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Optimal Pilot and Data Power Allocation for Joint Communication-Radar Air-to-Ground Networks

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ABSTRACT Integration of communication and radar functions with a single waveform has been actively investigated in various wireless communication applications, including unmanned aerial vehicles (UAVs). This means that communication frames consisting of a pilot part and subsequent data part can be utilized to transmit information and detect the surrounding objects simultaneously. Because a predetermined waveform is required for the radar function, the pilot part in the communication frame can be utilized for radar purposes. Specifically, the pilot is used for both channel estimation, which is required for data decoding, and a radar waveform. Assuming that the length of the pilot and data parts is given and the transmit energy for each frame is limited, the optimal transmit power for the pilot and data parts can be analytically obtained by considering both radar and communication performance metrics. The optimality of the proposed analytical solution was verified through numerical simulations.

INDEX TERMS Joint communication-radar, achievable rate, channel estimation, CRLB, optimization.


I. INTRODUCTION

Recently, various wireless communication services using unmanned aerial vehicles (UAVs) have emerged [1]–[4]. In these applications, low-latency high-speed data transmission between UAVs and ground base stations (BSs) is an essential requirement. In addition to wireless information transmissions, it is important to estimate the location of the objects in the air, i.e., the UAVs, using a radar waveform. Such location information is required for the trajectory control of UAVs and wireless communications. In particular, the location information of UAVs is beneficial for fast link setup and handover operations in wireless communication networks.

Generally, radar and communication systems can be implemented as independent, i.e., separate, systems. However, if two functions are performed simultaneously using a single waveform, their spectral utilization can be efficient in various respects. To realize such joint communication-radar (JCR) technology, some researches on it have been actively conducted [5]–[10]. For example, a JCR system based on

IEEE 802.11ad waveform, i.e., a 60 GHz wireless local area network (WLAN) packet, was proposed in [8]. When a high frequency (e.g., 60 GHz frequency) is used as a carrier frequency, transmitted signals are generally concentrated in a specific direction through beamforming to compensate for severe pathloss. Therefore, in the initial link-setting process, a beam-sweeping operation, which determines the optimal beam direction among various potential beams, is required. However, it is possible to reduce the burden on the initial link setting significantly by utilizing the radar function even if the location information of the UAV terminals is known only approximately.

In [8], the optimal preamble design, i.e., the pilot duration, which exploits the trade-off between radar parameter estimation accuracy and communication rate, was investigated. In [9], radar sensing-throughput tradeoff for JCR-based cognitive radio vehicular ad-hoc networks was investigated. Specifically, an optimal sensing duration maximizing the secondary throughput under a constraint of primary network protection. The authors of [10] proposed a dynamic frame structure configuration for sensing and communication functions based on the 5G NR protocol in 28 GHz frequency band.

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The best time duration allocation ratio for dual functions was investigated by using age of information and game theory. However, the role of the pilot part in communication, e.g., the channel estimation effects, was not considered in [8]–[10]. To overcome such a limitation, we investigate the effects of pilot resources on both communication and radar performances.

The packet-type communication signal consists of a pilot part (or training part) for initial synchronization and channel estimation and a data part, through which actual information is transmitted. In a bistatic radar operation scenario, in which a transmitter and the corresponding receiver are physically separated, the bistatic radar estimates the location of the target after the receiver receives a predetermined radar signal transmitted from the transmitter. In other words, the pilot part of the communication signal frame can be used for a predetermined radar waveform. Accordingly, the pilot signal is used for channel estimation in the communication receiver and position estimation of the target in the bistatic radar receiver.

The original purpose of communication is information transmission. The channel capacity of the data part, depending on the channel estimation, can be a performance measure. Specifically, the channel estimation error, which depends on the pilot power allocation and signal-to-noise ratio (SNR), can be an additional noise source for the data part. If the lengths of the pilot and data parts are fixed and the power of the two signal parts can be adjusted under the overall energy constraint for each frame, we can analytically evaluate the communication performance, i.e., the channel estimation based achievable rate. The well-known Cramer-Rao lower bound (CRLB) of range estimation in a radar function is an additional performance measure. Hence, to design the frame structure in JCR systems, we must consider both the performance measures simultaneously. The power allocation to the pilot and data parts, which is optimized with respect to the weighted sum of these two performance measures, i.e., the channel estimation based achievable rate and CRLB of range estimation, can be analytically obtained. In other words, we investigated the trade-off between the communication and radar functions depending on the frame structure design, i.e., the pilot power allocation.

