Computationally Intelligent Techniques for Resource Management in MmWave Small Cell Networks

Hamnah Munir, Haris Pervaiz, Syed Ali Hassan, Leila Musavian, Qiang Ni, Muhammad Ali Imran, and Rahim Tafazolli

Abstract

Ultra densification in HetNets and the advent of mmWave technology for 5G networks have led researchers to redesign the existing resource management techniques. A salient feature of this activity is to accentuate the importance of CI resource allocation schemes offering less complexity and overhead. This article overviews the existing literature on resource management in mmWave-based HetNets with a special emphasis on CI techniques and further proposes frameworks that ensure quality of service requirements for all network entities. More specifically, HetNets with mmWave-based small cells pose different challenges compared to an all-microwave-based system. Similarly, various modes of small cell access policies and operations of base stations in dual mode, that is, operating both mmWave and microwave links simultaneously, offer unique challenges to resource allocation. Furthermore, the use of multi-slope path loss models becomes inevitable for analysis due to irregular cell patterns and blocking characteristics of mmWave communications. This article amalgamates the unique challenges posed because of the aforementioned recent developments and proposes various CI-based techniques, including game theory and optimization routines, to perform efficient resource management.

Introduction and Motivation

According to a report from Cisco, the mobile data traffic is expected to reach 587 exabytes by 2021 [1]. In this regard, future fifth generation (5G) networks have gained tremendous attention in the wireless industry with the intention to manage the exponential growth of data traffic and to meet the demands for higher data rates. While third and fourth generation (3G and 4G) systems have already paved the way for high-speed connectivity, a new term recently coined for 5G systems is 5G New Radio (5G-NR), which is a new air interface that will be made available through advancements in current Long Term Evolution (LTE) and LTE-Advanced (LTE-A) networks. A core factor enabling 5G in future wireless networks is densification, that is, the deployment of a large number of base stations (BSs) in a given area. Heterogeneous networks (HetNets) realize densification by deploying low-powered BSs to complement the conventional cellular network and thus have a great potential to cope with the exponential increase in wireless data traffic by allowing the fusion of technologies, frequency bands, diverse cell sizes, and network architectures [2].

On another avenue, the fusion of diverse frequency bands in HetNets has resulted in bandwidth expansion by integrating millimeter-wave (mmWave) bands into the current cellular bands. This bandwidth expansion has the potential to overcome the problem of capacity shortage. MmWave technology, in fact, represents the next advance in the wireless industry to provide ubiquitous high data rates [3]. The possibility of utilizing this fragment of spectrum, ranging from 10–300 GHz, has stolen the limelight as a promising solution to provide high data rates to users. While transmission in the mmWave bands can improve network performance, it faces many challenges including hardware expenses, non-line-of-sight (NLoS) channels, and long-range communication. However, recent research results provide a promising solution to these challenges. With the help of highly directional antennas and beamforming, significant signal strength can be achieved within a range of about 150–200 m to overcome the blocking effects. The coalition of mmWave small cells with conventional microwave (μW) network in a hybrid HetNet has the potential to bolster network capacity and improve the mobile user experience. However, resource management becomes crucial when various technologies are combined.

For efficient network operation, computational intelligence is required in different aspects of hybrid HetNets, for example, mobility management, radio resource management, power control, user association, and traffic scheduling, to name a few. These computationally intelligent (CI) techniques include mathematical tools of optimization theory, game theory, and fuzzy/neural systems, some of which are briefly highlighted below.

Optimization theory deals with finding the best possible solution involving the minimization or maximization of the objective function given certain resource constraints. The optimization techniques mostly used for resource management are the Lagrangian Dual Decomposition method, Lagrange multiplier method, Karush–Kuhn–Tucker (KKT) conditions, and particle swarm optimization [4]. A single-objective optimization problem

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yields a single optimal solution corresponding to the minimum/maximum value of a single objective function. On the contrary, in the *multi-objective optimization*, several conflicting objectives are considered [5]. The interaction among these conflicting objectives results in a wide range of alternative solutions with different trade-offs known as Pareto optimal solutions (non-dominated solutions). After finding the Pareto optimal solutions, decision making to find a single most preferred solution is done by the decision maker (DM) that expresses preference information related to the alternatives. Preferences refer to the relative importance of different objectives where each objective has an individual utility function/loss function representing the relative importance of its objective. All individual objective functions are integrated into one objective function, which models the DM's preferences.

Game theory is another powerful mathematical modeling tool used for interactive decision making in resource optimization. It allows the design of flexible distributed schemes with less overhead. The players constituting users and BSs interact with each other in a cooperative or non-cooperative manner to maximize their utility, thus achieving equilibrium. This utility can be any parameter depending on the requirement of the player. Cooperative game allows bargaining among players where the players cooperate with one another to attain mutual benefits. On the other hand, in non-cooperative games, players maximize their own utility without any alliance. One of the most common assumptions in game theory is rationality, which implies that all players act in their own best interest. However, in future wireless networks, different players can have different objectives, and thus one player maximizing its energy efficiency (EE) is considered irrational by some other player whose objective is to maximize its spectral efficiency (SE). This matter is discussed in detail later.

The rest of this article is organized as follows. The following section explains the use of mmWave for next generation wireless networks. We then present the recent literature on the radio resource management in multi-tier 5G hybrid networks. Following that, we present the modeling and analysis of CI-enabled radio resource allocation frameworks for various simulated scenarios in 5G mmWave HetNets. Finally, we conclude the article.

