Reconfigurable Intelligent Surface-Assisted Heterogeneous Networks

Subjects: Telecommunications

Contributor: Abdel Nasser Soumana Hamadou , Ciira wa Maina , Moussa Moindze Soidridine

With the development of the next generation of mobile networks, new research challenges have emerged, and new technologies have been proposed to address them. On the other hand, reconfigurable intelligent surface (RIS) technology is being investigated for partially controlling wireless channels. RIS is a promising technology for improving signal quality by controlling the scattering of electromagnetic waves in a nearly passive manner. Heterogeneous networks (HetNets) are another promising technology that is designed to meet the capacity requirements of the network. RIS technology can be used to improve system performance in the context of HetNets.

RIS HetNet spectral efficiency cross-tier interference

1. Introduction

Future wireless communications will enable massive connectivity for mobile and fixed devices, which will require high demand for mobile data traffic on cellular networks in terms of data throughput and network capacity [1]. In order to respond to the requirements of high-transmission rates and quality of service (QoS) for 5G systems, multitier networks improve the spectrum efficiency and capacity of the systems by adopting a heterogeneous design with small cells and a macrocell tier [2]. High-spectrum efficiency (SE) is necessary to enable smooth communication in heterogeneous networks since the bandwidth resources become constrained as the number of cells grows [3]. Additionally, a multitier network with densely deployed cells experiences very high intercell interference as well as cross-tier interference, which may prevent macrocell users (MUEs) within the vicinity of small base stations (SBSs) from having a good signal-to-interference-plus-noise ratio (SINR) as well as reduce the network's capacity overall [4]. Recently, business and academics have both shown a lot of interest in a developing hardware technology called reconfigurable intelligent surfaces (RISs), which aims to address the aforementioned challenge in heterogeneous networks (HetNets) [5][6][7][8][9][10][11].

Specifically, RIS is a two-dimensional artificial surface made up of an array of discrete elements that can be controlled individually or collectively [12]. It is a novel method of controlling the previously uncontrollable wireless propagation medium.

RIS technologies are widely labelled in the literature under names such as software-defined or hypersurfaces, intelligent walls, software-controlled metasurfaces, large intelligent surfaces or antennas, intelligent reflected surfaces (IRSs), and reconfigurable intelligent surfaces. The implementation of an RIS-assisted system is similar to the use case for half-duplex relays, with the key difference that RIS implements passive beamforming [13]. RIS-assisted communication can be used to improve the performance of traditional wireless communication systems by allowing more degrees of freedom via wireless channel control, resulting in a more relaxed set of constraints. Further, reconfigurable intelligent surfaces (RISs) can control the radio environment using low-noise amplification and do not require an analogue, digital, or power amplifier [13]. An RIS can modify the phase shift, the amplitude, or even the polarisation of the incident signal. Notably, the RIS technology is nearly passive in that it is entirely based on electromagnetic wave scattering and does require power amplifiers for signal transmission. Indeed, some energy is only required for the smart controller and for enabling the reconfigurability of the RIS. As a result, RIS can mitigate the interference or improve the signal quality at some specific and localised network locations. The RIS technology shows promising potential for applications in future networks, as it can partially control and shape the propagation channels as one desires. The deployment of RISs can be combined with existing technologies, such as multiple-input multiple-output (MIMO) systems, heterogeneous networks (HetNets) systems, millimetre-wave (mmWave) communications, terahertz (THz) communications, machine learning (ML), and artificial intelligence (AI), for enhancing the performance of existing and future wireless networks [12][13][14].

In addition, RIS technology can be used in a heterogeneous network to assist communications by generating supplementary propagation paths, enhancing the characteristics of the existing paths, and mitigating interference. Additionally, the components of RIS are almost passive in that they passively filter incoming signals before passively reradiating them in the desired direction without the use of additional power. These are some additional defining qualities of RISs: RISs are built of materials that are inexpensive and are essentially passive. Due to their physical resemblance to mirrors, they may also be simply put on building facades, factory ceilings, and interior walls. Because of its capability to reconfigure signals, the RIS has some of the most advantageous use cases for line-of-site (LOS) paths or at the cell edge [15][16]. RIS neither amplifies nor decodes the incoming signal, unlike conventional relaying methods, such as amplify-and-forward (AF) and decode-and-forward (DF) relaying [15][17]. As a result, RIS contributes to the construction of a smart radio environment that may be adequately designed for inexpensive and energy-efficient communication in heterogeneous networks by offering essential flexibility. However, in reality, adaptive phase shifting requires some active components.

