Principles of RISs in 6G Networks

Yulan Gao, Yue Xiao, Xianfu Lei, Qionnan Zhu, Dusit Niyato, Kai-Kit Wong, Pingzhi Fan, and Rose Qingyang Hu

Abstract

Owing to the recent advancements of meta-materials and meta-surfaces, the concept of reconfigurable intelligent surface (RIS) has been embraced to meet the spectral and energy-efficient, as well as cost-effective solutions, for the sixth-generation (6G) wireless networks. From an operational standpoint, RISs can be easily deployed on the facades of buildings and indoor walls. Albeit promising, in the actual network operation, the deployment of RISs may face challenges because of the willingness and benefits of RIS holders from the aspect of installing RISs on their properties. Accordingly, RIS-aided wireless networks are faced with a formidable mission to balance the wireless service providers (WSPs) and RIS holders in terms of their respective interests. To alleviate this deadlock, we focus on the application of pricing models in RIS-aided wireless networks in pursuit of a win-win solution for both sides. Specifically, we commence with a comprehensive introduction of RIS pricing with its potential applications in RIS networks, meanwhile the fundamentals of pricing models are summarized in order to benefit both RIS holders and WSPs. In addition, a Stackelberg game-based model is exemplified to illustrate the operation of utility-maximization pricing. Finally, we highlight open issues and future research directions of applying pricing models to the RIS-aided wireless networks.

Introduction

With the commercialization of the fifth generation (5G) wireless network and the exploration and development of its applications in vertical industries, the vision of the sixth generation (6G) wireless network has gradually attracted wide attentions. 6G wireless networks introduce new application scenarios while proposing higher performance indicators, such as seamless global connectivity, higher spectral- and energy-efficient, ultra-reliable communications, security, etc. In conventional networks, the transceiver module is a symmetrical architecture with independent radio frequency (RF) chains with high energy consumption components, such as power amplifiers. Nevertheless, a large number of accessed devices in 6G networks will inevitably lead to a sharp increase in power consumption. Therefore, the realization of high data rate with significantly reduced energy consumption and implementation cost for 6G wireless networks is still imperative. Recently, RIS has been promoted as a promising technology to break the above-mentioned deadlock, driven by the artificial intelligence (AI) theory, emerging meta-materials, and integrated antenna technologies [1]. Benefiting from the breakthrough on the programmable meta-material, RIS was speculated as one of the key enabling technologies for the future 6G wireless networks to construct a smart radio environment. The prototype of RIS-aided wireless communication is shown in Fig. 1, and there are four types of use according to their individual functions and application scenarios [2, 3]. In particular, the anomalous reflection/transmission as shown in Fig. 1i is configurable for specific directions, regardless of the channel attenuation and user locations. As described in Fig. 1ii, beamforming/contouring usage type is designed for certain area with the challenge for optimizing the transmission according to the channel fading and the locations of receivers. The last two types shown in Fig. 1iii are joint active-passive beamforming and singleRF multi-stream transmitter design, respectively. The former focuses on the highest system performance via jointly active-passive beamforming design, while only one single RF chain is desired in the latter with low implementation cost by considering RIS as a special modulator. In summary, RIS can proactively modify the wireless environment via adjusting its capacitance, resistance, and inductance. Consequently, the energy efficiency, throughput, and coverage of networks can be significantly enhanced by manipulating the wireless signals.

In the vision of 6G, RISs will be deployed ubiquitously due to the request for seamless coverage. Consequently, in actual operation, the diversity of 6G entities with different objectives may introduce challenges for RIS deployment and multi-resource management. The reasons are described as:

- The diverse and dense deployment of wireless devices and RISs.
- The willingness of holders to install large RIS.
- The inherent constraints of the service range of RIS.
- A large number of users/stakeholders and...
RIS holders with different objectives. In general, the inherently heterogeneous nature of an ecosystem in which traditional wireless networks and RISs coexist is intuitively attributed to the different dimension of components. More precisely, in RIS-aided wireless networks, the fundamental infrastructures, such as base stations (BSs) and RISs may belong to or be operated by different entities, such as WSPs and RIS holders, resulting in them usually having different objectives and constrains. Accordingly, system optimization for a single objective may fail to model and determine an optimal interaction among these self-interested and rational entities. On the other hand, recently, pricing mechanisms have been widely developed and adopted as useful tools to address resource management issues in heterogeneous networks, whose components are with different objectives, such as high data rate, low latency, and revenue maximization. In the pricing process, each entity reaches the best decision according to the equilibrium analysis via the interactions among all the entities. Accordingly, the inherent and partial information exchange nature of pricing makes it suitable for the autonomous decision made in a distributed method. In short, the above mentioned mechanism may be applicable for the RIS-aided wireless network, which consists of a volume of autonomous entities, meanwhile meeting the demand for diverse objectives of a large number of entities in RIS-aided wireless networks. As such, the purpose of this article is to draw attention to and spur activities on this new research direction.

In this article we focus particularly on the applications of pricing models in RIS-aided wireless networks. Specifically, we first highlight the factors that make pricing imperative for RIS-aided wireless networks, and then review major approaches of pricing. Specifically, two major directions are presented, that is, the heterogeneous architecture of RIS-aided wireless networks and proper pricing of RIS. Next, we present a demonstrative pricing model based on Stackelberg game theory to study RIS service competition. Finally, open research directions are outlined.

**RIS-AIDED WIRELESS NETWORKS: PRICING AND MAJOR APPROACHES**

**Heterogeneity of RISs in Future Wireless Networks:** As shown in Fig. 2, RISs will eventually pervade almost all application scenarios in the future-generation wireless networks. For instance, RIS-aided mmWave networks are illustrated in case (a), where RIS is capable of enhancing the QoS and coverage in mmWave communication environments as diversely as indoor, open rural, suburban, and urban areas. This is achieved by overcoming or at least mitigating the problems imposed by the severe path loss associated with the above-mentioned diverse communication environments. Case (b) shows three dimensional networking architectures enabled by aerial RIS, where RIS is mounted on unmanned aerial vehicles (UAVs), so as to enable intelligent reflection to come from the sky. Case (c) exhibits the use of RIS for improving the physical layer security (PLS), where RIS is capable of mitigating the information leakage. This is achieved by deploying RIS in the vicinity of the eavesdropper, thus, the reflected signal by RIS can be weakened at the eavesdropper. In a nutshell, the ubiquitous applications of RISs illustrate their indispensability in future wireless communications. Obviously, the heterogeneity of RIS-aided wireless networks are determined by the inherently heterogeneous nature of 6G. This means that the adoption of the emerging RIS technology introduces challenges for multiple resource management, such as beamforming, site selection, spectrum allocation, and user schedule. These challenges result from two dimensions: 6G infrastructures (e.g., dense deployment of wireless devices, the coverage and data rate nonuniform of base stations, and the limitations of capacities) [4] and the incorporation of RISs into wireless networks (e.g., appropriate site selection, willingness of RIS holders, the service constraints of RIS, and numerous stakeholders with diverse objectives). The traditional resource management solutions focus exclusively on entire system maximization, which
relies on a centralized entity, resulting in considerable information exchange between users and the network operators. However, in RIS-aided wireless networks, not only the dimension of resource is increased, but also entities have multiple roles. Therefore, the traditional resource management strategies are not suitable for the complex RIS-aided wireless networks.

Multiple Entities and Rationality: The heterogeneity of an ecosystem in which traditional wireless networks and RISs coexist is intuitively attributed to that they may belong to or being operated by different entities, such as RIS holders, WSPs, and community developers, respectively with their individual interests and limitations. The key different relationships between the RIS holder and WSP are shown in Fig. 3, which includes two major categories: RISs and infrastructure/ transceivers from the same WSP and RIS holders different from service providers. In particular, there are three circumstances in the former type:

- RISs are installed on the devices deployed by the WSP.
- RISs are installed on walls or other places that WSP rents from homeowners.
- Wireless service providers lease positions from developers to deploy RISs for services. Correspondingly, the latter is further subdivided into three cases:
  - RISs are installed on the devices deployed by another WSP.
  - RISs are installed by individual homeowners.
  - RIS holders are community developers.

