Green Resource Allocation for Multiple OFDMA Based Networks: A Survey

A. S. Khan, J. Abdullah, H. Lenando, and J. M. Nazim

Abstract—**Orthogonal frequency division multiple access (OFDMA) is a popular and widely accepted multiple access technique to provide high data rate services in a mobile environment in the area of wireless communications. OFDMA can provide better flexibility in allocating the radio spectra by utilizing subcarrier allocations, scheduling, and energy control to obtain multi-dimension diversity gains. Due to its resource allocation flexibility, OFDMA has been widely used as a green air interface technology for the emerging broadband wireless access networks. This paper extensively addresses the integration of green OFDMA to the future air interface technologies, for instance: two-tier cellular, multi radio access technologies (RATs), FemtoCell, and relay networks. The main focus of the paper is to review and analyze the current OFDMA techniques to address the green resource allocation in multiuser diversity, where the critical constraints are the computational complexity, energy efficiency, and the sub-channel assignment. The future trend of OFDMA based networks will aim to maximize the energy efficiency of the exclusive channel assignment through a joint sub-channel and power allocation to accommodate high data traffic networks specially the relay based 5G cellular networks.**

Index Terms—**Dynamic, multiuser diversity, orthogonal frequency division multiple access (OFDMA), resource allocation, subcarriers.**

1. Introduction

The orthogonal frequency division multiplexing (OFDM) transmission technique has established itself as an elegant and popular method in broadband wireless systems[1]. For the better understanding, the word OFDMA (orthogonal frequency division multiple access) represents the green OFDMA in this paper. For instance, the IEEE 802.11 a/g standards for wireless local area networks (WLANs) also known as Wi-Fi have used OFDM to achieve speeds of the order of 50 Mbps in an indoor multipath environment. Various other systems using OFDM include power line communications, digital and video broadcasting systems, and ultra-wideband based systems for short range wireless.

Meanwhile, OFDMA is an effective technique that exploits the features of OFDM in combating channel noise and multipath effect, and finally enables high data rate transmission over a fading channel. In addition, OFDMA is able to provide good bandwidth scalability as the number of subcarriers can be flexibly configured. OFDMA appears as a new paradigm that is widely adopted in many standards of existing and upcoming wireless communication systems such as the third generation partnership project-long term evolution (3GPP-LTE/LTE-A) and WiMAX. In OFDMA systems, the multiple users' signals are separated in the time and/or frequency domains. Typically, a burst in an OFDMA system will consist of several OFDM symbols. The subcarriers and the OFDM symbol period are the finest allocation units in the frequency and time domains, respectively. Hence, multiple users are allocated different slots in the time and frequency domains[2]. In practise, the allocation in the frequency domain is not addressed at the level of subcarriers. Typically, sub-channels, which are the smallest granular unit in the allocation, are created by grouping subcarriers in an OFDM symbol in various ways. Because of its flexibility in allocating the radio spectrum, OFDMA has been used as the air interface technology by two-tier cellular, multi radio access technologies (RATs), FemtoCell, and relay networks.

Dense small cell heterogeneous networks have recently been promoted as an enabling solution to meet ever increasing demand for ubiquitous wireless coverage and higher throughput[3]. Small cells, such as FemtoCells overlaying the macrocell, can enhance the coverage of cellular wireless networks and increase the spectral efficiency by reusing the frequency spectrum assigned to the macrocells in the universal frequency reuse fashion. Compared with orthogonal deployment, co-channel

Manuscript received March 27, 2016; revised April 28, 2016. This work was supported by the Research and Innovation Management Centre, Universiti Malaysia Sarawak under Grant No. F08 (S150)/1131/2014/(15).

A. S. Khan (corresponding author), J. Abdullah, H. B. Lenando, and J. M. Nazim are with the Facutly of Computer Science and Information Technology, Universiti Malaysia Sarwak, Sarawak, Malaysia (email: skadnan@unimas.my).

Digital Object Identifier: 10.11989/JEST.1674-862X.603272

deployment is more attractive in these heterogeneous network scenerios as it can offer a much higher spectral efficiency.