The contribution of this paper can be summarized as follows:

- A utility function considering both communication and radar performance measures is defined. For the communication performance metric, an achievable rate based on channel estimation with the pilot signal is considered. CRLB of range estimation with the pilot signal is adopted as a radar performance metric. Then, the proposed utility function is a weighted sum of the achievable rate and CRLB. In JCR systems, the priority between the communication and radar performance can be expressed by adjusting the weight coefficient.
- An optimal power allocation problem to pilot and data parts in a JCR frame structure is formulated.

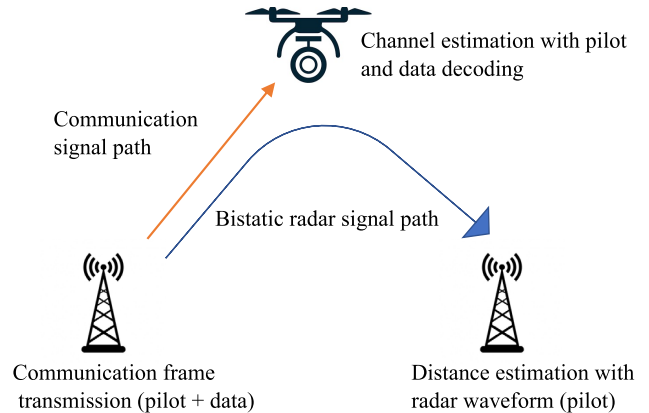


FIGURE 1. Joint communication-radar system model.

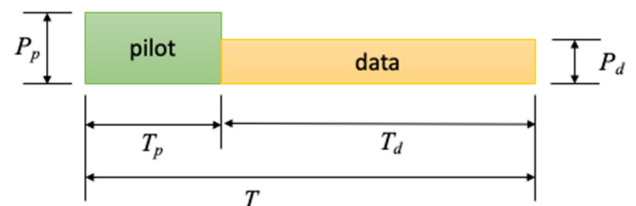


FIGURE 2. Communication frame structure including the pilot and data parts.

The solution to the formulated optimization problem is derived analytically. The characteristics of the optimal solutions are discussed. The validity of the analytical solution is examined through numerical simulations.

The rest of this paper is organized as follows: In Section II, we present the system and signal models. The performance measures for communication and radar functions are examined in Section III. A utility function for JCR systems and an optimization problem maximizing this utility were introduced in Sections IV and V. Section VI provides numerical results to verify the analytical results. Finally, Section VII concludes this paper.

II. SYSTEM AND SIGNAL MODEL

As shown in Fig. 1, a ground BS transmits a communication signal to send information targeted to an UAV. Simultaneously, the bistatic radar receiver receives the reflected signal to estimate the position change of the UAV. In this JCR scenario, the communication frame, which consists of pilot and data parts, as shown in Fig. 2, is transmitted for both purposes. At the UAV, channel estimation is performed before decoding the data part. The UAV decodes the data based on the channel estimate. At the bistatic radar receiver, e.g., another ground BS, the position of the UAV is estimated using the pilot part in the reflected communication frame.

In the outdoor applications, a global navigation satellite system (GNSS), e.g., global positioning system (GPS), is available in most of cases. To acquire the position information of UAVs, however, additional information transmission

from the UAV to the ground BSs, which are not the serving BS but neighboring BSs, is required. It can be burden for network operation. In urban areas with lots of high buildings and indoor applications, the accuracy of GNSS-based position estimation may not be acceptable. Therefore, the proposed JCR technique can be a potential solution for UAV networks. Additionally, vehicle-to-everything (V2X) or airplane network can be considered as another application.

As shown in Fig. 2, the durations of the pilot and data parts are denoted by T_p and T_d , respectively. P and T are the transmission time and average power of the whole frame. Then, the total energy of the entire frame is denoted as PT . The transmission powers of the pilot and data parts are denoted as P_p and P_d , respectively. Therefore, the following constraints can be obtained.

$$T = T_p + T_d, \tag{1}$$

$$PT = P_p T_p + P_d T_d. \tag{2}$$

In this study, we fix the durations, i.e., the numbers of symbols, in the pilot and data parts as $T_p = 1$ and $T_d = T - T_p = T - 1$. Although $T_p \geq 1$ in practice, we fix $T_p = 1$. For other pilot duration values, the main results of this study can be easily extended.

