Rethinking the Performance of ISAC System: From Efficiency and Utility Perspectives

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ABSTRACT
Integrated sensing and communications (ISAC) is an essential technology for the 6G communication system, which enables the conventional wireless communication network capable of sensing targets around. The shared use of pilots is a promising strategy to achieve ISAC. It brings a trade-off between communication and sensing, which is still unclear under the imperfect channel estimation condition. To provide some insights, the trade-off between ergodic capacity with imperfect channel estimation and ergodic Cramer-Rao bound (CRB) of range sensing is investigated. Firstly, the closed-form expressions of ergodic capacity and ergodic range CRB are derived, which are associated with the number of pilots. Secondly, two novel metrics named efficiency and utility are firstly proposed to evaluate the joint performance of capacity and range sensing error. Specifically, efficiency is used to evaluate the achievable capacity per unit of the sensing error, and utility is designed to evaluate the utilization degree of ISAC. Moreover, an algorithm of pilot length optimization is designed to achieve the best efficiency. Finally, simulation results are given to verify the accuracy of analytical results, and provide some insights on designing the slot structure.

KEYWORDS
ISAC, tradeoff between communications and sensing, efficiency, utility

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1 INTRODUCTION
As the raise of new intelligent services, such as extended reality (XR) and holographic awareness, it is challenging to guarantee the quality of service via the communication system that only have the ability of communication [1]. ISAC is emerged as a promising technology to solve this problem, which can provide sensing ability as a secondary function via sharing the wireless resources and hardware [2].

Currently, communication-centric design is regarded as one of three key fields in the research on ISAC [3]. In particular, sensing is designed as an extensional function under the condition that the basic communication requirements should be guaranteed. In [4], a pilots multiplexed based scheme has been proposed, where the pilots are used for estimating channels and sensing remote targets simultaneously. Then the trade-off between the error rate and range CRB has been studied. Moreover, a virtual pilots generated scheme has been proposed in [5] for enhancing the velocity sensing performance with a small reduction of data rate. In [6], the possibility of employing multiple slots in OFDM system for target detection has been investigated. Furthermore, the impact of imperfect self-interference cancellation at receiver has been considered in [7], and a synchronized scheme between received signal and self-interference has been designed to employ multiple slots to detect multiple targets.

All above works only consider the ideal channel conditions, which is not in line with the reality. Therefore, we...
Fig. 2. The structure of a slot.

transmission slot, which are named the pilot transmission phase and the data transmission phase, respectively. Without loss of generality, the pilot signals are assumed to be transmitted at the first $L_p$ symbols, and the rest $L - L_p$ symbols belong to the data transmission phase. Then, the received signals at User 1 can be expressed as:

$$y_p(t) = h_p(t)\sqrt{\rho_p}x_p(t) + w_p(t), \quad 1 \leq t \leq L_p,$$

$$y_d(t) = h_d(t)\sqrt{\rho_d}x_d(t) + w_d(t), \quad L_p + 1 \leq t \leq L,$$  

where $y_p$ and $y_d$ are received pilot and data signals at User 1, respectively, $x_p$ and $x_d$ are the transmitted pilot and data symbols, respectively, $h_p$ and $h_d$ represent the Rayleigh fading coefficient of the link between the BS and User 1 in the pilot and data transmission phase, respectively, $\rho_p$ and $\rho_d$ are the transmitted power of pilot and data symbols, respectively, and $w_p$ and $w_d$ are the Gaussian noise variable with variance $\sigma_p^2$ and $\sigma_d^2$, respectively.

Consider that only pilot signals are reused as the probe signal for sensing User 2. Besides, assuming that the transmitted signals can be cancelled successfully by the receiver at source such that the self-interference is ignored. Then, the echo that reflected by User 2 received at the BS can be expressed as:

$$y_s(t) = \sqrt{\rho_{p,r} s_{rcs}} h_s(t)x_p(t - \frac{2d}{c}) e^{j \frac{4\pi d t}{\lambda}} + w_s(t),$$

where $\rho_{p,r} = \rho_p / (4\pi d^2)$ denotes the received echo strength at BS, $h_s$ denotes the Rice fading coefficient of the link between the BS and User 2, $s_{rcs}$ is the radar cross section (RCS) of User 2, $d$ is the range between the BS and User 2, $c$ is the light of speed, $v$ is the speed of User 2 moving towards the BS, $\lambda$ is the wavelength of of the carrier, and $w_s$ is the additive white Gaussian noise with variance $\sigma_s^2$.

3 COMMUNICATION PERFORMANCE: ERGODIC CAPACITY WITH IMPERFECT CHANNEL ESTIMATION

In this section, we investigate the impact of imperfect channel estimation on the performance of ergodic capacity, and a closed-form expression of ergodic capacity associated with the number of pilots is provided.

3.1 Channel Estimation via Pilots

At first, the pilot channels need to be determined, which can be solved quickly by using the least-square estimation
method. Thus, the expected error of estimation for pilot channels can be written as $e_p = \sigma_p^2 / \rho_p$. Next, to achieve the minimum mean square error (MMSE) criteria, the wiener filtering interpolation algorithm [8] is employed. Then the error of estimation can be given by the following lemma.

**Lemma 3.1.** The expected error of estimation for data channels can be expressed as:

$$e_d = \sigma_d^2 - \frac{\sigma_d^2}{1 + \frac{\sigma_d^2}{\sigma_p^2 \rho_p}},$$

(3)

where $\sigma_d^2$ is the variance of the Rayleigh fading channel, $\rho_p = \rho_p / \sigma_p^2$ denotes the signal-noise-ratio (SNR) of pilot channels.

**Proof.** Due to the limitation of paper space, the detailed proof of lemma 3.1 is omitted. $\square$

### 3.2 Ergodic Capacity with Imperfect Channel Estimation

Based on the expression of $e_d$ given by Lemma 3.1, the ergodic capacity for User 1 can be investigated. By using the reparametrization trick [9], the Rayleigh fading coefficient of data channels $\hat{h}_d$ can be rewritten as:

$$\hat{h}_d = \hat{h}_d + w_{d,\text{wf}},$$

(4)

where $\hat{h}_d$ denotes the estimated result of data channels, and $w_{d,\text{wf}}$ is the Gaussian variable with mean 0 and variance $e_d$. Then, by substituting (4) into (1b), the received signals at User 1 in the data transmission phase can be rewritten as:

$$y_d(t) = (\hat{h}_d(t) + w_{d,\text{wf}}(t))\sqrt{\rho_d x_d(t)} + w_d(t)$$

$$= \hat{h}_d(t)\sqrt{\rho_d x_d(t)} + w_{d,\text{wf}}(t)\sqrt{\rho_d x_d(t)} + w_d(t).$$

(5)

As introduced in [10], the ergodic capacity with channel estimation error for User 1 can be derived as:

$$C = \mathbb{E}\left\{B(L - L_p) \log_2 \left(1 + \frac{|\hat{h}_d|^2 \rho_d}{\sigma_d^2 + |w_{d,\text{wf}}|^2 \rho_d}\right)\right\}.$$  

(6)

where $B$ is the bandwidth, and $|\cdot|$ denotes the norm operation.

Based on (6), an closed-form expression of $C$ can be given in the following theorem.

**Theorem 3.2.** The ergodic capacity $C$ with imperfect channel estimation can be expressed as:

$$C = \frac{B(L - L_p)}{1 - \frac{\sigma_d^2}{\sigma_p^2 \rho_p L_p}} \ln 2 \left[ e^{\frac{\sigma_d^2}{\sigma_p^2 \rho_p L_p}} \mathbb{E}\left(1 + \frac{1}{Y_d}\right) - e^{\frac{\sigma_d^2}{\sigma_p^2}} \mathbb{E}\left(1 + \frac{1}{Y_d \sigma_d^2}\right)\right],$$

(7)

where $Y_d = \rho_d / \sigma_d^2$ denotes the SNR of data channels, and $\mathbb{E}(x) = \int_{-\infty}^{\infty} x e^{x} / t dx$ is the exponential integral function.

**Proof.** The integral form of $\ln(1 + x)$ is used instead, which can be expressed as:

$$\ln(1 + x) = \int_{0}^{\infty} e^{-z} / z (1 - e^{-xz}) dz.$$  

(8)

By substituting (8) into (6), $C$ in (6) can be rewritten as:

$$C = \frac{B(L - L_p)}{\ln 2} \mathbb{E}\left\{\int_{0}^{\infty} e^{-z} / z \left(1 - \exp\left(-\frac{|\hat{h}_d|^2 \rho_d}{\sigma_d^2 + |w_{d,\text{wf}}|^2 \rho_d z}\right)\right) dz\right\}.$$  

(9)

By employing Fubini’s theorem, the order of the expectation operation and the integration operation can be exchanged. Besides, for simplicity, $z$ is substituted by $(\sigma_d^2 + |w_{d,\text{wf}}|^2 \rho_d)s$, then $C$ can be further expressed as:

$$C = \frac{B(L - L_p)}{\ln 2} \mathbb{E}\left\{\int_{0}^{\infty} e^{-\frac{|\hat{h}_d|^2 \rho_d}{\sigma_d^2 + |w_{d,\text{wf}}|^2 \rho_d s}} \times \left(\int_{0}^{\infty} 1 - e^{-\frac{I}{|w_{d,\text{wf}}|^2 \rho_d s}} ds\right) \right\}.$$  

(10)

Since $\hat{h}_d \sim \mathcal{CN}(0, \sigma_d^2)$ and $w_{d,\text{wf}} \sim \mathcal{CN}(0, e_d)$, their probability density function (PDF) can be expressed as follows, respectively.

$$f_{|\hat{h}_d|^2}(x) = \frac{1}{\sigma_d^2} \exp\left(-\frac{x}{\sigma_d^2}\right),$$  

(11a)

$$f_{|w_{d,\text{wf}}|^2}(x) = \frac{1}{e_d} \exp\left(-\frac{x}{e_d}\right).$$  

(11b)

By substituting (11a) and (11b) into $\mathbb{E}$ and $\int$ in (10), respectively, $\mathbb{E}$ and $\int$ can be derived as follows, respectively.

$$\mathbb{E} = \frac{1}{\sigma_d^2} \int_{0}^{\infty} (1 - e^{-\rho_d sx}) e^{-\frac{x}{\sigma_d^2}} dx = \frac{\rho_d \sigma_d^2 s}{1 + \rho_d \sigma_d^2 s},$$  

(12a)

$$\int = \frac{1}{e_d} \int_{0}^{\infty} e^{-\rho_d sx} e^{-\frac{x}{e_d}} dx = \frac{1}{1 + \rho_d e_d s}.$$  

(12b)

Then, by substituting (12) into (10), $C$ can be further derived as:

$$C = \rho_d \sigma_d^2 \int_{0}^{\infty} \frac{e^{-\frac{\sigma_d^2 s}{\rho_d e_d s}}}{(1 + \rho_d \sigma_d^2 s)(1 + \rho_d e_d s)} ds.$$  

(13)
where \( r = B(L - L_p)/(\ln 2) \), \((a)\) in the second equality can be obtained by extracting \( 1/(\rho_d^2e_d) \) from the denominator of the integral term, and \((b)\) in the third equality can be obtained by splitting the denominator of the integral term. Finally, \((7)\) can be obtained by substituting \((3)\) into \((13)\). Then, the proof has been finished.

As shown in Theorem 3.2, the relationship between \( C \) and \( L_p \) is not clear. Therefore, the following derivatives of \( C \) with respect to \( L_p \) are given in \((14)\). Since the first-order derivative can be positive or negative, and the second-order derivative is negative, \( C \) has a maximum value. It means that a performance gain can be obtained at first when increment of the number of pilot provides more precise channel estimation. However, the performance will be worse as the number of pilots increases continually due to the cost of symbols.

\[
\nabla^2_{L_p} C = -\frac{2B}{\ln 2} \int_0^\infty \frac{\rho_d^2ye^{-\rho_d^2s}}{1 + \rho_d^2s}(1 + y\rho_pL_p + \rho_d^2s)^2 ds - \frac{2(L - L_p)B}{\ln 2} \int_0^\infty \frac{\rho_d^2ye^{-\rho_d^2s}}{1 + \rho_d^2s}(1 + \rho_pL_p + \rho_d^2s)^2 ds \leq 0. \tag{14}
\]

4 SENSING PERFORMANCE: ERGODIC RANGE CRB

In this section, we investigate the performance of ergodic CRB for measuring the range of User 2, and provide its closed-form expression.

As introduced in \([4]\), the expression of CRB for range sensing can be expressed as:

\[
CRB_d(L_p) = \frac{\alpha}{L_p|h_1(t)|^2}, \tag{15}
\]

where \( \alpha = c^2/(8\pi^2\gamma_{p,s}\gamma_{r,c}B_{rms}^2) \), \( \gamma_{p,s} = \rho_p/\sigma_s^2 \) is the SNR of echo channels, and \( B_{rms} = \sqrt{\int_{-\infty}^{\infty} F^4|S(F)|^2dF/\int_{-\infty}^{\infty} |S(F)|^2dF} \) is the root-mean-square bandwidth.

Based on \((15)\), the closed-form expression of the expectation of \( CRB_d \), i.e., \( \bar{\delta}_d = \mathbb{E}(CRB_d) \), can be given by the following theorem.

Theorem 4.1. The ergodic CRB for measuring range \( \bar{\delta}_d \) can be expressed as:

\[
\bar{\delta}_d = \frac{\alpha \sqrt{\pi}}{L_p} \exp \left( -\frac{A_s}{2\sigma_s^2} \right) F_1 \left[ 1/2; 1; A_s/(2\sigma_s^2) \right] \tag{16},
\]

where \( F_1(\cdot) \) denotes the confluent hypergeometric function, \( A_s \) denotes the signal strength of LOS path, \( \sigma_s^2 \) is the signal strength of the multipath.

Proof. Recalling that the wireless link between the BS and User 2 follows Rice distribution. Its PDF is expressed as:

\[
 f_{h_s(t)}(x) = \frac{x}{\sigma_s^2} \exp(-\frac{x^2 + A_s}{2\sigma_s^2})I_0 \left( \frac{\sqrt{A_s}x}{\sigma_s^2} \right). \tag{17}
\]

where \( I_0(\cdot) \) is the zero-order Bessel function. Then, \( \bar{\delta}_d = \mathbb{E}(CRB_d) \) can be derived as follows by substituting \((17)\) into \((15)\) and expanding \( I_0(\cdot) \).

\[
\bar{\delta}_d = \frac{\alpha c}{\sigma_s^2} \sum_{k=0}^{\infty} \frac{1}{k!\Gamma(k + 1)} \int_0^\infty e^{-\frac{x}{\sigma_s^2}} \left( \frac{A_s x^2}{4\sigma_s^2} \right)^k dx, \tag{18}
\]

\( \kappa \)
\[ \kappa = \left( \frac{2\sigma_s^2}{k + 2} \right)^{k+1} \left( \frac{A_s}{4\sigma_s^2} \right)^k \int_0^\infty e^{-\frac{x}{\sigma_s^2}} \frac{d}{\sqrt{2\sigma_s^2}} \left( \frac{z}{\sqrt{2\sigma_s^2}} \right)^{2k} \tag{19} \]

Finally, by substituting \((19)\) into \((18)\), \( \bar{\delta}_d \) in \((16)\) can be obtained. Then, the proof of Theorem 3.2 has been finished.

5 NEW METRICS TO CHARACTERIZE ISAC PERFORMANCE: EFFICIENCY AND UTILITY

Recalling the ergodic capacity \( C \) given by Theorem 3.2 and the ergodic CRB of range sensing shown in Theorem 4.1, they are both concerned with the number of pilots \( L_p \). To make sense how \( L_p \) balances the trade-off between the communication performance and the sensing performance, the details about that will be discussed in this section.

5.1 Efficiency of ISAC

In particular, a novel performance metric named the efficiency of ISAC is proposed, which aims to determine the optimal \( L_p \) that can strike the balance between the capacity and the sensing error. It is defined as the ratio of capacity to CRB and can be written as:

\[
E_{\text{ISAC}}^E(L_p) = \frac{CY(L_p)}{\kappa + CRB_d(L_p)}, \tag{20}
\]

where \( \kappa \) is a constant that can limit the maximum value of the efficiency, \( \gamma \) denotes the SNR. \( E_{\text{ISAC}}^E(L_p) \) evaluates the achievable capacity per unit of the sensing error. It indicates that the efficiency can be improved as \( E_{\text{ISAC}}^E(L_p) \) becomes larger. Therefore, to reach the best efficiency, an optimization problem is formulated as:

\[
\mathcal{P}_1: \max_{L_p} E_{\text{ISAC}}^E(L_p), \text{ s.t. } 1 \leq L_p \leq L - 1. \tag{21}
\]
As $\mathcal{P}_1$ is a non-linear fractional problem, it can be solved by transforming the original problem to the following equivalent linear problem [11]

$$\mathcal{P}_2 : \max_{L_p} Q_2 = C^T(L_p^*) - q^T(\kappa + CRB^T(L_p)), \quad (22)$$

where $L_p^*$ is the optimal solution of $\mathcal{P}_1$, and $q^*$ denotes the maximum value of $\mathcal{P}_1$. By denoting $\delta_q$ given by (16) as $\beta(\gamma)L_p^{-1}$, the second-order derivative of $Q_2$ can be written as:

$$\nabla^2_{L_p} Q_2 = \nabla^2_{L_p} C^T(L_p) - 2q^* \beta(\gamma)L_p^{-3} \leq 0, \quad (23)$$

where $\nabla^2_{L_p}$ has already been given by (14).

According to (23), $Q_2$ is a concave function and its optimal solution can be determined by solving $\nabla_{L_p} Q_2 = 0$. By using Algorithm 1 provided in [11], the optimal solution of original problem $\mathcal{P}_1$ can be obtained, denoted as $L_p^{opt}$.

5.2 Utility of ISAC

Moreover, a novel concept named utility of ISAC is proposed, which is designed to evaluate the utilization degree of joint performance for communication and sensing. It contains two terms, the first term named capacity utility depicts the ratio of capacity with $L_p$ pilots to the maximum achievable capacity, and the second term named sensing utility depicts the ratio of CRB with $L_p$ pilots to the minimum achievable CRB. These two terms are integrated by an adjustable weighted factor, which is adaptable for specific services. Hence, the definition of utility can be given as:

$$U_{ISAC}^T = \eta \frac{C^T(L_p)}{C^T_{max}} + (1 - \eta) \frac{CRB_{\min}^T}{CRB_{\min}^T(L_p)}, \quad (24)$$

where $C^T_{max}$ denotes the maximum capacity, $CRB_{\min}^T$ denotes the minimum estimation error for sensing, and $\eta \in (0, 1)$ is the weighted factor.

Since the monotonicity of the capacity and CRB terms can be determined when parameters are fixed, the monotonicity of $U_{ISAC}^T$ is decided by $\eta$, which can be divided into the following two cases: 1) when $\eta$ is a small value, $U_{ISAC}^T$ is an increasing function as the CRB term plays a major role; 2) otherwise, $U_{ISAC}^T$ is a concave function owning a maximum value as the capacity term has more impact.

Therefore, to avoid the allocation of pilots to extremes, the threshold of capacity utility and sensing utility should be considered, which are denoted as $U_{cth}$ and $U_{sth}$, respectively. Only $L_p$ that satisfies the requirements is in consideration.

6 SIMULATION RESULTS.

In this section, simulation results are provided to verify the derived results and evaluate the joint performance of communication and sensing. In particular, the total symbols transmitted in a slot is set as $L = 14$, the bandwidth is set as $B = 200$ MHz, the variance of the link between BS and User 1 is set as $\sigma^2 = 2$, the Rician factor of the LOS path is set as $K = A_s/\sigma^2 = 3$. Moreover, the radar cross section is $s_{rcs} = 100$ m$^2$, and $B_{rms} = B/\sqrt{12}$ according to [12].

In Fig. 3, the performance of the expectation of capacity and range CRB are presented in (a) and (b), respectively. As shown in Fig. 3 (a), owing to the accuracy improvement of channel estimation, the capacity performance can be improved when $L_p$ begins to increase. However, total capacity decreases as $L_p$ keeps increasing, which results from the cost of resource block. Besides, channel estimation in low SNR case can provide larger performance gain than in high SNR case. In Fig. 3 (b), $\gamma_p = 10$ dB is considered. As shown in this figure, the increment of $L_p$ provides a more precise range estimation result. Moreover, all analytical results are matched perfectly with the Monte-Carlo results, which demonstrates the accuracy of our derived results.

![Fig. 3. Performance of ergodic capacity and range CRB with respect to the number of pilots.](image)

In Fig. 4, the trade-off between the capacity and range CRB with respect to the number of pilots is investigated. In particular, the measured range is set as 100 m. As shown in this figure, three regions can be divided as follows. 1) the upper right region: this region with high capacity but low sensing accuracy; 2) the bottom left region: this region with high sensing accuracy but low capacity; 3) the bottom right region: this region with high capacity and high sensing accuracy. Therefore, to achieve a balance between communication and sensing, the bottom right region is recommended to be considered more in the ISAC design.

In Fig. 5, the efficiency of ISAC proposed in (20) with $\kappa = 1$ is evaluated. As shown in Fig. 5 (a), the efficiency with respect to $L_p$ is depicted. It can be observed that the peak of efficiency is also related to the SNR settings. Therefore, we provide the efficiency with respect to SNR under different $L_p$ settings in Fig. 5 (b). In particular, the cases that $L_p = 2$, $L_p = 7$, and $L_p = 12$ are selected to be compared, which correspond to the upper right region, bottom right region and bottom left region, respectively. As shown in this figure, the case with optimal $L_p$ always achieves the best efficiency. In addition,
Efficiency with SNR.

it is implied that a certain amount of pilots is needed to maintain the balance between capacity and range CRB in medium and low SNR scenario. However, the decrement of $L_p$ would lead to a higher efficiency in high SNR scenario, as the accuracy of range measurement is precise enough.

7 CONCLUSIONS

In this paper, the trade-off between the communication and sensing performance in terms of the capacity and range CRB has been investigated. By modeling the communication link and the sensing link as the Rayleigh channel and Rice channel, the closed-form expressions of ergodic capacity with imperfect channel estimation and ergodic range CRB are provided, respectively. Based on the derived results, the trade-off between capacity and range CRB with respect to

Fig. 6. Utility of ISAC at range $= 100$ m.

the number of pilots is clear. Then two metrics named efficiency and utility are proposed to evaluate and optimize the joint performance of ISAC. Finally, simulation results are provided to verify the accuracy of our analysis and show the performance gain by designing the number of pilots.

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REFERENCES

[1] Zhiqin Wang, Ying Du, Kejun Wei, et al. Vision, application scenarios, and key technology trends for 6g mobile communications. Science China Information Sciences, 65(5):1–27, 2022.
[2] Fan Liu, Christos Masouros, Athina P Petropulu, et al. Joint radar and communication design: Applications, state-of-the-art, and the road ahead. IEEE Trans. Commun. 68(6):3854–3862, 2020.
[3] J Andrew Zhang, Fan Liu, Christos Masouros, et al. An overview of signal processing techniques for joint communication and radar sensing. IEEE J. Sel. Topics Signal Process., 15(6):1295–1315, 2021.
[4] Preeti Kumari, Sergiy A Vorobyov, and Robert W Heath. Performance trade-off in an adaptive ieee 802.11 ad waveform design for a joint automotive radar and communication system. In 2017 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pages 4281–4285. IEEE, 2017.
[5] Preeti Kumari, Sergiy A Vorobyov, and Robert W Heath. Adaptive virtual waveform design for millimeter-wave joint communication-radar. IEEE Trans. Signal Process., 68:715–730, 2019.
[6] Sayed Hossein Dokhanchi, Bhavani Shankar Mysore, Kumar Vijay Mishra, et al. A mmwave automotive joint radar-communications system. IEEE Trans. Aerosp. Electron. Syst., 55(3):1241–1260, 2019.
[7] Aimin Tang, Songqian Li, and Xudong Wang. Self-interference-resistant ieee 802.11 ad-based joint communication and automotive radar design. IEEE J. Sel. Topics Signal Process., 15(6):1484–1499, 2021.
[8] James K Cavers. An analysis of pilot symbol assisted modulation for rayleigh fading channels (mobile radio). IEEE Trans. Veh. Technol., 40(4):686–693, 1991.
[9] Diederik P Kingma and Max Welling. Auto-encoding variational bayes. arXiv preprint arXiv:1312.6114, 2013.
[10] Taesang Yoo and Andrea Goldsmith. Capacity and power allocation for fading mimo channels with channel estimation error. IEEE Trans. Inf. Theory, 52(5):2203–2214, 2006.
[11] Zhongyuan Zhao, Shuqing Bu, Tiezhu Zhao, et al. On the design of computation offloading in fog radio access networks. IEEE Trans. Veh. Technol., 68(7):7136–7149, 2019.
[12] Merrill I Skolnik. Radar handbook. McGraw-Hill Education, 2008.