloor \frac{(\rho_0 + \rho_w) L_{req}}{\epsilon} \right\rfloor\right)$

mutually exclusive parts: a radar dedicated portion and a communications dedicated portion. Then we ask what additional (synergistic) capabilities can each portion yield for the other's cause. E.g., what synergistic communications capability can the dedicated radar portion of the timeline produce? Or what synergistic radar capability can the dedicated communications portion of the timeline produce? These dedicated capabilities are combined with the synergistic capabilities to compute a metric we refer to as the Joint Figure of Merit (JFOM).

In Fig. 8 changing $\alpha \in [0,1]$ can be thought of as varying the system's exclusivity between radar and communications. Note that the figure is intended to illustrate that the α acts like a "slider" and thus drags the boundary between radar and communications to the left or right. It is also important to stress that the stark division of the timeline between radar and communications is only for illustrative purposes and in an actual timeline radar and communications dedicated portions will be tightly interleaved to meet radar and communications users QoS requirements.

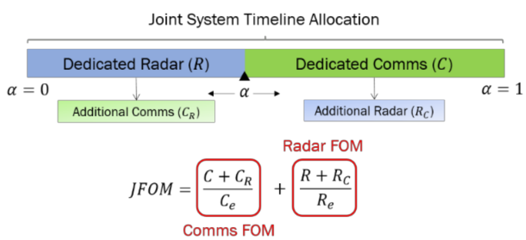

Fig. 8. A perspective for analyzing joint radar and communications capability.

To fix ideas an $\alpha = 0$ represents a system that is fully dedicated to communications (communications exclusive capability C_e) and an $\alpha = 1$ represents a system that is fully dedicated to radar (radar exclusive capability R_e). R and C represent the capability associated with the radar and communications dedicated modes respectively. C_R and R_C represent the synergistic contributions associated with the dedicated radar and communications modes respectively. The formula for computing the JFOM is shown in (3) below.

$$JFOM(\alpha) = \frac{C(\alpha)+C_R(\alpha)}{C_e} + \frac{R(\alpha)+R_C(\alpha)}{R_e} \quad (3)$$

We point out that the JFOM defined above is general in that we have not specified what we mean by "capability" and we don't specify the mechanics of how α is varied. In this paper we will equate communications capability with the number of supportable users at a specified QoS and equate radar capability with the maximum detection range. We vary α by proportionally reducing the radar beam dwells in each required mode which reduces the maximum detection range in that mode.

V. Results

A. Application of System Model

The formulas shown in Table VIII can be used to estimate the total system comms. user capacity for a specific comms. QoS using Monte-Carlo simulation. The simulation proceeds by incrementally selecting a user's location pseudo randomly from a geographic distribution. The user's associated achievable rates, q_0 and q_1 are computed using the path loss model and the number of supportable users M is computed based the QoS requirements. The user's per-link resource is equal to $\frac{1}{M}$ and is added to the total system link resource utilization. Once the system's communications resources are consumed (resource utilization ≥ 1) the simulation terminates. The system's user capacity is defined as the number of serviced users during the simulation rep. Multiple reps of the simulation are run for variance reduction and an average system user capacity is returned.

B. User Geographic Distribution

For the results presented in this paper communications users are distributed uniformly in range and azimuth (i.e. user density falls off with range^2). Furthermore, only users that can achieve the minimum side lobe data rate will be simulated for the NLOS communications. Under the free space path loss model users are simulated out to 30 km.

C. Exclusive System Capabilities

In this subsection we describe the computation of the exclusive radar and communications capabilities (C_e and R_e) used in computing the JFOM results presented later. Radar capabilities are straightforward to compute analytically (e.g., radar range equation, target model, timeline occupancy) given the radar QoS requirements in Table II and an assumed power-aperture product (see ref. [1]). Using the beam revisit interval we can compute the relative occupancy of each radar mode in the radar timeline. The system capability for a radar with five elevation beams and six active track beams is given in Table IX.

TABLE IX. EXCLUSIVE RADAR CAPABILITIES

Radar Mode	Dwell	Detection Range	Revisit Interval	# of Beams	% of Timeline
Low Elev. Search 1	16 ms	55 km	2 s	32	25.6
Low Elev. Search 2	16.5 ms	55.5 km	2 s	32	26.4
Med. Elev. Search 1	10 ms	49 km	4 s	32	8.0
Med. Elev. Search 2	10 ms	49 km	4 s	32	8.0
High Elev. Search	10 ms	49 km	4 s	32	8.0
Track	10 ms	69 km	250 ms	6	24.0

Table X shows user capacity (number of users supported) as a function of service class for two path loss models, line of site (LOS) and non-line of site (NLOS), the latter using the Okamura-Hata [3] urban propagation model. User throughput rates are based on the user's receive SNR and pathloss model. The service requirements used to produce these results are the same as in Table I. We note that the LOS and NLOS system capabilities in Table X are nearly similar because the system's power-aperture product is so large.

TABLE X. EXCLUSIVE COMMUNICATIONS CAPABILITIES

Waveform	Voice	Low Rate	Med. Rate	High Rate
Line of Site	16000	8888	1508	453
Non Line of Site	16000	8848	1547	465

D. Non-Synergistic Figures of Merit

In Fig. 9 we show the behavior of the JFOM in the non-synergistic case as a function of system exclusivity (communications gets no benefit from the radar dwells and vice versa). This case shows the trend of the JFOM when radar and communications modes are operated on a time sharing basis and provides a benchmark for interpreting synergistic JFOM results. We define the non-synergistic JFOM in (4):

$$JFOM_{NS}(\alpha) = \alpha^{1/4} + (1 - \alpha) \qquad (4)$$

Since α represents the proportion of time allocated to the radar mode and the mechanism being used to vary α is reduction in dwell time we can see that the radar FOM (based on detection range) is equivalent to $\alpha^{1/4}$. As the time allocated to communications is varied the communications FOM (user capacity) has a straightforward linear relationship of $1 - \alpha$.

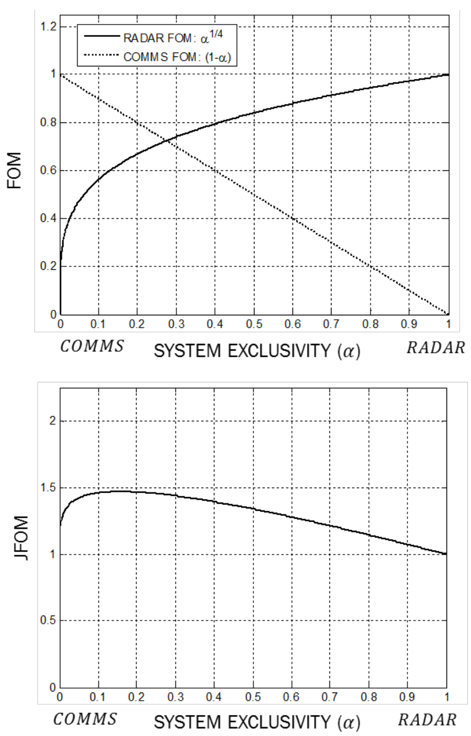

Fig. 9. The individual radar and communications figures of merit (top) and the joint figure of merit (bottom) as a function of system exclusivity.

E. Simulated Results

Figs. 10 and 11 show the JFOM as a function of radar/communications exclusivity (α) for the LOS and NLOS scenarios. Note that due to the different data rate and latency requirements the JFOM depends upon which communications service is analyzed.

Under the LOS propagation model (Fig. 10) the JFOM curves show clear separation from the non-synergistic JFOM illustrating that the joint capability is higher when the radar and communications modes operate synergistically in shared spectrum. The JFOM curves for the NLOS propagation model (Fig. 11) don't show much improvement over the non-synergistic JFOM, although when $\alpha = 1$ some small improvement is observed for the services with high-latency. It is clear that the sidelobe communications channel is necessary in realizing synergistic improvements but it is not available to a majority of the users in the NLOS case. In addition, the revisit interval for the low elevation beams is not compatible with voice and low-rate latency requirements so most users cannot be serviced.

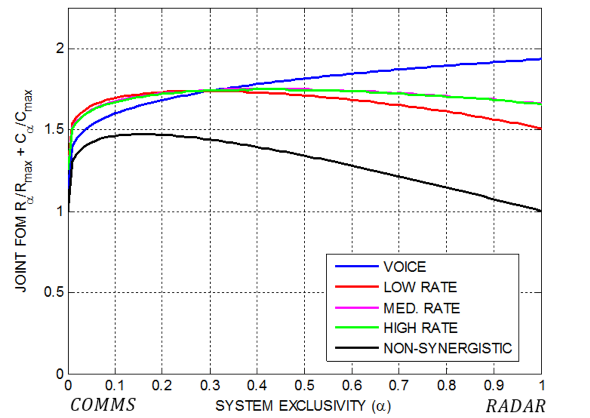

Fig. 10. JFOM as a function of α with LOS propagation model.

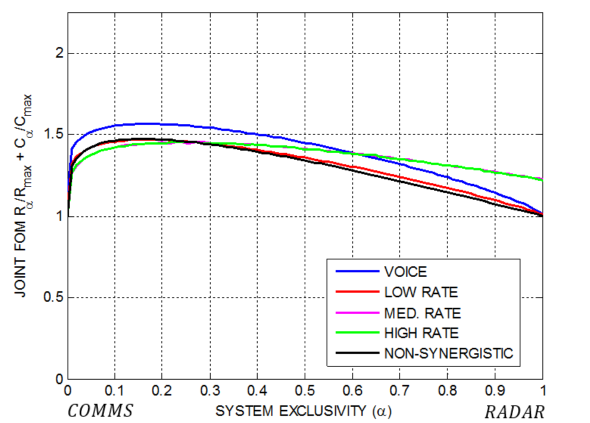

Fig. 11. JFOM as a function of α with NLOS propagation model.

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