The received signal at the UAV is expressed as

$$r[n] = \begin{cases} hp[n] + w[n], & n = 1 \\ hd[n] + w[n], & n = 2, \dots, T \end{cases} \tag{3}$$

where h is the channel gain between a ground BS, i.e., a transmitter to the UAV, $p[n]$ and $d[n]$ represent the pilot and data symbols at time n , respectively, and $w[n] \sim CN(0, 1)$, i.e., a complex Gaussian random variable with zero mean and unit variance, is the additive white Gaussian noise (AWGN).

In air-to-ground (A2G) networks with UAVs locating at sufficiently high altitude, a probability of line-of-sight (LoS) channel is much higher than that of non-LoS (NLoS) channel [11]. Additionally, we cannot obtain acceptable performance in milli-meter wave (mmWave) or sub-THz channels if an LoS path is not guaranteed. From these facts, we adopt a simple channel model without fading effects is considered. An extension to more practical channel models including fading effects can be considered. In terms of system design, however, fading effects, especially small-scale fading, cannot be reflected because the power allocation is performed not with each channel realization but with an average channel gain in practice.

III. COMMUNICATION AND RADAR PERFORMANCE EVALUATION

To evaluate the achievable rate, considering the channel estimation effects, we investigate the channel estimation with the received pilot symbol $r[n]$ at $n = 1$. Assuming a minimum mean square error (MMSE) approach to channel estimation, the variances of the channel estimate (\hat{h}) and channel

estimation error ($\tilde{h} = h - \hat{h}$) are given by [12]

$$\sigma_h^2 = E \left[|h - \hat{h}|^2 \right] = \left(\frac{1}{1 + P_p T_p} \right), \tag{4}$$

and

$$\sigma_{\tilde{h}}^2 = E \left[|\hat{h}|^2 \right] = \left(\frac{P_p T_p}{1 + P_p T_p} \right), \tag{5}$$

respectively.

The received signals in the data part are expressed as

$$\begin{aligned} r[n] &= \hat{h}d[n] + \tilde{h}d[n] + w[n] \\ &= \hat{h}d[n] + z[n], \quad n = 2, \dots, T, \end{aligned} \tag{6}$$

where $z[n] = \tilde{h}d[n] + w[n]$. Assuming that the additional noise caused by the channel estimation error is Gaussian distributed with a zero mean and variance of $\sigma_{\tilde{h}}^2$, the effective noise $z[n] \sim CN(0, 1 + P_d \sigma_{\tilde{h}}^2)$. Therefore, the achievable rate considering the channel estimation is as follows:

$$C = \frac{T_d}{T_p + T_d} B \log_2 \left(1 + \frac{P_d \sigma_h^2}{1 + P_d \sigma_{\tilde{h}}^2} \right) \tag{7}$$

where B represents the bandwidth of the transmit signal.

For radar performance to estimate the UAV's location, we adopt the CRLB of range estimation under an assumption of flat spectral shape of the pilot part, which is given as [8], [13], Chapter [7], [14]

$$\sigma_r^2 \geq \frac{c^2}{32\pi^2 B_s^2 T_p SNR_r} \left(\equiv \bar{\sigma}_r^2 \right) \tag{8}$$

where c is the speed of light, $B_s \left(= \frac{B}{\sqrt{12}} \right)$ is the root mean square (RMS) bandwidth of the radar waveform, i.e., the pilot signal, when a flat spectrum is assumed. $SNR_r = |g|^2 P_p$ is the received SNR at the bistatic radar receiver. Here, the channel gain between the transmitting and receiving ends of the bistatic radar is denoted by g , and the noise at the radar receiver is assumed white Gaussian noise with unit variance. The radar cross-section (RCS) is an important factor to determine the radar performance of range estimation. As the RCS increases, the power of reflecting signal increases and the CRLB of range estimation is improved, i.e., CRLB decreases. In this paper, the RCS is included in the channel gain of radar signal path, g , implicitly.

The performance of radar significantly depends on the radar waveform, i.e., pilot signal design. In the JCR system, the pilot signal is used for both channel estimation (in communication) and range estimation (in radar). For example, a flat spectral shape of the pilot signal can allow better channel equalization of the communication system, e.g., Zadoff-Chu sequences, and better radar parameter estimation of the target, e.g., linear frequency modulated chirp used in automotive radar. In this paper, however, the optimal power allocation to pilot signal is considered under an assumption that a pilot signal (pilot sequence) is optimally designed previously.