2. Reconfigurable Intelligent Surface-Assisted Heterogeneous Networks

Several studies have been published that examine RIS as a substitute for amplifying and forward (AF) relays in order to achieve high-performance gains in the spectrum and energy efficiency of future wireless networks. Specifically, the authors of [17] demonstrated that RIS-aided transmission can outperform the DF relaying protocol in terms of energy efficiency (EE) for high-rate communications. However, the main advantage of RIS in the network is the algorithm structure for managing the phase changes of the passive elements. By creating the phase shift controller using an alternating algorithm design, the authors of [18] examined a RIS-assisted cognitive radio (CR) communication strategy for optimising the achievable secondary user (SU) rate of the system. Moreover, the authors of [6] analysed the RIS-assisted dual-function radar communications (DFRC) scheme for increasing the system's secrecy rate through the use of a multi-eavesdropper, multi-cast, and multiantenna optimisation approach. Moreover, the performance of a RIS-aided single-cell wireless system with a multiantenna access point and multiple single-antenna users was examined by the authors in [10]. In particular, they focused on the asymptotic performance, or RIS, with an essentially unlimited number of elements and contrasted it with a benchmark enormous multi-input-multi-output (MIMO) system without RIS. Moreover, in [4], the authors developed an adaptative hybrid scheme technique that combined time domain techniques using reduced power Almost Blank Subframe (ABS) and power control techniques to mitigate the cross-tier interference between the femto base station and the macrocell user near the femtocell. Results obtained from the simulation demonstrated that the proposed technique could increase the spectral efficiency of femtocells. The technique only considers cross-tier interference between the femto base station and macrocell users. However, the energy efficiency of this technique was not considered as well. Additionally, in [19], the authors formulated a heuristic scheme called the Quality Efficient Femtocell Offloading Scheme (QEFOS), which classifies the users into three categories: macrocell users, which experience low cross-tier interference; macrocell users, which experience high cross-tier interference; and femtocell users. Nonetheless, the cross-tier interference in the case where the femto users experience high cross-tier interference and co-tier interference was not considered. Moreover, in [20], the authors proposed a method to mitigate downlink cross-tier interference between macrocells and small cells. The proposed method is based on an extended cross-tier interference mitigation scheme that coordinates not only cross-tier interference from macrocell to small cell users but also from small cell to macrocell users, which consists of mitigating cross-tier interference from small cell to macrocell users without changing the pilot allocation. Furthermore, the authors of [21] suggested a resource allocation scheme for RIS-assisted heterogeneous networks with non-orthogonal multiple access to improve spectrum efficiency and transmission rate. The proposed resource allocation scheme optimisation is based on the alternating iteration approach and successive convex approximations. Nevertheless, this study did not consider the performance of the proposed method with respect to the user's location. Moreover, in [22], the authors investigated the performance of RIS-assisted wireless communication systems under co-channel interference in order to determine the closed-form expressions for the outage probability and channel capacity. However, this study did not actually take into consideration the RIS phase shift optimisation as well as the trade-off between transmit power and co-channel interference. Moreover, in [23], the authors developed a novel scheme for efficient multiple access in RIS-aided multi-user, multi-antenna systems. A comprehensive comparison of different schemes and configurations was presented in order to determine which scheme is better for the 6G paradigm. However, this study did not consider co-channel interference or inter-user interference. Moreover, the study in [24] presented a survey of the design and applications of an RIS for beyond 5G wireless networks. A comprehensive, detailed survey of RIS technology limitations in current research, related research opportunities, and possible solutions was presented. Moreover, the study in [16] compared the RIS-assisted system with the distributed antenna-aided system. However, the non-line-of-site link between the transmitter and receiver was not considered. In continuation of the same objective, in [25], the authors investigate the intelligent reflecting surface (IRS) for sum-rate maximisation in cognitive radio-enabled wireless powered communications networks. They proposed an alternating (AO)-based solution with a successive convex approximation (SCA) technique to solve the unconvex optimisation problem. The result of conventional cognitive radio enabled wireless-powered communications networks. Nevertheless, this study only considered cognitive radio-enabled wireless-powered communications networks. Apart from cognitive radio (CR), MIMO, and DFRC communications, RIS has been used in D2D and IoT communication systems. For example, in [5], the authors analysed the performance of a RIS-assisted IoT network using two resource allocation problems, namely, spectral efficiency and energy efficiency maximisation. In [7], the authors investigated an RIS-based unmanned aerial vehicle (UAV)-assisted non-orthogonal multiple access (NOMA) downlink scheme for maximising the sum rate of the system by using a deep deterministic policy gradient (DDPG) algorithm. However, except for the works in [19][20][21][22], where the authors proposed to mitigate cross-tier interference in HetNets without taking the impact of the users and RIS location in the network into consideration, a study of cross-tier interference mitigation in RIS-assisted HetNet is necessary, especially for maximising system sum rate and network performance with respect to user location and RIS location. Therefore, in contrast to the aforementioned studies, researchers examine an RIS-assisted HetNet where the reflected link from RIS to the macrocell users (MUEs), as well as the reflected interference link from SBS-RIS-MUEs, are employed to mitigate interference from small cells (SBS).

