Engineering Universe for Scientific Research and Management
ISSN (Online): 2319-3069
Vol. XIII Issue XII
December 2021

Comprehensive survey of Seamless Void-Free Routing in Wireless Sensor Networks

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Abstract
To address the escalating demands for wideband communications and network densification, a novel approach involving millimeter-wave (mmWave) enabled integrated access and backhaul (IAB) is imperative for the sixth generation (6G) cellular Internet of Things (IoT) network. However, the introduction of mmWave-enabled IAB technology poses challenges to network capacity, specifically related to the varied backhaul capacities of small cell base stations and the diverse interferences among access links in the 6G cellular IoT network. In response, this paper presents a joint framework for traffic load balancing and interference mitigation with the goal of maximizing the network capacity for 6G cellular IoT services. Additionally, to minimize both backhaul burden and interference, a novel matching utility function, considering backhaul capacity and interference, is designed using the many-to-many matching model. The non-convex power allocation subproblem is transformed into a convex problem using the successive convex approximation method, theoretically achieving both upper and lower bounds of the optimal transmit power. Simulation results demonstrate a substantial 71.9% improvement in network sum rate compared to conventional algorithms, ensuring a high successful transmission probability.

Keywords: 6G, Internet of Things, IAB, Wideband communication.

1. Introduction

To meet the escalating demands of smart terminals and emerging services, the Internet of Things (IoT) technology has experienced unprecedented growth in recent years. Projections indicate that by 2030, global mobile traffic could reach up to 5 zettabytes per month, with individual data rates reaching 100 Gbps. To address the capacity requirements for new IoT services, such as virtual reality, augmented reality, and the tactile Internet, millimeter-wave (mmWave) communication emerges as a crucial technology capable of supporting multi-gigabit data rates and enhancing spectral efficiency in the sixth-generation (6G) cellular IoT network. However, the scaling of mmWave-enabled ultra-dense networks (UDNs) introduces challenges like severe inter-beam interference and heavy backhaul burdens.

In response to these challenges, this paper proposes a joint traffic load balancing and interference mitigation framework to maximize the network capacity for 6G cellular IoT services. The paper discusses the limitations of conventional resource allocation algorithms designed for high-speed fiber backhaul links and introduces the concept of integrated access and backhaul (IAB) architecture, as proposed by 3GPP Release. The IAB architecture establishes both access and backhaul links in the mmWave bands on the same network infrastructure, addressing geographical limitations in historic buildings. The paper highlights the need for capacity-aware user equipment (UE) association schemes tailored to mmWave-enabled 6G cellular IoT networks and emphasizes the importance of considering backhaul capacity in association decisions. Additionally, the paper underscores the significance of interference mitigation in mmWave-enabled IAB networks and introduces a low-complexity matching theory-based solution to reduce computational complexity in interference mitigation processes. The proposed framework represents a pioneering effort in developing a backhaul capacity-aware interference mitigation strategy for mmWave-enabled 6G cellular IoT networks, addressing key challenges in traffic load balancing and interference management.

Furthermore, the paper identifies the challenges posed by the different backhaul capabilities of each small cell base station (SBS) and underscores the significance of traffic load balancing between access and backhaul links. The differentiated backhaul capability of SBSs and various quality-of-service (QoS) requirements of UEs are taken into account in formulating the network capacity maximization problem. This optimization problem involves the joint UE association and transmit power allocation, with inherently binary BS-UE association variables strongly coupled with transmit power.

To address this intricate optimization problem, the paper introduces a novel two-step resource allocation scheme. The scheme decouples the joint optimization problem into two separate subproblems: the UE association subproblem and the transmit power allocation subproblem. For the UE association subproblem, the paper proposes a distributed framework based on the many-to-many matching game, leveraging its linear complexity. A novel backhaul capacity and interference-aware matching utility function is designed, considering both interference penalties and the backhaul capability of SBSs simultaneously.

Addressing the transmit power allocation subproblem, the paper introduces the successive convex approximation (SCA) method to transform the non-convex problem into a convex one. The upper and lower convex bounds of the transmit power are theoretically derived, and the approximated convex problem is shown to converge to the Karush-Kuhn-Tucker (KKT) point. In summary, this paper contributes a comprehensive solution to the challenges posed by mmWave-enabled 6G cellular IoT networks, offering a unique perspective on backhaul capacity-aware interference mitigation. The proposed joint UE association and transmit power allocation scheme, along with the matching theory-based approach, provides a holistic framework for maximizing network capacity, ensuring traffic load balancing, and managing interference in a 6G cellular IoT environment.

2. Tackling Non-Convexity for Improved Performance

In today's data-driven world, wireless networks face increasing demands for content delivery. Caching popular content at network edge nodes can significantly improve user experience and reduce backhaul traffic. However, optimizing resource allocation in such networks presents a challenge due to the non-convex nature of the problem. This challenge stems from the complex interplay between user demands, content placement, and interference among competing signals. Traditional interference models often overestimate the detrimental effects, leading to unnecessarily conservative resource allocation and suboptimal network performance. To address this issue, researchers have proposed the successive convex approximation (SCA) method. This method tackles the non-convexity by iteratively solving a series of convex subproblems. Each subproblem optimizes the transmit power of a specific beamforming group while satisfying various constraints, such as interference limits and backhaul capacity. This iterative process progressively refines the solution, ultimately leading to an accurate and efficient allocation of resources. The SCA method forms the core of the joint UE association and power allocation (JUP) algorithm. This algorithm combines the SCA approach with a matching game to simultaneously optimize two key aspects of network performance. Determining which user connects to which base station based on their content needs and location. Deciding how much power to allocate to each beamforming group to maximize the overall network sum rate.