IV. UTILITY FUNCTION OF JCR SYSTEMS

JCR systems simultaneously use radar and communication functions with a single waveform, i.e., a communication frame consisting of pilot and data parts. In this study, the optimal transmit power allocation between the pilot and data parts maximizes both the communication and radar performance measures, i.e., maximizes the achievable rate and minimizes the estimation error simultaneously, which are defined in the previous section.

To use the performance indicators of two different characteristics as an objective function of the optimization problem, a new utility function for JCR systems was defined using the sum of the weighted two performance indicators. From a communication perspective, we aim to maximize the achievable rate. On the other hand, from a radar perspective, a lower CRLB indicates a more accurate estimation. Therefore, a negative weight is assigned to the CRLB. Moreover, to match the scale of both the performance measures, we apply a log function to the CRLB to evaluate and compare the performance values with a communication rate, which is on a log scale. Therefore, the utility as a function of the pilot power allocation based on (7) and (8) is expressed as follows:

$$U(P_p, P_d) = w_c C(P_p, P_d) - w_r \log_{10} \bar{\sigma}_r^2(P_p), \quad (9)$$

where w_c and w_r denote the positive weighting coefficients for communication and radar performance, respectively. In this study, we fixed $w_c = \frac{1}{B}$. The priority between the communication and radar performance can be expressed by adjusting w_r . That is, as w_r increases, it becomes a utility function, which emphasizes the radar performance.

V. OPTIMAL POWER ALLOCATION FOR JCR SYSTEMS

Based on the above utility function, the performance optimization problem for JCR systems can be formulated as follows:

$$\max U(P_p, P_d) \quad (10a)$$

$$s.t. \quad P_d \geq 0 \quad (10b)$$

$$P_p \geq 0 \quad (10c)$$

$$P_p T_p + P_d T_d \leq PT. \quad (10d)$$

The above problem can be simplified according to the following lemma, as in [15].

Lemma 1: The optimal pilot power allocation problem given by (10) has an optimal solution when the energy constraint is satisfied with equality, i.e., $P_p T_p + P_d T_d = PT$.

Proof: To find the solution to the power allocation problem, we can consider the Lagrangian as follows:

$$L = U + \lambda_1 P_d + \lambda_2 P_p + \lambda_3 (PT - P_p T_p - P_d T_d). \quad (11)$$

where λ_1 , λ_2 and λ_3 are Lagrangian dual variables. The Karush-Kuhn-Tucker (KKT) conditions are given by

$$\frac{\partial L}{\partial P_d} = \frac{\partial U}{\partial P_d} + \lambda_1 - T_d \lambda_3 = 0, \quad (12a)$$

$$\frac{\partial L}{\partial P_p} = \frac{\partial U}{\partial P_p} + \lambda_2 - T_p \lambda_3 = 0, \quad (12b)$$

$$\lambda_1 P_d = 0, \quad (12c)$$

$$\lambda_2 P_p = 0, \quad (12d)$$

$$\lambda_3 (PT - P_p T_p - P_d T_d) = 0, \quad (12e)$$

$$P_d \geq 0, P_p \geq 0, P_p T_p + P_d T_d \leq PT, \quad (12f)$$

$$\lambda_1 \geq 0, \lambda_2 \geq 0, \lambda_3 \geq 0. \quad (12g)$$

Here, $P_p = 0$ or $P_d = 0$ is a trivial solution because they mean no power allocation to the pilot or data part, respectively. Hence, we can assume that $P_p > 0$ and $P_d > 0$. To satisfy the complementary slackness conditions of (12c) and (12d), we set $\lambda_1 = \lambda_2 = 0$. If we assume that $P_p T_p + P_d T_d < PT$, we have $\lambda_3 = 0$ to meet the complementary slackness condition of (12e). Then, (12a) is rewritten by

$$\frac{\partial L}{\partial P_d} = \frac{\partial U}{\partial P_d} = w_c \frac{T_d}{T_p + T_d} \frac{B}{\ln 2} \frac{1 - \sigma_h^2}{(1 + P_d)(1 + P_d \sigma_h^2)} > 0. \quad (13)$$

Therefore, there is no solution satisfying (12a). It means that the optimal solution to (10) exists only when $P_p T_p + P_d T_d = PT$. \square

Based on the above lemma, we can reformulate the original optimization problem as follows:

$$\max U(P_p, P_d) \quad (14a)$$

$$s.t. \quad P_p \geq 0, \quad (14b)$$

$$P_p T_p + P_d T_d = PT. \quad (14c)$$

Therefore, the modified problem (14) has a single optimization variable.