References

1. Nasser, A.; Muta, O.; Elsabrouty, M.; Gacanin, H. Interference Mitigation and Power Allocation Scheme for Downlink MIMO–NOMA HetNet. IEEE Trans. Veh. Technol. 2019, 68, 6805–6816.
2. Nasser, A.; Muta, O.; Gacanin, H.; Elsabrouty, M. Non-Cooperative Game Based Power Allocation for Energy and Spectrum Efficient Downlink NOMA HetNets. IEEE Access 2021, 9, 136334–136345.
3. Iqbal, M.U.; Ansari, E.A.; Akhtar, S. Interference Mitigation in HetNets to Improve the QoS Using Q-Learning. IEEE Access 2021, 9, 32405–32424.
4. Kassim, A.Y.; Tekanyi, A.M.S.; Abdulkareem, H.A.; Muhammad, Z.Z.; Almustapha, M.D.; Abdu-Aguye, U.F. An Improved Cross-Tier Interference Mitigation Scheme In A Femto-Macro Heterogeneous Network. J. Electr. Eng. Technol. 2020, 9, 62–70.
5. Mondal, A.; Al Junaedi, A.M.; Singh, K.; Biswas, S. Spectrum and Energy-Efficiency Maximization in RIS-Aided IoT Networks. IEEE Access 2022, 10, 103538–103551.
6. Mishra, K.V.; Chattopadhyay, A.; Acharjee, S.S.; Petropulu, A.P. OptM3Sec: Optimizing multicast IRS-aided multiantenna DFRC secrecy channel with multiple eavesdroppers. In Proceedings of the ICASSP 2022-2022 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), Singapore, 22–27 May 2022; pp. 9037–9041.
7. Jiao, S.; Xie, X.; Ding, Z. Deep Reinforcement Learning-Based Optimization for RIS-Based UAV-NOMA Downlink Networks (Invited Paper). Front. Signal Process. 2022, 2, 915567.
8. Jian, M.; Alexandropoulos, G.C.; Basar, E.; Huang, C.; Liu, R.; Liu, Y.; Yuen, C. Reconfigurable intelligent surfaces for wireless communications: Overview of hardware designs, channel models,

and estimation techniques. Intell. Converg. Netw. 2022, 3, 1–32.