The traditional methods, for example, the system optimization via active-passive beamforming design, can provide optimal resource allocation for the RIS-aided wireless network. However, they usually support a unilateral objective and, thus, may fail to model and determine an optimal interaction among these self-interested and rational entities. Therefore, the traditional methods may not be suitable for the RIS-aided wireless network, especially when the rationality of RIS holders and WSPs is considered as the most important factor. Meanwhile, pricing approaches have been recently developed and adopted as useful tools to address resource management in the 5G wireless networks, where different wireless components also have different objectives, such as high data rate, low latency, and revenue maximization [5].

Major Approaches of Pricing

In this subsection, two major approaches for pricing based on optimization formulation and game theory are discussed.

Optimization-Based Pricing: As widely accepted, an optimization formulation can be used to obtain the price strategy for a given objective and a set of constraints, when there is only one WSP. The authors of [6] have proposed price-based rate allocation to maximize the system utility, as a groundbreaking work. An established theoretical tool for this kind of problems is provided by the theory of dual-primal method. More precisely, the optimization formulation has been decomposed into multiple sub-problems for optimizing the network and user
utility, respectively, which is built on the premise of constructing rate as a function of price. In line with this work, a vast corpus of literature has focused on developing optimization-based pricing strategies for rate adaptation, access control, radio resource management, etc. For instance, Ref. [7] has investigated pricing-based power allocation for code division multiple access (CDMA) systems, in which the utility of user is considered as a mapping of the signal-to-noise ratio (SINR) and the price charged for per unit of the transmit power. Ref. [8] has studied a radio resource management and pricing scheme for multimedia wireless local area networks. Again, solutions that focus exclusively on the objective of the entire system are not aligned with the individual interests of the entities, which, as we mentioned above, are crucial for the deployment and operations in RIS-aided wireless networks.

**Game-Theoretic Pricing:** Game theory has propelled to the forefront of investigating the interaction among multiple entities in a wireless network [9]. Compared to optimization-based approaches, game-theoretic formulations focus on providing individual optimal solutions rather than system optimal utility. According to the corresponding incentive mechanism design, there are several different pricing models, such as noncooperative game and Stackelberg game shown as follows:

**Non-Cooperative Game**: Non-cooperative game (NCG) is a competition among individual players, in which players pursue their individual highest utilities and never consider the possibility of trying to form a coalition. The typical radio resource market in wireless networks is given as an example to show the detailed process in the following. In particular, there are N network operators competing with each other to sell spectrum to users. The game can be expressed as: \( G = (\Omega, \chi, (U_n)) \), where \( \Omega = \{1, 2, ..., N\} \) is the set of rational players, \( \chi = \chi_1 \times ... \times \chi_N \) is the strategy space with \( \chi_n \) being the strategy of player \( n \), and \( U_n(x_1, x_2, ..., x_N) \) is the utility of player \( n \), which depends on the strategies of all players. Each player \( n \) is interested in maximizing its own utility \( U_n(x_1, ..., x_N) \) via selecting spectrum price \( x_n \). Let \( x^*_n \) be the best strategy of player \( n \), which maximizes its utility. Then the set of the best strategies is \( x^* = (x^*_1, ..., x^*_N) \) is the Nash equilibrium (NE) if no player can gain higher utility by changing its own strategy when the strategies of the others remain the same.

**Stackelberg Game**: Stackelberg game is a sequential game in which the first mover of the strategy is the leader, and then the follower makes the corresponding strategy (best response) according to the leader’s strategy. Considering power management market in cognitive radio

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**Figure 3.** The key different relationships between RIS holder and wireless service provider.
Naturally, by bringing pricing approaches from the existing works to the resource management strategies for RIS-aided wireless networks, the diverse objectives can be reached. Moreover, the pricing approaches only have the characteristic of partial information exchange, making them suitable for autonomous decision-making in a distributed method.

networks, in which the primary user (PU) are the games leaders and jointly determines their power allocation to guarantee their QoS requirements and interference price charged for the secondary user (SU) as the game follower. In stage I, PU decides its power allocation $\pi_1$ and interference price $x_1$ to maximize its profit function $U_l(\pi_1, x_1, p_s)$, where $p_s$ denotes the power allocation demand of SU. Subsequently, in stage II, given PU’s power allocation $\pi_1$ and interference price $x_1$, the follower maximizes its utility function $U_f(p_s, \pi_1, x_1)$ by determining its power allocation $p_s$. The objective of such a game is to find the Stackelberg equilibrium (SE).