When $T_p = 1$, the solution to the optimization problem in (14) can be obtained through the following lemma:

Lemma 2: The optimal pilot power allocation that maximizes the utility function of the JCR systems, i.e., the optimal solution to the optimization problem in (14), is given by the largest positive root among the solutions of the following cubic equation:

$$c_3 P_p^3 + c_2 P_p^2 + c_1 P_p + c_0 = 0 \quad (15)$$

where

$$c_3 = -(\alpha + \beta)(T_d - 1),$$

$$c_2 = \beta(T_d - 1)(PT - T_d - 1) - (2\alpha + \beta)(PT - T_d),$$

$$\frac{dU}{dP_p} = \frac{T_d}{T \ln 2} \frac{-(T_d - 1)P_p^2 - 2(PT - T_d)P_p + PT(PT + T_d)}{\{-P_p^2 + (PT + T_d - 1)P_p + PT + T_d\} \{(T_d - 1)P_p + PT + T_d\}} + \frac{w_r}{\ln 10} \frac{1}{P_p}. \quad (16)$$

$$c_1 = (PT - T_d) \{(\alpha + \beta) PT + 2\beta (T_d - 1)\}$$

$$c_0 = \beta (PT + T_d)^2,$$

$$\alpha = \frac{T_d}{T \ln 2}, \text{ and } \beta = \frac{w_r}{\ln 10}.$$

Proof: To find a solution to (14), the first-order optimality condition, i.e., $\frac{dU(P_p)}{dP_p} = 0$ with $P_d = \frac{PT - P_p}{T_d}$, is used. The derivative of $U(P_p)$ is given by, (16), as shown at the bottom of the previous page.

Considering the numerator on the right-hand side (RHS) in (16), the first-order optimality condition can be written as the following cubic equation:

$$\begin{aligned}
 & -(\alpha + \beta)(T_d - 1)P_p^3 \\
 & + \{\beta(T_d - 1)(PT - T_d - 1) - (2\alpha + \beta)(PT - T_d)\}P_p^2 \\
 & + (PT - T_d)\{(\alpha + \beta)PT + 2\beta(T_d - 1)\}P_p \\
 & + \beta(PT + T_d)^2 = 0,
 \end{aligned} \tag{17}$$

where $\alpha = \frac{T_d}{T \ln 2}$ and $\beta = \frac{w_r}{\ln 10}$. Defining the coefficient of the i th order term with c_i , we have $c_3 < 0$ and $c_i > 0$ for $i = 0, 1, 2$, when $T_d \gg T_p$, as in the practical communication systems. This means that a cubic function, $c_3P_p^3 + c_2P_p^2 + c_1P_p + c_0$, has two critical points: one is positive, and the other is negative. Because the y-intercept of the cubic function is positive, the cubic function in (17) has one positive and two negative solutions. Therefore, only the largest solution to (17) satisfies the positive constraint $P_p > 0$. \square

Even though we assume $T_p = 1$, actual pilot signal in the time domain might be multiple symbols in orthogonal frequency division multiplexing (OFDM) systems. In this paper, we focus on a single subcarrier in an OFDM signal for simple notation and analysis. Therefore, the results in this paper can be extended to practical OFDM waveforms.

Remark 1: The optimal pilot power maximizing the achievable rate based on channel estimation, without considering a radar function, is lower than that maximizing a utility, including both achievable rate and CRLB of radar estimation.

Remark 2: The optimal pilot power allocation that maximizes the utility function increases with an increase in w_r .

As w_r increases, the radar performance has priority over the communication performance. Because the CRLB given by (7) monotonically decreases as P_p decreases, the optimal pilot power increases to obtain a lower CRLB with a higher priority. This has been verified in the next section.

Because the channel gain of a radar link, g , includes the target RCS, g can be an unknown parameter. In this case, we can consider a CRLB minimization problem under a constraint of the achievable rate. This optimization problem can be formulated as follows:

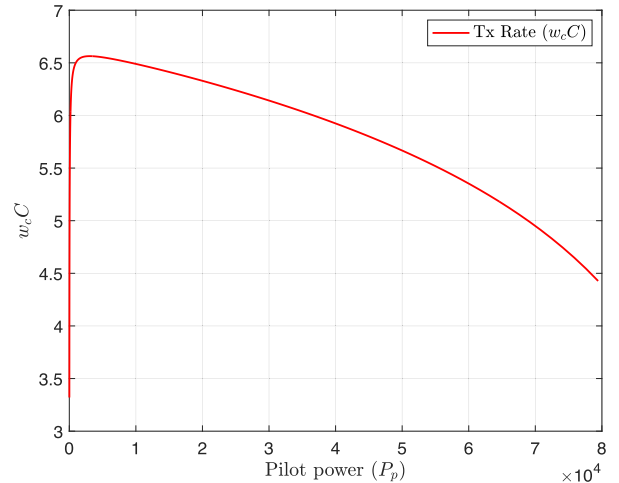
$$\min \quad \sigma_r^2 = \frac{c^2}{32\pi^2 B_s^2 T_p |g|^2 P_p} \tag{18a}$$

$$\text{s.t.} \quad P_d \geq 0, \tag{18b}$$

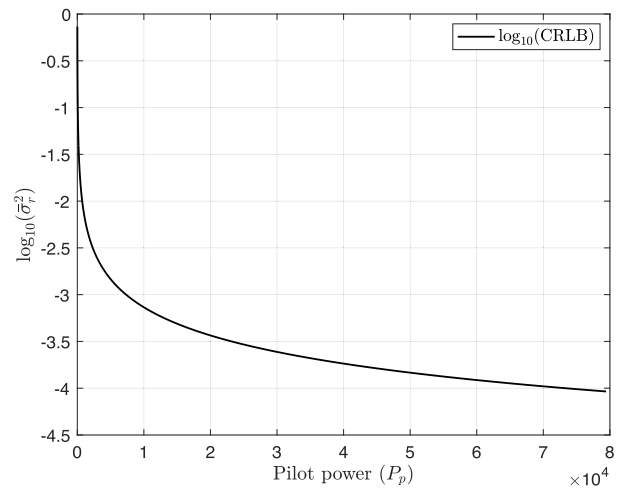
$$P_p \geq 0, \tag{18c}$$

$$P_p T_p + P_d T_d \leq PT, \tag{18d}$$

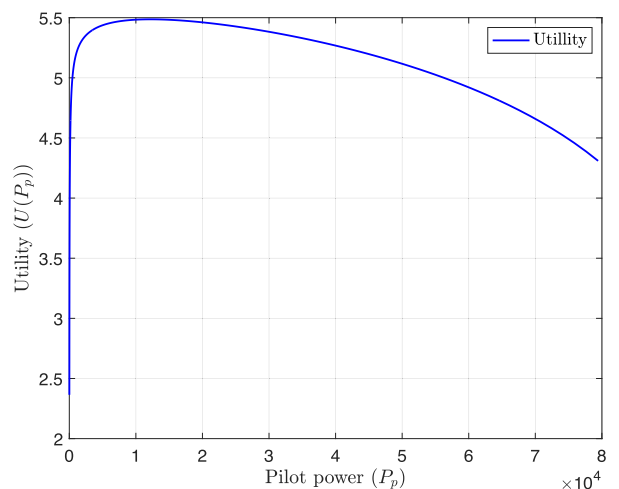
$$C \geq C_{req} \tag{18e}$$



(a)



(b)



(c)

FIGURE 3. (a) Achievable rate, (b) CRLB in log scale, and (c) utility with respect to pilot power allocation when $w_r = 0.3$.

where C_{req} is the minimum required data rate in a communication function. To find the solution to the optimization problem (18), we consider the Lagrangian which is

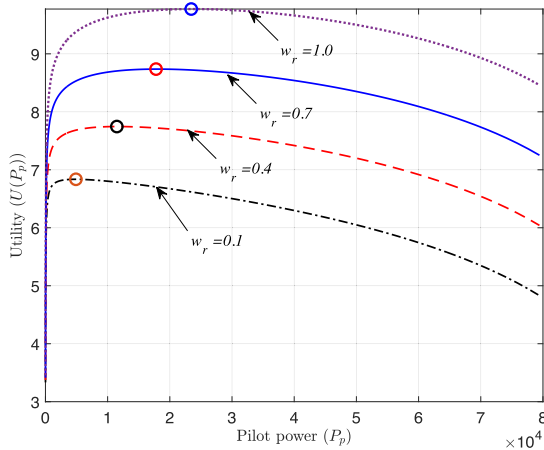


FIGURE 4. Utility with respect to pilot power when $w_r = \{0.1, 0.4, 0.7, \text{ and } 1.0\}$ (marks denote the optimal solutions calculated using Lemma 2).