9. Mei, W.; Zheng, B.; You, C.; Zhang, R. Intelligent reflecting surface aided wireless networks: From single-reflection to multi-reflection design and optimization. arXiv 2021, arXiv:2109.13641.
10. Wu, Q.; Zhang, R. Intelligent Reflecting Surface Enhanced Wireless Network via Joint Active and Passive Beamforming. IEEE Trans. Wirel. Commun. 2019, 18, 5394–5409.
11. Di Renzo, M.; Zappone, A.; Debbah, M.; Alouini, M.-S.; Yuen, C.; de Rosny, J.; Tretyakov, S. Smart Radio Environments Empowered by Reconfigurable Intelligent Surfaces: How It Works, State of Research, and The Road Ahead. IEEE J. Sel. Areas Commun. 2020, 38, 2450–2525.
12. Fara, R.; Ratajczak, P.; Phan-Huy, D.T.; Ourir, A.; Di Renzo, M.; De Rosny, J. A prototype of reconfigurable intelligent surface with continuous control of the reflection phase. IEEE Wirel. Commun. 2022, 29, 70–77.
13. Pérez-Adán, D.; Fresnedo, Ó.; González-Coma, J.P.; Castedo, L. Intelligent Reflective Surfaces for Wireless Networks: An Overview of Applications, Approached Issues, and Open Problems. Electronics 2021, 10, 2345.
14. Pei, X.; Yin, H.; Tan, L.; Cao, L.; Li, Z.; Wang, K.; Björnson, E. RIS-aided wireless communications: Prototyping, adaptive beamforming, and indoor/outdoor field trials. IEEE Trans. Commun. 2021, 69, 8627–8640.
15. Di Renzo, M.; Ntontin, K.; Song, J.; Danufane, F.H.; Qian, X.; Lazarakis, F.; De Rosny, J.; Phan-Huy, D.-T.; Simeone, O.; Zhang, R.; et al. Reconfigurable Intelligent Surfaces vs. Relaying: Differences, Similarities, and Performance Comparison. IEEE Open J. Commun. Soc. 2020, 1, 798–807.
16. Kamaruddin, N.A.; Mahmud, A.; Bin Alias, M.Y.; Aziz, A.A.; Yaakob, S. Performance Evaluation of Reconfigurable Intelligent Surface against Distributed Antenna System at the Cell Edge. Electronics 2022, 11, 2376.
17. Bjornson, E.; Ozdogan, O.; Larsson, E.G. Intelligent Reflecting Surface Versus Decode-and-Forward: How Large Surfaces are Needed to Beat Relaying? IEEE Wirel. Commun. Lett. 2019, 9, 244–248.
18. Guan, X.; Wu, Q.; Zhang, R. Joint Power Control and Passive Beamforming in IRS-Assisted Spectrum Sharing. IEEE Commun. Lett. 2020, 24, 1553–1557.
19. Agarwal, B.; Togou, M.A.; Ruffini, M.; Muntean, G.M. Mitigating the impact of cross-tier interference on quality in heterogeneous cellular networks. In Proceedings of the 2020 IEEE 45th Conference on Local Computer Networks (LCN), Sydney, Australia, 16–19 November 2020; pp. 497–502.

20. Kamiwatari, S.; Muta, O. Cross-tier interference mitigation considering pilot overhead for TDD MIMO heterogeneous networks. IEICE Commun. Express 2020, 9, 230–237.
21. X, Y.; Yang, Z.; Huang, C.; Yuen, C.; Gui, G. Resource Allocation for Two-Tier RIS-Assisted Heterogeneous NOMA Networks. ZTE Commun. 2022, 20, 36–47.
22. Bian, Y.; Dong, D.; Jiang, J.; Song, K. Performance Analysis of Reconfigurable Intelligent Surface-Assisted Wireless Communication Systems Under Co-Channel Interference. IEEE Open J. Commun. Soc. 2023, 4, 596–605.
23. Jiang, W.; Schotten, H.D. Orthogonal and Non-Orthogonal Multiple Access for Intelligent Reflection Surface in 6G Systems. In Proceedings of the 2023 IEEE Wireless Communications and Networking Conference (WCNC), Thessaloniki, Greece, 26–29 March 2023; pp. 1–6.
24. Okogbaa, F.C.; Ahmed, Q.Z.; Khan, F.A.; Bin Abbas, W.; Che, F.; Zaidi, S.A.R.; Alade, T. Design and Application of Intelligent Reflecting Surface (IRS) for Beyond 5G Wireless Networks: A Review. Sensors 2022, 22, 2436.
25. Hameed, I.; Camana, M.R.; Tuan, P.V.; Koo, I. Intelligent Reflecting Surfaces for Sum-Rate Maximization in Cognitive Radio Enabled Wireless Powered Communication Network. IEEE Access 2023, 11, 16021–16031.