The work in [10] has used a non-cooperative game-theoretic approach to analyze energy-efficient power control in CDMA systems, where the objective of each user is to maximize its own utility. The utility was computed based on the number of reliable bits transmitted over all the carriers per joule of energy consumed, which is particularly suitable for future networks. The work in [11] has investigated the pricing problem in two-tier femtocell networks, where distributed femtocells coexist with a central macrocell and share the same frequency band. In this model, the macrocell charges the femtocells with interference prices, including uniform and non-uniform pricing. First, assuming that the femtocells are sparsely deployed within the macrocell, the closed-form price and power allocation solutions for the formulated Stackelberg game were derived. Then the model was extended for densely deployed case in which the cross-femtocell interference was presented and lower and upper bounds on the achievable revenue for the macrocell were obtained as a function of price.

Naturally, by bringing pricing approaches from the existing works to the resource management strategies for RIS-aided wireless networks, the diverse objectives can be reached. Moreover, the pricing approaches only have the characteristic of partial information exchange, making them suitable for autonomous decision-making in a distributed method.

Pricing Models for RIS-aided Wireless Networks

Stackelberg Game Formulation

As shown in Fig. 3b2, the RIS-aided wireless network contains $S$ RIS holders that competitively forward signals generated from a BS with $M$ antennas to $K$ single-antenna mobile users. Denote the total number of elements of RIS $s$ as $L_s$, and the reflecting coefficient is restricted by the peak power. As discussed earlier, RIS is ubiquitous in the wireless networks, the BS can buy use rights of the single and multiple RISs for their own applications. Specifically, thus, the BS is charged the price $q_s > 0$ to lease the use rights of RISs.

Given the above RIS services, we tend to study the competition in setting the price of RIS. For the substitute case, in this section, we present the Stackelberg game formulation for the price-based resource management. The Stackelberg game model [14] is, thus, applied in this scenario. The players, strategies, and process of Stackelberg game are presented in Fig. 3. Specifically, Stackelberg game is a strategic game that con-


The proposed Stackelberg game method is regarded as an alternative when designing and implementing RIS services. The approaches aim to analyze how RIS pricing works and how RIS network entities interact economically.

Therefore, Stackelberg game methods are regarded as an alternative when designing and implementing RIS services. The approaches aim to analyze how RIS pricing works and how RIS network entities interact economically.

In this subsection, the performance of pricing-based resource management in an RIS-aided wireless network is evaluated, relying on the Stackelberg game-based method developed in the last section. We consider an RIS-aided wireless network for both the BS and 5 RISs as well as 4 single-antenna users. The BS with 4 antennas is deployed at (0,0) m, and users are uniformly distributed within a circle, whose size and locations are prescribed by its radius 10 m and coordinate (200, 0) m. Furthermore, for the convenience to rationalize to maximize their profits, we present the backward induction algorithm for solving the Stackelberg game problem. The algorithm consists of two phases: BS transmit power allocation and RIS beamforming phase and prices updating phase, as illustrated in Fig. 4. In phase 1, we first apply the Lagrangian dual transform to tackle the logarithm in the BS’s utility function. Then, given price $q(\mathbf{r})$, the BS transmit power allocation and RIS beamforming can be obtained by solving the equivalent optimizing problem (P1) as presented in Fig. 4. In order to develop a tractable algorithm for (P1), a convenient approach is to employ the alternating optimization technique to separately and iteratively solve for $\mathbf{w}$ and $\mathbf{r}$. More specifically, in each iteration, we first update the nominal SINR $\mathbf{a}$, and then better solution for $\mathbf{w}$ and $\Phi$ is updated by addressing (P1-1) and (P1-2), respectively. Based on the best response of the BS, the RIS holders can adjust the price $q$ to achieve the highest profit. In addition, all the control variables and auxiliary variables are initialized. We introduce the auxiliary variables as $\mathbf{a} = [a_1, a_2, ..., a_L]$, $\mathbf{b} = [b_1, b_2, ..., b_L]$, $\mathbf{\phi} = [\phi_1, ..., \phi_N, \phi_S, \psi_1, \psi_2]$}. Here, $q_k$ is used to decode SINR $\gamma_k$, $e_k$, and $e_2$ are used to control the stopping time of algorithms. Auxiliary variables $b_k$ and $\phi$ are introduced to deal with the multiple-input fractional programming problem (P1-1) and (P1-2), respectively. Moreover, $\lambda_0$ and $\mathbf{\phi}$ are the corresponding Lagrangian multipliers for BS power budget of (P1-1) and reflection coefficient constraints of (P1-2), respectively.