given by

$$L' = -\sigma_r^2 + \kappa_1 P_d + \kappa_2 P_p + \kappa_3 (PT - P_p T_p - P_d T_d) + \kappa_4 (C - C_{req}) \quad (19)$$

where κ_i for $i = 1, \dots, 4$, are Lagrangian dual variables. When we define $\kappa_4 C - \sigma_r^2 = U$, (19) is identical to the Lagrangian of the proposed problem, (11). Here, $-\kappa_4 C_{req}$ can be ignored because it is a constant. It means that both optimization problems of (10) and (18) can be regarded as an identical problem.

VI. SIMULATION RESULTS

This section provides the numerical results to verify the analytical results provided in the previous section. In the simulations, the total number of symbols and average transmit power in each frame were set as $T = 1000$ and $P = 100$, respectively. As mentioned earlier, $T_p = 1$ and $T_d = 999$. The signal bandwidth is given by $B = 2.16$ GHz, which is one of the bandwidth options in the IEEE 802.11ad. To reflect the pathloss difference in the communication and bistatic radar links, we assumed $|h|^2 = 1$ and $|g|^2 = 0.0001$, i.e., the radar link had -40 dB lower pathloss than in the communication link owing to the longer distance and high reflection loss. Because unit noise variance was assumed, the average SNR of the communication link became 20 dB and that of the bistatic radar link was -20 dB. The weight for communication performance was fixed at $w_c = \frac{1}{B}$.

Fig. 3 shows the achievable rate, CRLB on a log scale, and utility with $w_r = 0.3$. The utility function defined in (9) is concave with respect to P_p . An optimal pilot power that maximizes the utility exists and its uniqueness can be observed. The analytical solution calculated using Lemma 2 was $P_p^* = 9332.5$, which coincides with the numerical solution, as shown in Fig. 3. Therefore, Lemma 2 is validated.

Fig. 4 shows the utility functions for $w_r = \{0.1, 0.4, 0.7, \text{ and } 1.0\}$. Here, the circles indicate the optimal pilot powers based on Lemma 2 calculated analytically. Furthermore, the

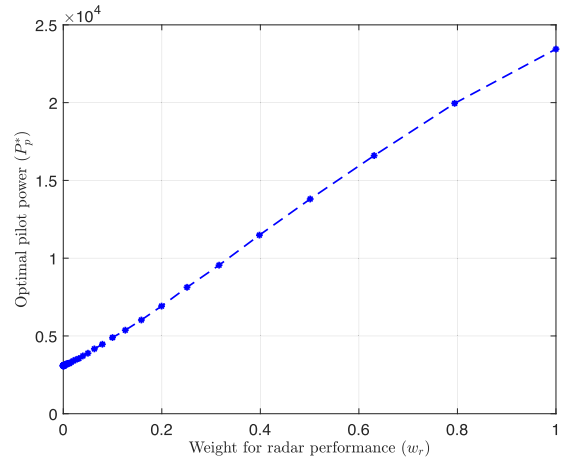


FIGURE 5. Optimal pilot power depending on w_r .

optimal pilot power depends on the weight factor of the radar performance, w_r . As shown in Figs. 4 and 5, the optimal pilot power increased as w_r increased. Based on these results, we can verify Remark 2 in the previous section.

VII. CONCLUSION

In this study, optimal power allocation to the pilot and data parts in a frame structure for JCR systems is proposed. To exploit the communication and radar performance measures, i.e., the achievable rate considering the channel estimation effects and the CRLB for distance estimation, a new utility function was defined. The optimal solution to the utility maximization problem under a total energy constraint was derived, and its characteristics were investigated. The validity of the analytical results was examined using the numerical results. In the future, optimal duration of the pilot and data parts with fixed power allocation will be investigated [16].