Use of MmWave for 5G Networks

The future generation networks such as 5G systems are expected to provide higher throughput in tons of gigabits per second and support heavier traffic loads that are impossible to accommodate in the current sub-6 GHz networks. In this recent trend, mmWave bands are emerging as a key enabler for the future generation networks due to their extensive available radio spectrum. It is worthwhile to mention that the propagation characteristics in mmWave bands are unpredictable due to shorter wavelengths, highly directional communication, and severe penetration losses due to solid objects, the human body, and rain. This can lead to frequent transmission interruptions and handovers between the serving mmWave small cells. However, initial access design, consisting of the cell search (CS) procedure over the downlink and the random access (RA) procedure on the uplink, is a challenging task in mmWave-enabled cellular networks due to their highly directional communication paradigm.

Furthermore, the higher density of mmWave radio access technology (RAT) may be needed to reduce the blockage probability, which arises because of high propagation and penetration losses. Hence, the integration of mmWave bands and ultra-densification in the future cellular network has led us to a new challenge of centralized monitoring with high complexity. In this regard, user-centric schemes have emerged as a key potential solution to overcome the complexity of centralized monitoring by allowing users to make individual decisions, which can reduce the computational complexity. In fact, traditional cellular networks have inherited network-centric approaches that make solely coordinated decisions, but usually fall short in providing trenchant user requirements [6]. User-centric approaches for which a user is at the center of decision making with or without network assistance [6] have come to aid in realizing users' preferences and requirements.

Another important concern is to minimize the energy consumption due to the exponential growth in the data traffic and substantial growth of network infrastructures. This challenge necessitates the development of the energy-efficient system, which is considered as a key enabler for next generation networks. Hybrid HetNets consisting of small cells operating at both μW and mmWave bands with their smaller coverage radii can allow BSs and user equipments (UEs) to communicate at lower operating transmission power, resulting in reduction of energy consumption and also mitigating the overall interference. An efficient radio resource management can enable us to utilize the real potential of HetNets (i.e., improved SE and EE) simultaneously. However, an effective optimization of resources in complicated networks with diverse cell sizes, relays, and rapidly increasing data traffic is a challenging task. Thus, bringing intelligence into the management and optimization of resources in a HetNet is the need of the hour. The integration of intelligence in future cellular networks can be achieved via many sophisticated techniques, including, but not limited to, optimization theory, game theory, and fuzzy systems. The efficient resource management can be further enhanced by combining the benefits from both user-centric and network-centric designs with CI techniques.

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Recent Advances in Multi-Tier 5G Hybrid HetNets

With the advent of mmWave communications and densification, the future HetNets will offer significant increase in SE and EE. However, these future technologies will cause challenges in different aspects of wireless communication radio resource management, cell association, interference management, network planning, and so on. Thus, the design and implementation of efficient resource management schemes are required in order to realize the true benefits of HetNets. In this section, we provide an overview of the existing research on the CI resource allocation frameworks in HetNets exploiting futuristic technologies.

Macrocellular networks cannot provide further significant increase in capacity. The next generation multi-tier HetNets offer massive deployment of small

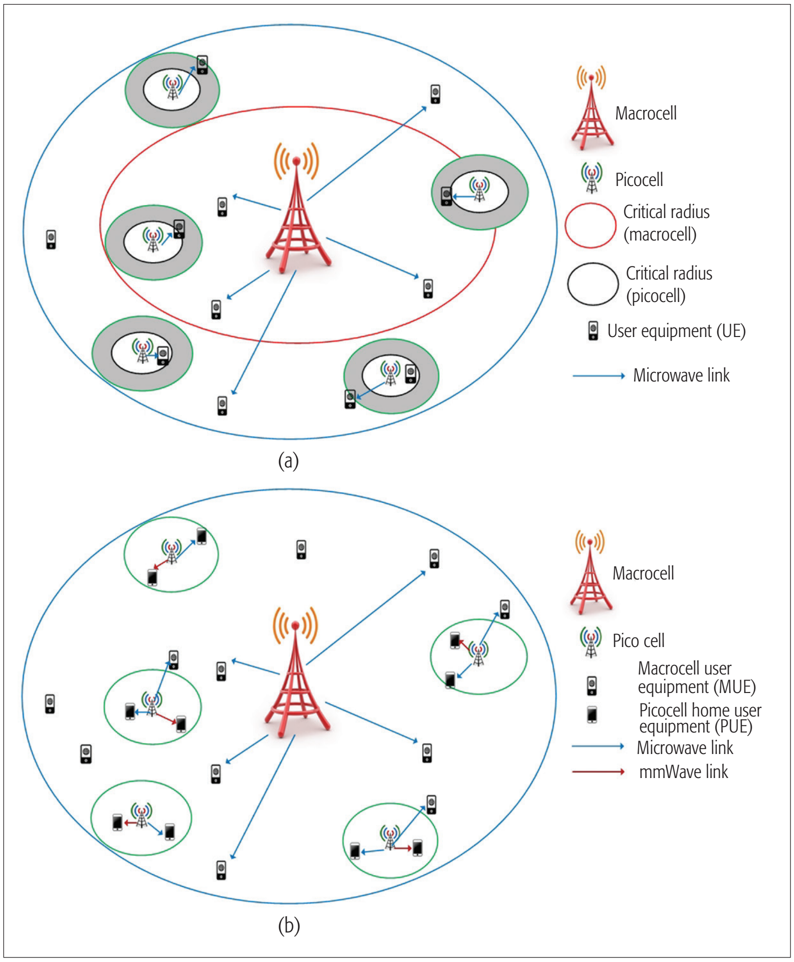

FIGURE 1. Snapshot of a multi-tier hybrid HetNet: a) a two-tier heterogeneous network with a dual slope path loss model; b) a two-tier heterogeneous network with dual-mode SCBSs.

cells (microcell, picocell, femtocell) over macrocellular networks to ensure better coverage for cell edge users, thereby increasing capacity gains [7]. However, dense deployment makes scalable and distributed radio resource management difficult and complex in HetNets due to increased interference. Several schemes have been proposed for efficient resource allocation using game theory, graph theory, stochastic spectrum allocation, distributed learning, and optimization techniques [8–10]. A comprehensive literature on resource allocation for HetNets has been presented, ensuring interference mitigation, fairness, reduced complexity, and quality of service (QoS) using different approaches [8]. However, the next generation wireless networks will feature mmWave communication, densification, and massive data traffic in a complex HetNet, which will bring exceptionally high complexity and increased overhead for resource management.

With the extreme shortage of available spectrum and demand for higher data rates, mmWave communication has triggered a great deal of interest. The mmWave frequency bands for cellular networks were first studied in the 1980s. The mmWave cellular networks, however, face many challenges, including high sensitivity to blocking and strong directionality requirements [11]. Indeed, the realization of a reliable communication network can only be achieved when mmWave networks coexist with conventional μW networks. There are various modes of operation. In a *single-mode hybrid network*, small BSs can operate exclusively on one frequency band, whereas macro BSs mainly operate on the μW band. A preliminary study regarding mmWave HetNets exploiting different frequency bands to boost the throughput with improved bandwidth efficiency was discussed in [12]. On the other hand, in a *dual-mode hybrid network*, the BSs exploit dual frequency bands simultaneously to achieve performance enhancements in a reliable manner while overcoming the challenges associated with mmWave links. Most of the existing literature allows only a single frequency band at each BS in a HetNet. However, in the most recent work, dual band BSs have been studied [9]. The study in [9] formulates a two-stage game theoretic framework for context-aware scheduling and resource allocation. In the first stage, resource allocation at μW band is performed using two-sided stable matching between user applications and μW resource blocks. The econd stage caters the scheduling and selection of user applications, which were not scheduled in the first stage, over the mmWave frequency band on a priority basis using a knapsack approach. The proposed framework achieves an effective solution with polynomial time complexity. A downlink mmWave HetNet with macrocell base station (MBS) operating on mmWave (V-band and E-band) and LTE bands, and small cells operating only on mmWave band is considered in [10]. Relays are also incorporated to guarantee reliable coverage.

In cellular networks, many physical factors, including ground reflections, scattering, and interference, make path loss modeling a complex task. The standard path loss models characterize all the links in a cell with a single path loss exponent (PLE), which lacks precision. While this model is easy to study and analyze, it sometimes characterizes the network unrealistically. In fact, this simplest path loss model does not provide the precise dependence between the PLEs and the link distances. There is an increasing need for an accurate path loss model for future wireless networks that is mostly influenced by network densification and mmWave communications. Network densification causes more irregularities in cell patterns, which affect the interference composition. Thus, the links cannot be accurately modeled by a single PLE. A dual slope path loss model can better approximate the line-of-sight (LoS) and non-LoS (NLoS) links in mmWave systems using different PLEs.

Modeling and Analysis of CI-Enabled Resource Management in 5G MmWave HetNets

In this section, we propose a CI resource allocation framework for various scenarios. A snapshot of a two-tier HetNet where all BSs use a dual slope path loss model is shown in Fig. 1a. This model considers different slopes above and beyond the critical distance, which can be used to approximate the two regimes of LoS and NLoS links [13]. The critical distance is the distance where the first Fresnel zone becomes obstructed, and below this distance all links are considered LoS. In mmWave communication, this distance is an environment-dependent random variable, which increases with low blocking environment, but can be approximated by taking the average LoS link distance [14].

We consider the uplink of a two-tier HetNet composed of a set of $\mathbb{M}$ small cell BSs (SCBSs) overlaid on a macrocell where a set of $\mathbb{N}_o$ macrocell user equipments (MUEs) are randomly distributed. The MBS is represented by $\mathbb{M}_{\mathbb{O}}$. The set of home users served by the mth SCBS is represented by $\mathbb{N}_M$ where

$$\mathbb{N}_{\mathbb{M}} = \prod_{m=1}^{\mathbb{M}} \mathbb{N}_m$$

represents the set of all the small cell home users. The set of all the users in the system is finally represented as $\mathbb{N} = \mathbb{N}_{\mathbb{M}} \cup \mathbb{N}_o$. The single-mode µW network scheme deals with the current state-of-the-art traditional HetNet wherein both macrocell and small cells share the same conventional µW frequency band. In the single-mode hybrid network scheme, the macrocells operate on conventional µW frequency band, and the small cells can operate excursively on either mmWave or µW frequency band. This proposed scheme highlights the importance of mmWave frequency band and the capabilities of a hybrid HetNet exploiting both µW and mmWave frequency bands. The dual-mode hybrid network scheme presents a dual-mode hybrid HetNet, wherein the macrocell operates on µW band and the small cells support both µW and mmWave frequency band simultaneously, thereby providing a higher degree of freedom for resource allocation.

Scheme 1: Single-Mode µW Networks

In this section, the heterogeneous deployment is considered in accordance with the 3GPP LTE-A standard. Here, all BSs as well as users operate on a conventional µW network. We propose a hierarchical game theoretical framework consisting of two sub-games. The first game strategically decides the preferred access policies of SCBSs followed by the second game where MUEs finalize their association using a user-centric approach. To solve this, we devise a distributed scheme that always reaches a pure strategy Nash equilibrium. The system bandwidth, B, is allocated to the MBS. The same bandwidth, B, is reused in the small cell tier, that is, the available bandwidth per SCBS is B_m, where $B_m = B/|\mathbb{M}|$, where $|\mathbb{M}|$ is the cardinality of set M. This orthogonal bandwidth distribution has been considered to avoid the co-tier interference among small cells.