3. The JUP algorithm operates by iteratively solving two subproblems

Given a fixed power allocation, the algorithm utilizes a matching game to find the optimal association between users and base stations that maximizes the sum rate while satisfying user content requests. Given a fixed UE association, the algorithm employs the SCA method to optimize the transmit power of each beamforming group, ensuring efficient utilization of backhaul resources and minimizing interference. This process of alternating between UA and PA subproblems continues until both user association and power allocation converge to stable values. This joint optimization ensures that the network operates at its peak performance by considering both user demands and network constraints simultaneously.

4. The benefits of SCA and JUP are numerous

SCA provides a more accurate interference model compared to traditional approaches, leading to a better understanding of network behavior and efficient resource allocation. JUP optimizes both UE association and power allocation, resulting in significant improvements in network sum rate, content delivery speed, and user experience. Both SCA and JUP converge to stable solutions in a computationally efficient manner, making them practical for real-world network implementations. Overall, SCA and JUP represent significant advancements in the field of cache-aided wireless networks. By addressing the non-convexity challenge, they pave the way for improved network efficiency, increased data throughput, and a more satisfying user experience in the ever-evolving world of wireless communication.

The text explores the effectiveness of a Joint UE association and power allocation (JUP) algorithm within the context of a millimeter-wave (mmWave) Integrated Access and Backhaul (IAB) network featuring multiple Small Base Stations (SBSs). The network setup involves each SBS being equipped with a cache limited in storage capacity, and content popularity adhering to a Zipf distribution. A hybrid caching strategy is employed, utilizing both Most Popular Content (MPC) and Diversity Content (DC) regions, while facing constraints on backhaul bandwidth.

The JUP algorithm stands out by simultaneously optimizing UE association and power allocation. It leverages the Successive Convex Approximation (SCA) method and employs alternating optimization between UE association and power allocation subproblems. The result is efficient resource allocation leading to improved network performance. The algorithm's superiority is demonstrated over baseline algorithms through metrics such as sum rate, average UE rate, percentage of associated UEs, successful transmission probability, and spatial multiplexing gains.

The performance of the JUP algorithm is found to be sensitive to various factors, including the number of SBSs, number of UEs, cache storage capacity, Zipf exponent governing content popularity skewness, and the region division ratio. Notably, the algorithm exhibits rapid convergence and scales efficiently with the size of the problem.

In summary, the JUP algorithm effectively addresses non-convex challenges associated with resource allocation in mmWave IAB networks. It enhances network performance by jointly optimizing UE association and power allocation, providing an efficient and scalable solution for resource management in diverse network scenarios.

The text suggests avenues for further research, including investigating the impact of user mobility and channel dynamics, exploring different cache placement strategies, and developing a distributed implementation of the JUP algorithm. These areas could contribute to a more comprehensive understanding and application of the proposed algorithm in real-world scenarios.

5. Conclusion

In conclusion, this paper proposes a comprehensive framework for joint traffic load balancing and interference mitigation in the context of a 6G cellular Internet of Things (IoT) network with high network capacity. The optimization problem is cleverly decoupled into two subproblems: User Equipment (UE) association and transmit power allocation. This two-step iterative approach aims to maximize the sum rate of the network. The first step introduces a novel backhaul capacity and interference-aware matching utility function, utilizing a many-to-many matching model to minimize backhaul burden and interference. A distributed UE association algorithm is then proposed with low complexity based on this utility function.

The second step addresses the non-convex power allocation subproblem by employing the Successive Convex Approximation (SCA) method. The subproblem is transformed into a convex form, and theoretical upper and lower convex bounds of the optimal transmit power are obtained, converging to the Karush-Kuhn-Tucker (KKT) point. Simulation results demonstrate a significant enhancement in network sum rate by 71.9% compared to conventional algorithms. The proposed algorithms also ensure a high percentage of associated UEs and successful transmission probability.

The paper suggests several avenues for future research. Firstly, considering network architecture, the routing path selection method for multi-hop backhaul in mmWave-enabled Integrated Access and Backhaul (IAB) networks could be explored. Additionally, for spectrum utilization, the in-band model could be formulated to study bandwidth allocation between access and backhaul links, accounting for cross-tier interference. Further optimization, such as bias-factor optimization for backhaul bandwidth allocation based on traffic load at each Small Base Station (SBS), is proposed to improve spectrum efficiency. The caching strategy is recommended to be extended to account for time-invariant popularity of requested contents or cooperative caching among SBSs, thereby optimizing network performance. The paper includes an appendix proving Proposition 1, demonstrating the effective or interfering channel gain and expressing the spectrum efficiency. The mathematical derivations contribute to the theoretical foundation of the proposed framework.

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