To support the heterogeneous equipment for the network and mobile users, multiple RATs operating with different system configurations and resources have evolved and now coexist. Recently, with data traffic exponentially increasing, there has been a significant expansion in wireless network infrastructure, as a result, raising a justifiable concern over the concomitant drastic increase in energy consumption. Thus, the energy-efficient design in multi-RATs networks is becoming increasingly important. Moreover, the management of both the cross tier and co-tier interference is one of the most critical issues for the two-tier cellular network. Centralized solutions for interference management in a two-tier network with OFDMA which yields optimal or near optimal performance, are impractical due to the computational complexity. Distributed solutions on the other hand, lack the superiority of the centralized scheme. Recent works on the subject usually ignore either the selection of relays, asymmetry of the source to relay, and relay to destination links, or the imperfections of channel state information. Besides that, the sub-channel assignment involves allocating the limited radio frequencies to different user equipment in multiple cells. Therefore, the successful deployment of any resource allocation scheme relies upon how one can efficiently overcome such a difficult problem.

A joint sub-channel and power allocation for the downlink of OFDMA addresses the resource allocation problem in collaborative OFDMA based two-tier cellular, multi-RATs, FemtoCell and relay networks. Furthermore, there are another solutions: 1) the resource allocation that maximizes the energy efficiency of OFDMA in multi-RATs networks for parallel transmission utilizing multiple RATs by exploiting the intrinsic quasiconcavity and a semi distributed interference management scheme based on joint clustering, and 2) the resource allocation for FemtoCells as a mixed integer nonlinear program in which the solution is obtained by dividing the problem into two sub-problems, where the related tasks are shared between the FemtoCell gateaway and FemtoCell[4]. The system throughput of source-to-destination link with limited information and various constrains is maximized by optimizing the set of collaborative relays and link asymmetries together with subcarrier and power allocations.

In this paper, we survey various OFDMA assisted networks, namely two-tier cellular, multi-RATs, FemtoCells, and relay networks, aiming at presenting the overview of the network, its architecture principle, and discussing the related research issue and approaches mentioned earlier. This paper is organized as follows. The resource allocation in various OFDMA based networks is presented in Section 2. The discussion and comparison analysis table is set up in Section 3. Finally, we conclude this survey paper with future trends in OFDMA research in Section 4 and brief conclusions in Section 5.

2. Resource Allocation in OFDMA Based Networks

2.1 OFDMA Two-Tier Cellular Network

Over the last decade, the market of cellular networks has been growing rapidly, due to the exponentially increase in the mobile users and consequently the high demand of data traffic. Thus, the massive number of users and applications demands efficient and excessive deployments. However, such deployments not only enhance the energy consumption leading towards the hazards but also increase the operator cost. Therefore, there must be some mechanism to reduce such deployments and improve energy efficiency[5],[6]. Several attempts by the researchers are carried out to maximize the energy efficiency by considering the quality of services (QoS) in terms of designing and introducing the relay stations and joint relay selections, subcarrier allocations, pairing and the power allocations. However, the energy efficiency metric is a fractional and non-linear functions, which complexes the problem.

Introducing relays and their selection normally park under cooperative relaying technologies, which have been found as one of the significant methods to improve the energy efficiency[7],[8]. The direct path is distributed into shorter links in cooperative communication, so destructive factors such as path loss and shadowing become less dominant, which possibly makes the low power transmission[9],[10]. The 3GPP, LTE-A, and IEEE 802.16 are the examples of the technology that can sustain for the next generation of wireless networks[11]. Decode-and-forward (DF) and amplify-and-forward (AF) are more famous among the different relaying protocols[9]. There are the fixed relays stations again gaining the importance in recent research[12],[13]. However, the key drawback with operational and maintenance costs for the operators also increase due to installing fixed relays. Another attempt is to utilize the mobile users as relays without increasing the cost of the mobile operators if they are with good channel conditions and low traffic demands[14],[15]. No doubt fixed relays can accommodate ample amount of users as compared with mobile users as relays, but fixed relay needs extensive constant power supply as compared with the mobile relays.

Nevertheless, emerging research found OFDMA systems as one of appealing technique to accommodate maximum users with an energy-efficient way. In this technique, frequency spectrum is divided into plenty of subcarriers (smaller bands) which can be allocated to multiple users in an OFDMA system. OFDMA systems are with high spectral efficiency and they are strong against multipath interference. OFDMA is appropriate for wireless networks such as worldwide interoperability for microwave access (WiMAX) and LTE-A[16]. Some research work is done by integrating OFDMA and relaying technologies to obtain the advantage of both OFDMA and cooperative relaying systems[17]-[19]. The solution to meet the rising demand with the limited resources will be questioned once the network is fixed. So developing resource optimization schemes that can meet the certain demands of users and upgrade the performance of the network is the best solution for this situation.