The proposed approach involves two non-cooperative games played in sequential order. The first game models the preferred access policy of the SCBSs among open, closed, and hybrid. The open access policy permits SCBSs to connect MUEs in order to reduce interference at the expense of resource sharing, whereas the closed access policy saves resources at the price of interference. On the other hand, the hybrid access policy is the trade-off between interference avoidance and resource sharing. In order to analyze these conflicting interests, the SCBSs play a non-cooperative game to select their access policies with the goal of maximizing their utility function (i.e., the data rate of their home users). The strategy vector/actions of the mth SCBS is the fraction of frequency band assigned to the MUEs. The utility function of the mth SCBS is the sum rate of its home users. In order to maximize the utility function, each SCBS explores the favorable set of MUEs to connect in each iteration, given the strategy vectors of other SCBSs. To avoid complexity, the SCBS could find an optimal set of MUEs with the help of a greedy algorithm as used in [15] rather than testing all possible combinations of MUEs. The greedy algorithm helps the SCBSs by finding highly interfering MUEs in each iteration. These iterations continue until the algorithm reaches a pure strategy Nash equilibrium (PSNE) while achieving stable action profiles.

After maximizing the rates of small cell home users, MUEs play the next game to maximize their rates using a user-centric approach. MUEs that are connected to SCBSs, as a result of a previous game, examine the rates they are getting from SCBS and MBS. The second non-cooperative game allows MUEs to re-evaluate their connectivity under a QoS constraint. The strategy vector of the nth MUE is the fraction of band allocated to it by all the BSs, and the utility function is its data rate. The algorithm ensures that each MUE opts for the strategy where the system is not affected and it gets a rate greater than a defined minimum rate requirement threshold $R_{\min}$. If the constraint of $R_{\min}$ is not met, the particular MUE goes into outage. This proposed algorithm optimizes the network performance while achieving PSNE.

The single-mode µW scheme is used to highlight the importance of user-centricity. The proposed scheme exploiting both the user-centric and network-centric approaches is compared to the network-centric scheme and the all-closed network-centric scheme, as shown in Fig. 2. The proposed scheme is referred to as a user-centric scheme. We can see that as the number of small cells increases, the sum rate increases for the proposed scheme. This is because the likelihood of the SCBSs playing open access increases with an increase in the number of small cells, which in turn service the interfering MUEs, thus improving the performance of the system and decreasing the outage probability. The same trend of sum rate is followed in the network-centric scheme, but the user-centric scheme yields significant improvement in terms of utilities. In the case of the all closed access scheme, the sum rate almost remains constant, although the number of small cells increases. This is due to the fact that as the density of small cells increases in the network, the MUEs appear closer to them, resulting in increased interference.

In order to investigate the effect of the dual slope path loss model on the performance of a HetNet, we analyzed this scheme under both the single-slope and dual-slope path loss models. We compare the performance of the proposed game theoretic framework with different path loss models in a HetNet where it is desirable to shift the traffic load from the macrocell to the small cells. The dual-slope model pushes the users to the nearby BS using smaller PLE within the critical radius, which represents less attenuation. Thus, the dual-slope model reduces the number of edge users in comparison to the single-slope model by offloading the majority of users to the closest BSs, and thus improves the network performance. The dual-slope path loss model is beneficial for user offloading from the macro tier to the small cell tier. This offloading effect will be stronger when the dual-slope model is used with biasing in the small cell tier. However, this increasing trend in offloading will result in connecting almost all the users to the small cell tier, whereas the power budget at the SCBS is small compared to the MBS, which decreases the received power. This decrease in received power results in decreased SE.

The critical distance is the distance where the first Fresnel zone becomes obstructed, and below this distance all links are considered LoS. In mmWave communication, this distance is an environment-dependent random variable, which increases with low blocking environment but can be approximated by taking the average LoS link distance.

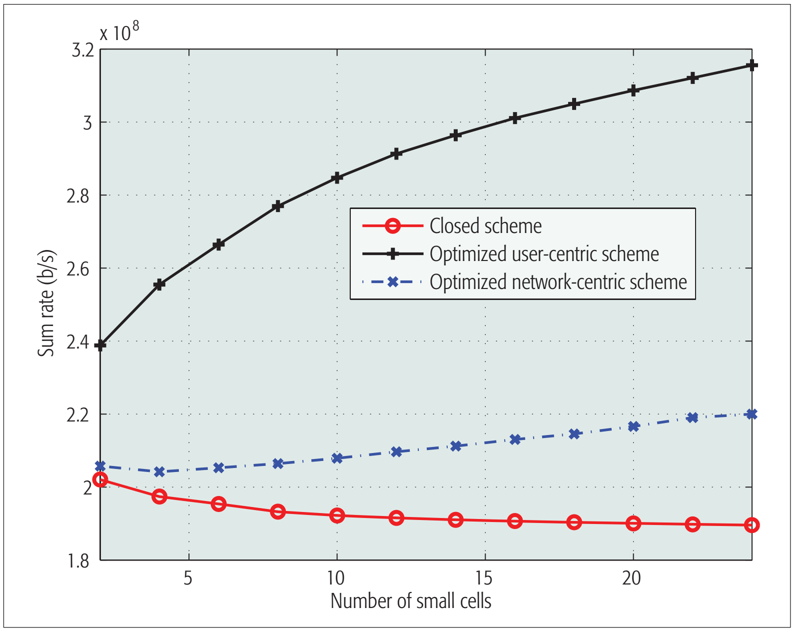

FIGURE 2. Sum rate of the all closed, optimized network-centric, and proposed optimized user-centric schemes for varying number of small cells for a single mode μW network with |ℕ| = 7, R_{min} = 0.5 Mb/s and BμW = 10 MHz.