As shown in Fig. 4, in each iteration step for solving (P1), the highest complexity is for finding $\Phi^*$ in which the complexity of the summation operation, the matrix inversion, and the final matrix multiplication is quantified by $O(N_\Omega \Sigma_\Omega \psi(s))$, $O(\Sigma_\psi \psi(s^2))$, and $O(\Sigma_\psi \psi(s^2))$, respectively. Thus, the complexity of the Lagrangian dual decomposition is $O(\Sigma_\psi \psi(s^2))$. Obviously, the density of RIS deployment and a large number of reflection elements installed in each RIS seriously impact the scalability of the proposed algorithm. Therefore, it is worthy designing low-complexity algorithm to this Lagrangian dual decomposition method. Continuing the previous work [13], the modular RIS can be fully utilized in the proposed pricing model for RIS-aided wireless networks, which is expected to be a new research direction in future.

**Numerical Results**

In this subsection, the performance of pricing-based resource management in an RIS-aided wireless network is evaluated, relying on the Stackelberg game-based method developed in the last section. We consider an RIS-aided wireless network for both the BS and 5 RISs as well as 4 single-antenna users. The BS with 4 antennas is deployed at (0,0) m, and users are uniformly distributed within a circle, whose size and locations are prescribed by its radius 10 m and coordinate (200, 0) m. Furthermore, for the convenience to
describe the distribution of 5 RISs, we construct a diamond, in which two diagonals are parallel to the horizontal and vertical, respectively. More precisely, the horizontal and vertical diagonal lengths are 25 m and 50 m, respectively. The locations of 5 RISs are described as follows: RIS 5 is deployed at the intersection of diagonal lines and the remaining RISs fall from the top of the diamond counterclockwise in an ascending order. In particular, we assume RIS 3 located at (50, 0) m except for special instruction. As for the communications channel, we consider both the small scale fading and the large scale path loss. Specifically, the path loss exponent of the link between the BS and the user, that of the link between the user and RISs, as well as that of the link between RISs and the BS are 3.5 and 2, respectively, and the path loss at the reference distance 1 m is set as 30 dBm for each individual link, while the small scale fading is accounted by Rayleigh fading model [13].

The following details our simulation results, in terms of the utility performance in both the WSPs and the RIS holders in the proposed Stackelberg game-based and random pricing methods for various simulation environments. The following two pricing schemes are considered: uniform pricing and non-uniform pricing. To quantify the impact of power budget, Fig. 5 depicts the utilities of the BS and RISs' prices with respect to the distance from the BS in Fig. 6a and b, while setting the power budget of the BS as 10 dBm. As can be observed from Fig. 6a, the BS’s utility performance of uniform-pricing and non-uniform pricing first decreases and then increases while increasing the distance between RIS 5 and the BS. In fact, this in essence attribute to the double-fading path-loss model in SINR gk. In contrast, from Fig. 6b, we observe that the prices of RISs first slightly increase and then decrease while increasing the distance between RIS 5 and the BS. This in essence attribute to the double-fading path-loss model that using more RIS elements can
increase the utility of the BS, especially when the cluster of RISs is deployed far away from the BS or the users’ cluster. Correspondingly, for the cluster of RISs, the RIS’s price is negatively correlated to the cascade channel gain of BS-RIS-User.