Although the optimal resource allocation problem for multiple user cooperative OFDMA systems is hard to solve, there are several works on resource allocations, which try to solve it such as capacity maximization[13],[20] and power minimization[21],[22], for cooperative systems. Back to the cost effective issue, nowadays, most of the existing works can be considered as fixed relays and most of the solutions do not meet the requirement which is cost effective. Besides that, from the existing solutions provided, they are overlooking the energy consumption of the system.

At the same time, both the maximization of the system capacity and the minimization of power should be taken into account due to the optimal resource allocation which considers the energy efficiency metric as the objective function. In [12], the power efficiency maximization issue has been studied for collective OFDMA systems. It is considered that the users are fixed to the fixed relays in advance, although the power and subcarrier allocation schemes are deployed.

The performance of the system is influenced if it does not take into account the optimal relay selection in its design and QoS provided for the users using real-time applications. The power efficiency maximization problem considering QoS provisioning was studied for non-cooperative systems which had been mentioned in [23] to [26]. The literature on optimal resource allocation schemes for cooperative OFDMA systems to resolve power efficiency and QoS provisioning is scarce, and demands researchers' attention.

However, in future generation, to accommodate the number to users, the network capacity is one of the most concern requirements due to rapid improved QoS and the high data rate of mobile data traffic. These requirements mostly come from housing and offices. Again, it is not a cost efficient solution to use macro base stations (MBSs) to improve network coverage. Therefore, a small and low power consumption base station named as FemtoCells or femto access points (FAPs) is introduced. To increase indoor coverage and data rate, the immediate requirement is to shorten the distance between the transmitter and receiver[27].

To deploy FemtoCells on the existing network technology which is macrocell, some technical challenges are raised[28],[29]. Among all challenges, the spectrum allocation between two technologies is one problem. Most of the wireless operators favor to deploy both FAPs and MBSs on one single licensed spectrum and operate them simultaneously. It promotes the universal frequency reuse fashion and brings out high frequency reuse efficiency. However, this mode of operation is less suitable in an OFDMA-based two-tier cellular network. Through spectrum sharing, the network performance is strongly affected by the co-tier and cross-tier interference[29]. As QoS has been affected, a technique is required to resolve and manage the FemtoCells' radio resources.

The cross-tier and co-tier have different solutions to mitigate interference. For the co-tier, the cooperative resource allocation technique is used among the FemtoCells[29]. The example is based on clustering of FemtoCells. The cross-tier uses the radio resource allocation technique to mitigate interference and the examples are sub-channel and power allocation methods.

FemtoCells and the macrocell operate in a shared spectrum environment. FemtoCells have unique cell-IDs. All the FemtoCell user equipment is capable of performing interference measurements and reporting them to FAP_S. FemtoCells are equipped with the global position system (GPS) devices to obtain the accurate estimate of FemtoCells locations, so that FemtoCell clusters can be formed. Communication within FemotCells is only possible via air or backhaul. The FemtoCells are divided into disjoint clusters. The idea behind clustering is to divide the joint sub-channel and power allocation problems in the FemtoCell network into smaller sub-problems. Within each cluster one FemtoCell is elected as a head and is responsible for performing sub-channel and power allocations within the cluster. Clustering is simple done by grouping FemtoCells closely located to each other. Furthermore, the entire set of sub-channels is available to each cluster, and within a cluster no two FemtoCells transmit simultaneously on the same sub-channel.

Therefore no co-tier interference exists within a cluster. Various configurations are available for cluster sizes. The extreme situation is to have a grand cluster, where all FemtoCells are in one cluster. One benefit of this configuration is that it eliminates co-tier interference among FemtoCells. However, in addition to the huge burden imposed on the head to perform resource allocations, the share of each FemtoCell in the available spectrum is small. The other extreme is to let one FemtoCell acting independently, which means no clustering. In this case, each FemtoCell has the entire spectrum available and the complexity of resource allocations is the lowest. However, co-tier interference is severe[30],[31].

2.2 OFDMA Multi-RATs Network

Nowadays, the use of high-end mobile smart phones is gaining more attention, which in return requires wide deployment of advanced and improved wireless networks. