Time Allocation for Integrated Bi-static Radar and Communication Systems

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***Abstract*— Integrated radar and communications systems are increasingly important for applications requiring both sensing and information exchange. In this letter, we study the time allocation problem for an integrated bi-static radar and communications system. A closed-form expression for the achievable rate considering radar detection accuracy is derived analytically for this problem and optimized. Numerical results reveal that the optimum time allocation is characterized by the signal-to-noise ratio and the prior probability of target.**

***Index Terms*— Bi-static radar, communications, optimization, probability of detection.**

I. Introduction

Recently, the research interest in the integration of radar and communications has increased dramatically [1]. Firstly, due to the rapidly growing number of wireless applications and devices, wireless communication is facing the challenge of spectrum scarcity. Consequently, frequency bands have to be shared between long-term evolution (LTE) and radar [2]. Secondly, many emerging applications require the cooperation of radar and communications in their operations. Intelligent transportation [3] is one example, which requires both radar for obstacle detection and communications for information exchange. Also, in the fifth generation (5G) system, due to the high frequency, blockage becomes serious and needs to be detected before information exchange [4]- [6].

Existing works on the tradeoff between radar and communications include the following. In [7] and [8], the target detection performance was optimized by maximizing the probability of detection (P_D) for bi-static and multi-static radar systems, respectively. A MIMO radar-communications system was designed in [9], where separated and shared deployments were compared. Reference [10] improved the communication performance of the shared deployment proposed in [9].

Several generalized likelihood ratio test (GLRT) detectors for bi-static radar system were proposed in [11]. Approximate distributions for the GLRT detection variable were derived in [12]. All these works have provided very useful insights into integrated radar-communications designs. The main function of radar is target detection, while the main function of communications is information exchange. In these previous works, although radar and communications are co-designed by optimizing their transmission parameters, the two functions are still separate, that is, the target to be detected does not affect communications. However, this may not be the case in practice. For example, in 5G using millimeter-wave [4], [5], when no obstacle is detected, the communications signal only comes from the direct link transmitting regular information, but when an obstacle is detected, the communications signal comes from both direct and reflected links containing useful information. Thus, the communications receiver should be adapted to radar detection to improve energy efficiencies, different from [13]- [14]. None of [4]- [5], [11]- [14] has considered tradeoff between radar and communication.

In this work, we consider an integrated bi-static radar and communications (RadCom) system. If an obstacle is detected, a maximal ratio combiner (MRC) will be used to combine signals from the direct and reflection links. If no obstacle is detected, only signal from the direct link will be used. Time allocation between radar detection and information communication is examined, subject to a fixed total time. Numerical results indicate that optimum time allocation exists that maximizes the achievable rate. It is determined by the detection threshold and signal-to-noise ratio (SNR).

II. System Model and Optimization

A. System Model

Consider a joint bi-static radar and communications system with one colocated radar/communications transmitter (Tx.), one receiver (Rx.), as illustrated in Fig. 1. The transmitted signals travel from Tx. to Rx. in the direct link, and is also reflected by the obstacle in the reflection link if the obstacle exists. In this system, Tx. and Rx. are stationary and their locations are assumed known. Since this is a passive radar, the same signals can be sent for both radar detection and information exchange, except that part of the signal is used for radar and part used for information. The model in Fig.1 is the same as that in [7], whereas the model in [15] is different in that they have separate radar and communications transmitters as well as optimize waveform instead of time.

Assume that the total transmission time is T seconds and the transmission power is P_T for both radar and communications functions. Since this is a passive radar, radar power and communication power are the same. We consider a time division scheme for the integration of radar and communications. One has $T_r + T_c = T$, where T_r and T_c are the time duration for radar and communications, respectively. The benefit of time division over dual-functional system is that time division simplifies the system by performing radar and communications alternately, while dual-functional system requires joint waveform, joint beamforming etc, which are often complicated.

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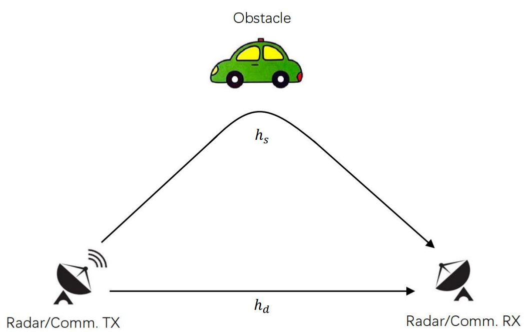

Fig. 1. Joint bi-static RadCom system

B. Radar Detection

Radar detection is performed first for T_r seconds, as a binary hypothesis testing problem of [7], [11]- [12]

$$H_0 : \begin{cases} \mathbf{y}_d = \sqrt{P_T} h_d \mathbf{s}_r + \mathbf{n}_d \\ \mathbf{y}_s = \mathbf{n}_s \end{cases} \quad (1)$$

for the null hypothesis and

$$H_1 : \begin{cases} \mathbf{y}_d = \sqrt{P_T} h_d \mathbf{s}_r + \mathbf{n}_d \\ \mathbf{y}_s = \sqrt{P_T} h_s \mathbf{s}_r + \mathbf{n}_s \end{cases} \quad (2)$$

for the alternative hypothesis, where $\mathbf{y}_d = [y_{d1}, y_{d2}, \cdots, y_{dL}]^T$, $\mathbf{s}_r = [s_{r1}, s_{r2}, \cdots, s_{rL}]^T$ and $\mathbf{n}_d = [n_{d1}, n_{d2}, \cdots, n_{dL}]^T$ are all $L \times 1$ vectors, $[\cdot]^T$ represents the transpose operation, $\mathbf{y}_s$ and $\mathbf{n}_s$ are also $L \times 1$ vectors, $L = [\frac{T_r}{T_s}]$ is the total number of samples used for radar detection, $[\cdot]$ is the integer function, h_d is the complex channel coefficient in the direct link, h_s is the complex channel coefficient in the reflection link, s_r is the transmitted signal for radar detection, n_d and n_s are the complex additive white Gaussian noise (AWGN) with mean zero and variance σ^2. Assume constant modulus modulation in this work so that $|s_r|^2 = 1$ and $\mathbf{s}_r^H \mathbf{s}_r = L$, where $(\cdot)^H$ is the Hermitian operation. Assume that the noise samples are independent such that the covariance matrices of $\mathbf{n}_d$ and $\mathbf{n}_s$ are both given by $\sigma^2 \mathbf{I}_L$, where $\mathbf{I}_L$ is the L-th order identity matrix. Using the above signals, a GLRT detector is [12]

$$A = ||\mathbf{y}_s||^2 - ||\mathbf{y}_d||^2 + \frac{1}{\sigma^2 \lambda} |\mathbf{y}_d^H \mathbf{y}_s|^2 \underset{H_0}{\overset{H_1}{\gtrless}} \sigma^2 \lambda, \quad (3)$$

where $||\cdot||$ represents the Euclidean norm and λ is the detection threshold. This GLRT detector has a closed-form expression for the probability of false alarm but not the probability of detection. However, approximations can be used [12].

Using the generalized extreme value (GEV) in [12], the probability of false alarm (P_{FA}) is approximated as

$$P_{FA}(L) = Pr\{A > \sigma^2 \lambda | H_0\} \approx 1 - e^{-(1+\frac{v(x-w)}{u})^{-\frac{1}{v}}}, \quad (4)$$

where

$$\frac{\Gamma(1-3v) - 3\Gamma(1-2v)\Gamma(1-v) + 2\Gamma^3(1-v)}{sgn(v)[\Gamma(1-2v) - \Gamma^2(1-v)]^{1.5}} = \frac{E_3^0(L) - 3E_2^0(L)E_1^0(L) + 2(E_1^0(L))^3}{(E_2^0(L) - (E_1^0(L))^2)^{1.5}} \quad (5)$$

gives v, $u = \sqrt{\frac{E_2^0(L)-(E_1^0(L))^2}{\Gamma(1-2v)-\Gamma^2(1-v)}} v$, $w = E_1^0(L) - \frac{u}{v}(\Gamma(1-v) - 1)$, $E_1^0(L) = E\{A|H_0\}$, $E_2^0(L) = E\{A^2|H_0\}$ and $E_3^0(L) = E\{A^3|H_0\}$ are the first-, second-, and third-order moments of A, in the null hypothesis H_0, $\Gamma(\cdot)$ is the gamma function and $sgn(\cdot)$ is the signum function. P_D is approximated as

$$P_D(L) = Pr\{A > \sigma^2 \lambda | H_1\} \approx 1 - e^{-(1+\frac{v'(x-w')}{u'})^{-\frac{1}{v'}}}, \quad (6)$$

where

$$\frac{\Gamma(1-3v') - 3\Gamma(1-2v')\Gamma(1-v') + 2\Gamma^3(1-v')}{sgn(v')[\Gamma(1-2v') - \Gamma^2(1-v')]^{1.5}} = \frac{E_3^1(L) - 3E_2^1(L)E_1^1(L) + 2(E_1^1(L))^3}{(E_2^1(L) - (E_1^1(L))^2)^{1.5}} \quad (7)$$

gives v', $u' = \sqrt{\frac{E_2^1(L)-(E_1^1(L))^2}{\Gamma(1-2v')-\Gamma^2(1-v')}} v'$, $w' = E_1^1(L) - \frac{u'}{v'}(\Gamma(1-v') - 1)$, $E_1^1(L) = E\{A|H_1\}$, $E_2^1(L) = E\{A^2|H_1\}$ and $E_3^1(L) = E\{A^3|H_1\}$ are the first-, second-, and third-order moments of A in the alternative hypothesis H_1. Note that all these moments are functions of the sample size L. Hence, P_{FA} and P_D are also functions of L in (4) and (6).

C. Communication Information Exchange

After radar detection is completed, communications will be performed. The signals at the communications Rx. are $\mathbf{y}_{c1}^1 = \sqrt{P_T} h_d \mathbf{s}_c + \mathbf{n}_{c1}$, $\mathbf{y}_{c2}^1 = \sqrt{P_T} h_s \mathbf{s}_c + \mathbf{n}_{c2}$, $\mathbf{y}_{c1}^0 = \sqrt{P_T} h_d \mathbf{s}_c + \mathbf{n}_{c1}$, $\mathbf{y}_{c2}^0 = \mathbf{n}_{c2}$, where $\mathbf{y}_{c1}^1$ is the received signal from the direct link when obstacle exists, $\mathbf{y}_{c2}^1$ is the received from the reflection link when obstacle exists, $\mathbf{y}_{c1}^0$ is the received signal from the direct link when obstacle does not exist, $\mathbf{y}_{c2}^0$ is the received from the reflection link when obstacle does not exist. $\mathbf{s}_c$ is the transmitted signal for information exchange, and $\mathbf{n}_{c1}$ and $\mathbf{n}_{c2}$ are the complex AWGNs with mean zero and covariance matrix σ^2. They are all $K \times 1$ vectors and $K = [\frac{T_c}{T_s}]$ is the total number of samples used for communication.

The operation of the communication Rx. is adapted to the radar detection result. If the radar detects an obstacle, maximal ratio combining will be used [16] to combine signals received from the direct and reflection links as

$$\mathbf{y}_{c1}^{Total} = a_1 \mathbf{y}_{c1}^1 + a_2 \mathbf{y}_{c2}^1 \quad (8)$$

when the obstacle actually exists, and

$$\mathbf{y}_{c2}^{Total} = a_1 \mathbf{y}_{c1}^0 + a_2 \mathbf{y}_{c2}^0 \quad (9)$$

when the obstacle actually does not exist but the radar detects, where $a_1 = \frac{h_d*}{\sqrt{|h_d|^2+|h_s|^2}}$ and $a_2 = \frac{h_s*}{\sqrt{|h_d|^2+|h_s|^2}}$. If the radar does not detect an obstacle, only signals from the direct link are used so that

$$\mathbf{y}_{c1}^{Total} = \mathbf{y}_{c1}^1 \quad (10)$$

when there is actually obstacle and

$$\mathbf{y}_{c1}^{Total} = \mathbf{y}_{c1}^0 \quad (11)$$

when there is actually no obstacle. When the radar detects the obstacle and the obstacle actually exists, the achievable rate in bits per Hertz can be derived from (8) as $C_1 = T_c \log_2(1 + P_T \gamma_{mrc})$, where $\gamma_{mrc} = \frac{|h_d|^2+|h_s|^2}{\sigma^2}$ is SNR for maximal ratio combining. Since we use passive radar, the radar signal contains useful information and combining it with the signal form the reflection can provide diversity gain. When the radar detects the obstacle but the obstacle actually does not exist, the achievable rate is derived form (9) as $C_2 = T_c \log_2(1 + \frac{P_T {\gamma_d}^2}{\gamma_{mrc}})$, where $\gamma_d = \frac{|h_d|^4}{|h_d|^2+|h_s|^2}$ is the SNR of direct link. When the radar does not detect the obstacle but the obstacle actually exists, one has from (10) $C_3 = T_c \log_2(1 + P_T \gamma_d)$. When the radar does not detect the obstacle and the obstacle actually does not exist, one has from (11) $C_4 = T_c \log_2(1+P_T\gamma_d)$. Thus, the overall achievable rate for the communication signal is given as

$$\begin{aligned} C = & P_{h_1} T_c[(1 - P_D) \log_2(1 + P_T \gamma_d) \\ & + P_D \log_2(1 + P_T \gamma_{mrc})] + P_{h_0} T_c[P_{FA} \log_2(1 + \frac{P_T \gamma_d^2}{\gamma_{mrc}}) \\ & + (1 - P_{FA}) \log_2(1 + P_T \gamma_d)], \end{aligned} \tag{12}$$

where P_{h_1} is the probability of having an obstacle, $P_{h_0} = 1 - P_{h_1}$ is the probability of having no obstacle. P_{h_0} and P_{h_1} are used to show the effects of the prior probabilities of obstacle existence and related to the application environment.

D. Multi-target model

From [17], when multiple obstacles exist, one has,

$$P_{FA} = Q_{F_{1,L-N-1}}(\lambda), P_D = Q_{F'_{1,L-N-1}(\gamma_d ||\mathbf{s}_r||^2)}(\lambda), \tag{13}$$

where N is the number of targets, $Q_{F_{1,L-N-1}}(\lambda)$ and $Q_{F'_{1,L-N-1}(\gamma_d||\mathbf{s}_r||^2)(\lambda)}$ denote the right-tail probabilities of central and non-central complex F distributions with one degree of freedom and $L - N - 1$ degrees of freedom, respectively, and $\gamma_d||\mathbf{s}_r||^2$ is the noncentrality parameter for F'. Thus, one has the overall rate given by (12) but using (13) for P_{FA} and P_D instead. Also, γ_{mrc} becomes $\gamma_{mrc} = |\gamma_d|^2 + \sum_{i=1}^{N-1} |\gamma_{si}|^2$.

E. Optimization

Define $\beta = \frac{T_r}{T}$ as the time allocation coefficient. Thus, $T_r = \beta T$ and $T_c = (1 - \beta)T$, which gives $L = [\beta \frac{T}{T_s}]$. Then, the achievable rate can be rewritten using β as

$$\begin{aligned} C \quad & = P_{h_1}(1 - \beta) T P_D(\beta) \log_2(1 + P_T \gamma_{mrc}) \\ & + P_{h_0}(1 - P_{FA}(\beta))(1 - \beta) T \log_2(1 + P_T \gamma_d) \\ & + P_{h_1}(1 - P_D(\beta))(1 - \beta) T \log_2(1 + P_T \gamma_d) \\ & + P_{h_0} P_{FA}(\beta)(1 - \beta) T \log_2(1 + \frac{P_T \gamma_d^2}{\gamma_{mrc}}). \end{aligned} \tag{14}$$

The optimization is formulated as

$$P : \max_{\beta} \{C\}, \quad s.t. \quad 0 \leq \beta \leq 1, \tag{15}$$

The formula for C is too complicated to derive any analytical solution to the optimization. However, this is a simple one variable optimization, which can be numerically solved by using MATLAB function 'fminbnd'. Also, approximation is possible. Using the simple approximations of P_D and P_{FA} in [7], the first order-derivative of C in (14) can be approximated as

$$\begin{aligned} C' \approx & [(P_{h_1} T \log_2(1 + P_T \gamma_{mrc}) - P_{h_1} T \log_2(1 + P_T \gamma_d)] \\ & * [Q_1(\sqrt{2 P_T \beta \gamma_s}, \sqrt{2\lambda})' - Q_1(\sqrt{2 P_T \beta \gamma_s}, \sqrt{2\lambda})' \beta \\ & - Q_1(\sqrt{2 P_T \beta \gamma_s}, \sqrt{2\lambda})] - P_{h_0} e^{-\lambda} \log_2(1 + \frac{P_T \gamma_d^2}{\gamma_{mrc}}) \\ & - P_{h_0}(1 - e^{-\lambda}) T \log_2(1 + P_T \gamma_d) - P_{h_1} T \log_2(1 + P_T \gamma_d), \end{aligned} \tag{16}$$

where $Q_1(\cdot, \cdot)$ is Marcum Q function. Using curve fitting in MATLAB, $Q_1(\sqrt{2P_T\beta\gamma_s}, \sqrt{2\lambda})' - Q_1(\sqrt{2P_T\beta\gamma_s}, \sqrt{2\lambda})'\beta - Q_1(\sqrt{2P_T\beta\gamma_s}, \sqrt{2\lambda}) \approx e^{(53.34\beta^2+2.03\beta-1.85)} - 0.9156$, when $P_T = 1$, $\lambda = 3$, $\gamma_s = -5$ dB and Q is the constant part in C'. Hence, $\beta_{opt}^{app} \approx \frac{-2.03 - \sqrt{4.121 + 213.36Q}}{-106.68}$. Note that channel knowledge is not required in radar detection but in MRC. They can be estimated by using the received signals blindly.

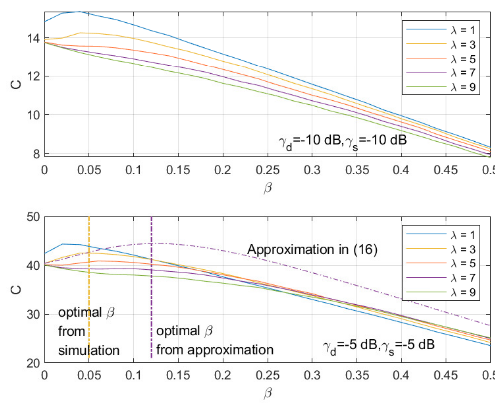

Fig. 2. The effect of λ on the optimum achievable rate.

III. Numerical Results and Discussion

In this section, we present the numerical results on the performance of the considered joint radar-communications system. In the examples, we set $T_s = 1$, $P_T = 1$, $T = 100$ and $P_{h_0} = P_{h_1} = 0.5$, and use the single target model unless otherwise stated. We focus on the effects of γ_d, γ_s and λ on the system performance.

Fig. 2 shows the effect of the detection threshold λ. As shown in Fig. 2, for $\gamma_d = -10$ dB and $\gamma_s = -10$ dB, the optimal value of β only exists when $\lambda \leq 3$, while for $\gamma_d = -5$ dB and $\gamma_s = -5$ dB, the optimal value of β exists for $\lambda \leq 5$. For other values of λ, $\beta = 0$ is the optimal, that is, transmission without radar detection. At $\gamma_d = -5$ dB and $\gamma_s = -5$ dB, the optimum β is about 0.12 for the approximation in (16), differ from simulated value but agrees with β_{opt}^{app}. In the following, we will use $\lambda = 3$. Fig. 3 shows the effect of β for different SNRs. The multi-target result is shown as '5-target' considering five targets. One sees that, as γ_s increase from -7 dB to -5 dB, or both γ_d and γ_s increase from -10 dB to -5 dB, the achievable rate increases and the optimum β becomes more visible. The optimum values of β for both GEV approximation and simulation are around 0.08, at $\gamma_d = -5$ dB

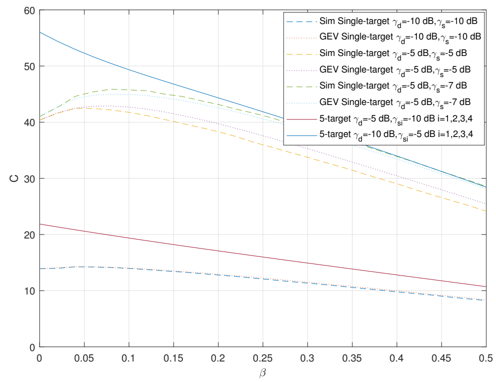

Fig. 3. Comparison of simulation and GEV, λ = 3.

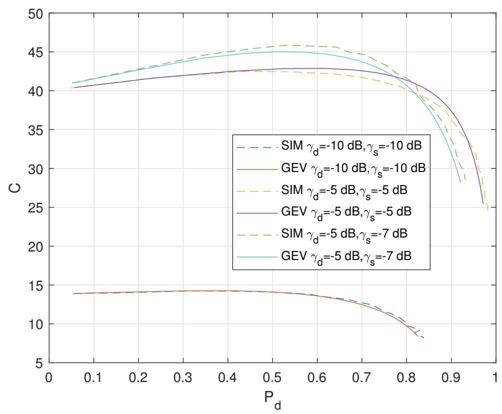

Fig. 4. P_D versus achievable rate, λ = 3.

and $\gamma_s = -7$ dB. For 5-target case, the optimal value of β is about zero in all cases considered, because the increasing target number leads to higher detection probability as well as higher SNR in MRC to make communications more effective.

Fig. 4 shows the relationship between P_D and C. When P_D is very large, there is a visible decline in the rate. The optimum P_D is about 0.5 and 0.6 for $\gamma_d = -5$ dB, $\gamma_s = -7$ dB, and $\gamma_d = -5$ dB, $\gamma_s = -5$ dB, respectively. In Fig. 5, we set $P_{h_0} = 0.1$, $P_{h_1} = 0.9$ and $P_{h_0} = 0.9$, $P_{h_1} = 0.1$, respectively, to see the effects of P_{h_0} and P_{h_1}. At $P_{h_0} = 0.1$ and $P_{h_1} = 0.9$, the optimum P_D for the overall rate is about 0.6 and 0.8 for $\gamma_d = -10$ dB, $\gamma_s = -10$ dB, and $\gamma_d = -5$ dB, $\gamma_s = -5$ dB, respectively. However, when $P_{h_0} = 0.9$ and $P_{h_1} = 0.1$, the overall rate decreases monotonically with P_D. The optimum P_D increases as P_{h_0} increases or γ_d and γ_s increase. This is expected. When the probability of obstacle increases, the optimal value of communication rate is greater.

IV. Conclusion

We have analyzed the performance trade-off for a time division scheme where radar detection of obstacle is performed followed by data communication. Future works will consider MIMO radar and communications, as well as other diversity combining.

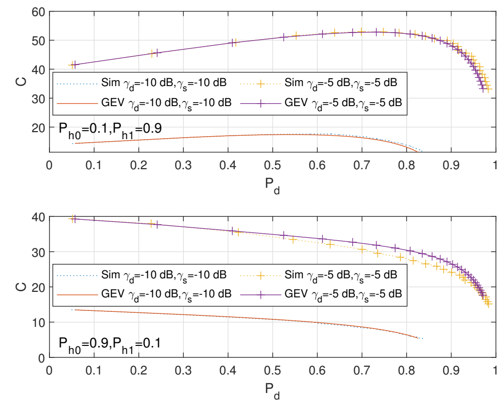

Fig. 5. The effect of P_{h_0} and P_{h_1} on P_D versus C, λ = 3.

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