**Future Research Directions**

As observed, pricing for RIS-aided wireless networks is a meaningful research area. Since it is an emerging topic, there are still many open issues to be addressed, some of which are listed as follows:

**Community Pricing:** It is necessary to investigate the community pricing for the RIS-aided wireless networks in complex urban environments, since there are a large number of residents in each community. To be more specific, during the construction of communities, the community developers can price the deployment of RISs rather than householders. Community pricing can well reduce the complexity, since all the RISs in one community belong to one holder.

**Function Pricing:** Function pricing is needed to meet diverse user requirements in different communication scenarios. The function pricing is based on serving different communication needs, which can provide guidance of the deployment and size of RIS.

**Vickrey Auction Pricing:** With the increasing contradiction between the shortage of wireless resources and soaring performance requirements, the on-demand resource allocation is significantly important. Fortunately, auction is an efficient way of scheduling resources to buyers which value the resources most. In the Vickrey action, WSPs (bidders) will bid prices since they are willing to pay for using RISs to the auctioneer. The highest bidder will win, as determined by the auctioneer. In the end, the winner will pay the second-highest price rather than his own submission.

**Conclusion**

RIS has emerged as one of the promising technologies for 6G wireless networks. In this article, we have considered the pricing approaches for resource management in RIS-aided wireless networks. Firstly, we have described the principles and some typical RIS applications in various emerging systems. Then we have specifically introduced the heterogeneous characteristics of RIS networks with the aim to understand the motivations of using...
pricing models in RIS-aided networks. Afterwards, to demonstrate the application of pricing model, we presented the Stackelberg game theoretic model for RISs service competition.

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**Biographies**

**Yuean Gao** is currently a research fellow in the School of Computer Science and Engineering, at Nanyang Technological University. She received a Ph.D. in communication and information systems and M.Sc. in mathematics from UESTC, China, in 2021 and 2016, respectively. Her research interests are machine learning and wireless networks.

**Yue Xiao** is currently a Professor with National Key Laboratory of Science and Technology on Communications, University of Electronic Science and Technology of China. He received his Ph.D. in communication and information systems from UESTC, in 2007. His research interests are in system design and signal processing toward future wireless communication systems.

**Xianfu Liu** received his Ph.D. from Southwest Jiaotong University, in 2012. He has been an Associate Professor with the School of Information Science and Technology at Southwest Jiaotong University, since 2015. His research interests include 5G/6G networks, cooperative and energy harvesting networks, and physical-layer security.

**Quocan Zhu** is currently pursuing a Ph.D. at Southeast University. She received her B.S. and M.S. degree in communication engineering from UESTC, China, in 2019 and 2022, respectively. Her main research interests include optimization theory, intelligent reflecting surface-aided wireless, mobile edge network, and internet of vehicles.

**Dust Niyato** is currently a Professor in the School of Computer Science and Engineering, at Nanyang Technological University. He received the B.Eng. from King Mongkut Institute of Technol- ogy Ladkrabang (KMITL), Thailand in 1999, and Ph.D. in electrical and computer engineering from the University of Manitoba, Canada, in 2008.

**KaiKai Wong** received his Ph.D. in electrical and electronic engineering from the Hong Kong University of Science and Technology, in 2001. He is currently a Chair in Wireless Communications at the Department of Electronic and Electrical Engi- neering, University College London, United Kingdom.

**Pangzhi Fan** received his Ph.D. in electronic engineering from Hull University, UK, in 1994. He is currently a distinguished professor at Southwest Jiaotong University, China, and a Visiting Professor at Leeds University, UK. His research interests include high mobility wireless communications, massive random-access techniques, signal design, and coding.

**Rong Qingyang Hu** is a Professor in the Electrical and Computer Engineering Department and an Associate Dean for research at the College of Engineering at Utah State University. Her current research interests include next-generation wireless system design and optimization, V2X communications, artificial intel- ligence in wireless networks, wireless system modeling, and performance analysis.