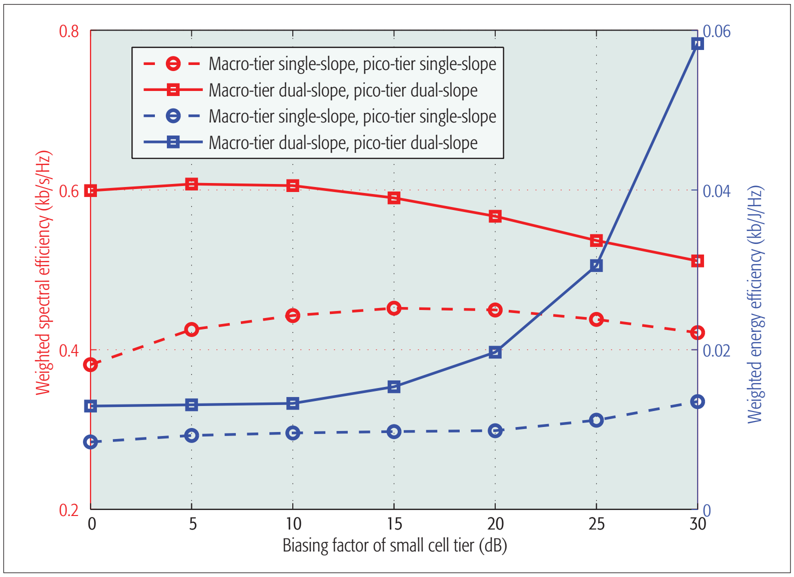

FIGURE 3. Weighted SE and EE for a single-mode μW network for |ℕ| = 25, |𝕄| = 5, critical radius (small cell) = 60 m, and critical radius (macrocell) = 375 m.

However, with the decrease in power consumption, the weighted EE shows a huge improvement for these schemes, as shown in Fig. 3.

Scheme 2: Single-Mode Hybrid Networks

The second scheme presents a two-layer framework for mmWave overlay with HetNet. The outer layer models the access policy of the SCBSs along with the selection of frequency band between μW and mmWave. The solution to this non-cooperative game can be obtained using PSNE. The inner layer ensures energy-efficient user association subject to the minimum rate, maximum transmission power, and maximum tolerable interference threshold constraints by using the Lagrangian dual decomposition approach. We assume that the SCBSs can operate exclusively on either μW frequency band or mmWave frequency band. Each SCBS operating on mmWave frequency band has the entire mmWave band, B_{mm}, whereas the SCBSs operating on μW frequency band has the entire μW band, $B_{\mu W}$. The μW frequency band, $B_{\mu W}$, is reused in the macro-tier.

A two-layer framework for energy-efficient resource allocation in a hybrid HetNet is considered. In the outer layer, each SCBS needs to choose its preferred access policy between either open or closed access for both mmWave and μW frequency bands in order to maximize its home users' data rate. The open access policy allows SCBSs to connect MUEs in order to reduce interference at the expense of resource sharing, whereas closed access saves resources at the price of interference. Then each SCBS opts for one of these bands in the best interest of the network. Initially, all SCBSs have an open access policy, which allows them to connect with the MUEs to reduce the interference and maximize the rate of their home users. The SCBSs play a non-cooperative game to finalize their access policies and frequency bands. The strategy of each SCBS is the fragment of both frequency bands that it assigns to its home users and all the MUEs in the network. The utility function of an SCBS is the sum rate of its home users and the MUEs connected to it. This non-cooperative game achieves convergence using the solution of PSNE.

At the end of the aforementioned game, each SCBS has decided its operating frequency band along with its access policy. Now the macrocell user association and optimal power allocation is done jointly in the inner layer to maximize the EE of the network. Let $\delta_{n,m} \in \{0,1\}$ indicate the connection between the nth user and the mth BS. In the case of connectivity, $\delta_{n,m} = 1$; otherwise, $\delta_{n,m} = 0$.

The EE is defined as the amount of energy consumed by the system to transmit the data, and the optimization problem to maximize the system EE is formulated as follows:

$$\begin{aligned}
&\max_{\delta_{n,m},p_{n,m}} \ \eta_{EE} = \frac{R_T}{P_T} \\
&\text{s.t.} \\
&\text{C1:} \sum_{m\in\mathbb{M}\cup\mathbb{M}_{\mathbb{O}}} R_{n,m} \geq R_{\min}, \qquad \forall n \in \mathbb{N}_{\mathbb{O}}, \\
&\text{C2:} \sum_{m\in\mathbb{M}\cup\mathbb{M}_{\mathbb{O}}} \delta_{n,m} p_{n,m} \leq P_n^{\max}, \qquad \forall n \in \mathbb{N}_{\mathbb{O}}, \\
&\text{C3:} \sum_{\substack{m\in\mathbb{M}\cup\mathbb{M}_{\mathbb{O}} \\ \hat{m}\neq m}} \sum_{n\in\mathbb{N}_{\mathbb{O}}} \delta_{n,m} g_{n,\hat{m}} p_{n,m} \leq I_{\max}, \qquad (1)
\end{aligned}$$

where R_T is the overall rate of the network and P_T is the total transmit power consumed by the network. Constraint C1 guarantees that the achievable rate of the user is at least as high as R_{min}. Constraint C2 limits the transmission power of each MUE to its maximum allowable budget (i.e., P_n^{max}). Constraint C3 ensures that the maximum interference introduced by the MUEs should be less than the allowable interference threshold, I_{max}. The achievable rate always increases with an increase in the allocated transmission power, that is, achievable rate is a non-decreasing function of transmission power. On the other hand, the EE increases with an increase in transmission power up to an optimal point, and afterward it starts decreasing (i.e., EE is a quasi-concave function of transmission power). In the high signal-to-interference-plus-noise ratio (SINR) regime, the achievable rate is logarithmic in transmission power and approximately linear in bandwidth. When the SINR is small, the achievable rate is linear in transmission power but insensitive to bandwidth. The optimal solution for the above optimization problem is found by using Lagrangian dual decomposition. The optimal solution of Eq. 1 is given as $p^*_{n,m} = \min(p_{n,m}, P_n^{\max})$, where $p_{n,m}$ is the optimal transmit power of the nth user connected to the mth BS obtained by the dual decomposition approach.

This proposed scheme allows SCBSs to decide their access policy in the best interest of their users and MUEs to finalize their connectivity to maximize the EE while fulfilling all the constraints. It outperforms the single-mode μW scheme, as shown in Fig. 4, because the μW network provides better coverage for the cell edge users, whereas the mmWave network provides better coverage for near users. This fusion of μW and mmWave networks leads to better performance. The increasing trend in all schemes in the sum rate and EE with increasing number of small cells is due to the fact that as SCBSs increase, they connect more MUEs and thus reduce the interference in the network. The performance of this hybrid scheme further improves when power control is applied. By limiting transmit power to an optimal value, the cross-tier interference reduces, which increases the SINR, thus improving sum rate and EE.

The trends of sum rate and EE across the ratio of mmWave SCBSs to the total number of SCBSs for this scheme is shown in Fig. 5. We can observe that the sum rate and EE are very small when the density of mmWave SCBSs is zero (i.e., the single-mode μW scheme). As the ratio (i.e., the density of SCBSs operating on mmWave) increases, the users located near the SCBSs will get better coverage, and thus the performance improves. This trend becomes steady after a while as the SCBSs serving the MUEs start dominating. This reveals the fact that the MUEs connected with the mmWave SCBSs over long distances experience greater attenuation and obstructions, and it is in the best interest of the network that these SCBSs should operate on the μW band. Thus, a hybrid approach offers better performance than a standalone μW network and a stand-alone mmWave network.

Scheme 3: Dual-Mode Hybrid Networks

In contrast to the above two schemes, we present an optimization of a QoS-aware dual-mode hybrid network with the goal of maximizing the sum rate and EE of the network. The SCBSs operate in dual-mode, thus supporting both μW and mmWave frequency bands simultaneously, whereas the MBS operates only on μW frequency band. We assume that all SCBSs are equipped with both frequency band interfaces. Each SCBS has the entire mmWave band, B_{mm}, and the entire μW frequency band, BμW. The μW frequency band, BμW, is reused in the macro-tier. The proposed approach caters to users with different objective functions. We assume that small cell home users aim at maximizing their data rates, whereas, MUEs aim at maximizing their EE. At the SCBS, the μW frequency band is assigned to MUEs, whereas mmWave frequency band is assigned to home users, as shown in Fig. 1b.

We develop a game theoretic framework for resource allocation in a hybrid HetNet exploiting both μW and mmWave frequency bands simultaneously. The resource allocation at each frequency band is modeled as a two-sided *stable matching* problem between users, represented in set ℕ, and subcarriers, denoted by set 𝕂. Stable matching achieves perfect matching between two sets of disjoint players according to their preference relations, with no unstable pair. The unstable player is defined as a pair, (n, k), where player n prefers player k over the currently assigned $\acute{k}$, and player k prefers player n over player $\acute{n}$. The problem is designed as a one-to-many matching game, where one user can be matched to multiple subcarriers.

For mmWave resource allocation, a matching game is played between two disjoint sets, that is, the home users of a SCBS, $\mathbb{N}_m$, and a set of mmWave

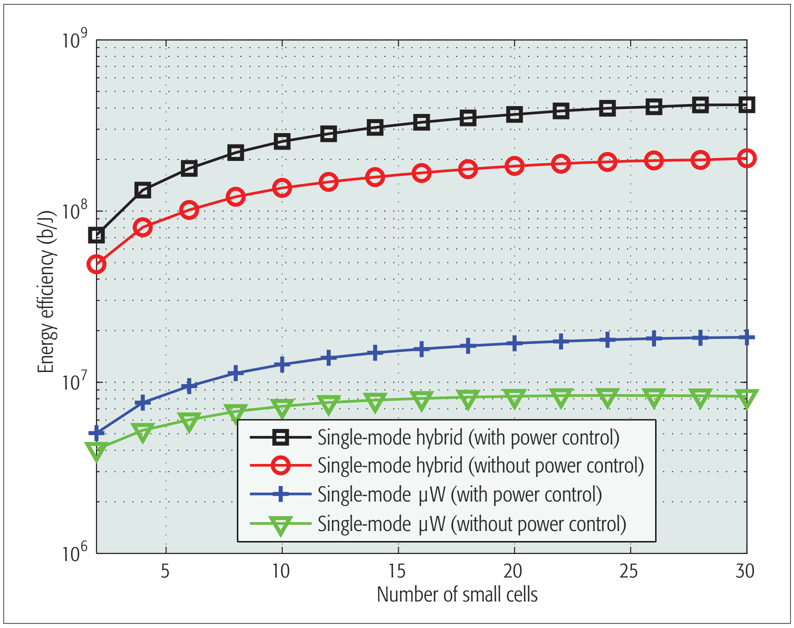

FIGURE 4. EE with and without power control across varying number of small cells for scheme 1 and scheme 2 for |ℕ| = 100, $|\mathbb{N}_M|$ = 5, B_{mm} = 2 GHz, and $B_{μW}$ = 20 MHz.

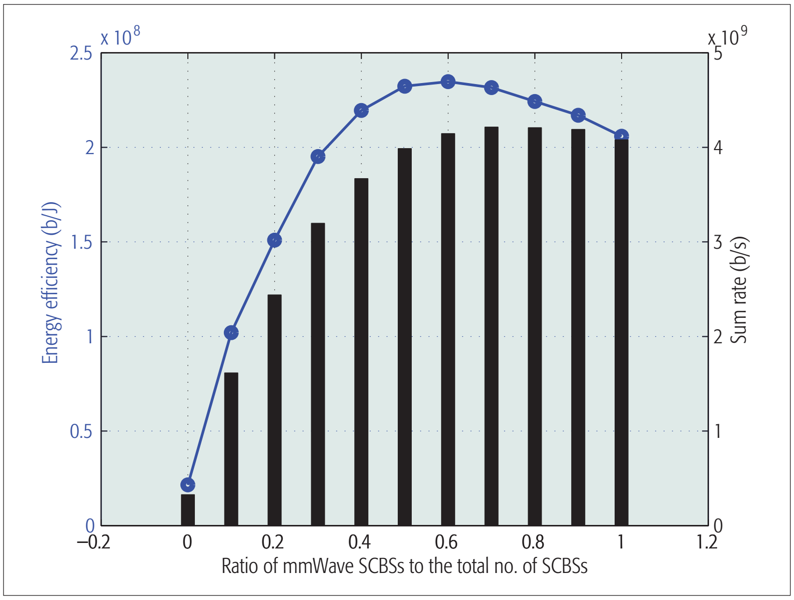

FIGURE 5. Sum rate and EE for the single-mode hybrid scheme across varying ratio of mmWave SCBSs to the total number of SCBSs for |ℕ| = 55, |𝕄| = 10, B_{mm} = 2 GHz, and $B_{μW}$ = 20 MHz.

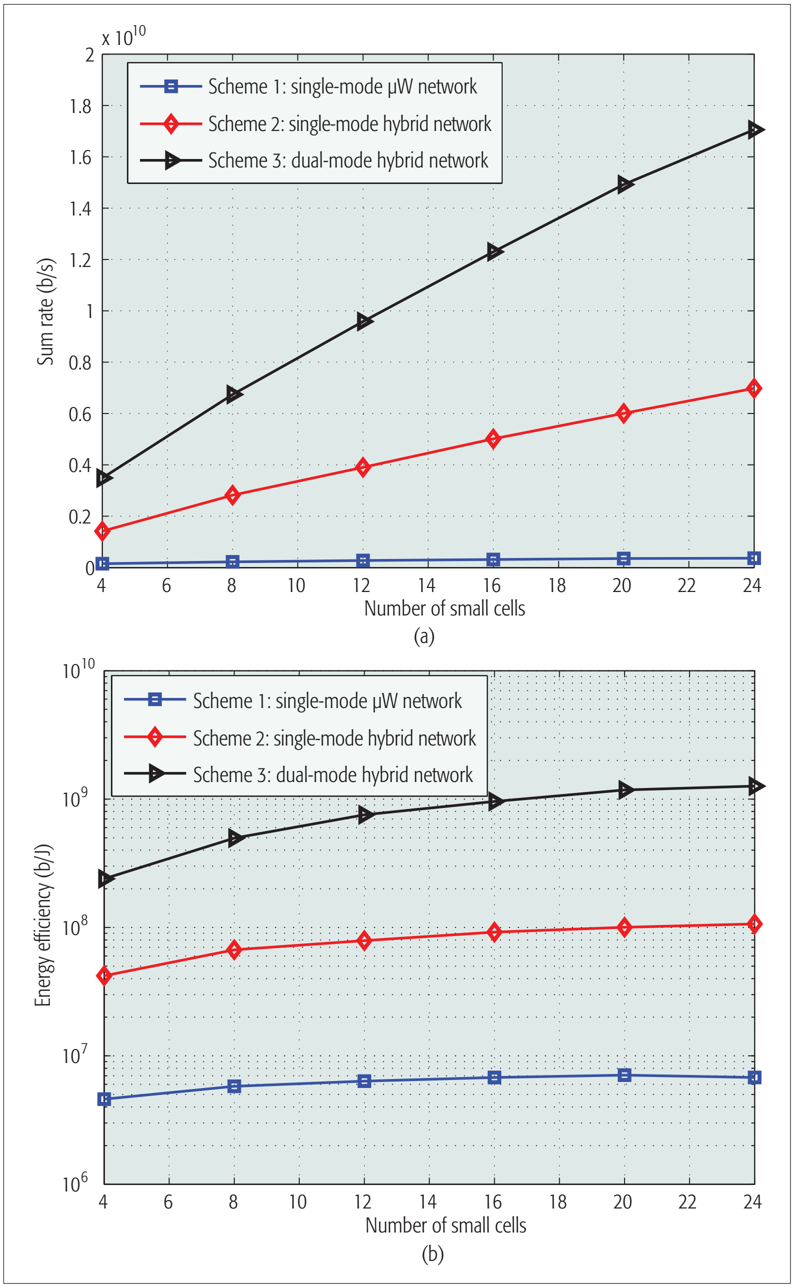

FIGURE 6. Comparison of all three proposed schemes across varying number of small cells for $|\mathbb{N}_0| = 150$, $|\mathbb{N}_m| = 8$, $B_{\text{mm}} = 2$ GHz, and $B_{\mu\text{W}}$ 20 MHz: a) sum rate; b) energy efficiency.