REFERENCES

- [1] Z. Xiao, H. Dong, L. Bai, D. O. Wu, and X.-G. Xia, "Unmanned aerial vehicle base station (UAV-BS) deployment with millimeter-wave beamforming," *IEEE Internet Things J.*, vol. 7, no. 2, pp. 1336–1349, Feb. 2020.
- [2] H. Yu, H. Lee, and H. Jeon, "What is 5G? Emerging 5G mobile services and network requirements," *Sustainability*, vol. 9, no. 10, pp. 1848–1870, Oct. 2017.
- [3] S. Lee, H. Yu, and H. Lee, "Multiagent Q-learning-based multi-UAV wireless networks for maximizing energy efficiency: Deployment and power control strategy design," *IEEE Internet Things J.*, vol. 9, no. 9, pp. 6434–6442, May 2022.
- [4] S. Lim, H. Yu, and H. Lee, "Optimal tethered-UAV deployment in A2G communication networks: Multi-agent Q-learning approach," *IEEE Internet Things J.*, early access, Mar. 22, 2022, doi: 10.1109/JIOT.2022.3161260.
- [5] F. Liu, C. Masouros, A. P. Petropulu, H. Griffiths, and L. Hanzo, "Joint radar and communication design: Applications, state-of-the-art, and the road ahead," *IEEE Trans. Commun.*, vol. 68, no. 6, pp. 3834–3862, Jun. 2020.
- [6] R. Thomä, T. Dallmann, S. Jovanoska, P. Knott, and A. Schmeink, "Joint communication and radar sensing: An overview," in *Proc. 15th Eur. Conf. Antennas Propag. (EuCAP)*, Mar. 2021, pp. 1–5.
- [7] O. B. Akan and M. Arik, "Internet of radars: Sensing versus sending with joint radar-communications," *IEEE Commun. Mag.*, vol. 58, no. 9, pp. 13–19, Sep. 2020.

- [8] P. Kumari, D. H. N. Nguyen, and R. W. Heath, Jr., "Performance trade-off in an adaptive IEEE 802.11AD waveform design for a joint automotive radar and communication system," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process. (ICASSP)*, Mar. 2017, pp. 4281–4285.
- [9] S. Huang, N. Jiang, Y. Gao, W. Xu, Z. Feng, and F. Zhu, "Radar sensing-throughput tradeoff for radar assisted cognitive radio enabled vehicular ad-hoc networks," *IEEE Trans. Veh. Technol.*, vol. 69, no. 7, pp. 7483–7492, Jul. 2020.
- [10] Q. Zhang, X. Wang, Z. Li, and Z. Wei, "Design and performance evaluation of joint sensing and communication integrated system for 5G mmWave enabled CAVs," *IEEE J. Sel. Topics Signal Process.*, vol. 15, no. 6, pp. 1500–1514, Nov. 2021.
- [11] Y. Zeng, Q. Wu, and R. Zhang, "Accessing from the sky: A tutorial on UAV communications for 5G and beyond," *Proc. IEEE*, vol. 107, no. 12, pp. 2327–2375, Mar. 2019.
- [12] H. Yu, Y. Sung, and Y. H. Lee, "On optimal operating characteristics of sensing and training for cognitive radios," in *Proc. IEEE Int. Conf. Acoust., Speech Signal Process.*, Mar. 2008, pp. 2785–2788.
- [13] M. A. Richards, *Fundamentals of Radar Signal Processing*. New York, NY, USA: McGraw-Hill, 2005.
- [14] P. Kumari, J. Choi, N. González-Prelcic, and R. W. Heath, Jr., "IEEE 802.11ad-based radar: An approach to joint vehicular communication-radar system," *IEEE Trans. Veh. Technol.*, vol. 67, no. 4, pp. 3012–3027, Apr. 2018.
- [15] H. Yu and H. Lee, "Joint optimization of power and fronthaul compression for data and pilot signals in uplink C-RANs," *IEEE Syst. J.*, vol. 14, no. 4, pp. 4990–5001, Dec. 2020.
- [16] H. Yu and J. Joung, "Optimization of frame structure and fronthaul compression for uplink C-RAN under time-varying channels," *IEEE Trans. Wireless Commun.*, vol. 20, no. 2, pp. 1278–1292, Feb. 2021.



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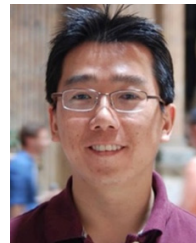
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