subcarriers, $\mathbb{K}_{\text{mm}}$, at each SCBS. The utility function of the user, $U_n(k_{\text{mm}})$, and subcarrier, $U_{k_{\text{mm}}}(n)$, is the data rate of the nth user connected to the mth SCBS over k_{mm} subcarrier (i.e., $U_{k_{\text{mm}}}(n) = U_n(k_{\text{mm}}) = R_m(n, k_{\text{mm}})$). For μW resource allocation, a matching game is played between the connected MUEs and the set of μW subcarriers, $\mathbb{K}_{\mu\text{W}}$, at each SCBS. The utility function of the user, $U_n(k_{\mu\text{W}})$, and the subcarrier, $U_{k_{\mu\text{W}}}(n)$, is the EE achieved by the nth user connected to the mth SCBS over subcarrier $k_{\mu\text{W}}$ where $U_n(k_{\mu\text{W}}) = U_{k_{\mu\text{W}}}(n) = \eta_m(n, k_{\mu\text{W}})$. The EE, $\eta_m(n, k_{\mu\text{W}})$, is defined as

$$\eta_m(n, \kappa_{\mu\text{W}}) = \frac{R_m(n, \kappa_{\mu\text{W}})}{p_{n,m}[\kappa_{\mu\text{W}}] + p_c}, \quad (2)$$

where $p_{n,m}[k_{\mu\text{W}}]$ is the transmit power of the nth user connected to the mth SCBS over subcarrier $k_{\mu\text{W}}$, and p_c is the circuit power. At the MBS, the μW resource allocation is done in the same way as at the SCBS for μW frequency band.

We assume that the user proposes to the frequency bands aiming to achieve its minimal throughput requirement by using the lowest possible transmission power. The users set up their preference lists. The availability of frequency bands is sensed at the small cells and then updated to all users. The bands that are not able to fulfill a user's minimum rate requirement will be deleted, that is, the preference lists of users are incomplete: only a subset of bands are in the preference lists of users and vice versa. On the other hand, the preference lists of bands are actually performed at the small cells. The interactions between users and bands are, in fact, interactions between users and small cells. Each iteration begins with the unmatched users proposing to their favorite (i.e., the first frequency) band on their current preference lists. The bands that have been proposed will be removed from users' preference lists. For each band f, small cells decide whether to accept or reject users proposing band f based on small cells' preference lists over ($user_n$, $band_f$) pairs. The small cells choose to keep the several most preferred users as long as these users do not occupy more resource than the band can offer, and reject the remaining users. This procedure keeps running until either every user is matched or its preference list is empty. The comparison among the above-mentioned schemes in terms of sum rate and EE is shown in Fig. 6.

The goal of the proposed schemes is to efficiently optimize the network resources using CI techniques. We have used optimization and game theory to develop these resource allocation frameworks. It can be noticed that both hybrid schemes outperform the all-μW scheme. This is because although the μW network exhibits better coverage probabilities even at lower SINR thresholds, especially for the cell edge users, the mmWave network, on the other hand, provides better coverage and data rates when the users are in proximity of SCBSs. Thus, a fusion of both technologies leads to performance enhancement. This performance can further be elevated by introducing the dual-mode technique where both frequency bands are available at SCBSs. It can be seen that scheme 3 with a dual-mode hybrid network exploiting both μW and mmWave frequency bands simultaneously yields the best performance in terms of both sum rate and EE. The proposed framework in scheme 3 allows nearly located home users of SCBSs to operate on mmWave frequency band. As attenuation grows with the increase in distance, the MUEs located comparatively far away from SCBSs will experience performance degradation over the mmWave links. To cater to these users, μW frequency band is assigned to improve the quality of the link. These results portray the hybrid network as a strong candidate in 5G HetNets as the coexistence of μW and mmWave frequency bands in the network can provide seamless and reliable coverage with significant capacity gains.

Conclusion and Future Work

CI techniques are promising solutions to meet the increasing complexity and overheads associated with next generation wireless systems. This article highlights the resource optimization problem in hybrid mmWave HetNets and proposes solutions using various CI techniques, including optimization and game theories. Various recent advancements in the wireless industry have been incorporated to build the system models, and the simulation results validate the effectiveness of CI-based proposed frameworks under mmWave technology, dual-mode BSs, and using dual-slope path loss models.

There are numerous open issues in this domain. For instance, the integration of dual-mode BSs and the dual-slope path loss model in a hybrid HetNet exploiting both μW and mmWave frequency bands should be studied. The objective is to achieve high capacity gains with robust and reliable coverage under various constraints. This can further be integrated where the central BS can be assumed to be massive multiple-input multiple-output. However, integrating various technologies for the future mobile networks pose unique challenges, and sophisticated CI techniques are required to obtain QoS. Machine learning, deep learning using convolutional neural networks, and reinforcement learning are new paradigms in CI approaches, which are actively under research for various solutions in mobile networks. Similarly, another new direction is the downlink/uplink decoupling, which allows a UE to connect to one tier of BSs in the downlink (e.g., μW MBS) and another tier in the uplink (e.g., mmWave SCBS). This situation is further complicated if BSs operate in dual-mode. Therefore, elegant CI techniques are extremely necessary to solve various design issues in the aforementioned scenarios.

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Various recent advancements in wireless industry have been incorporated to build the system models, and the simulation results validate the effectiveness of CI-based proposed frameworks under mmWave technology, dual-mode BSs, and using dual-slope path loss models.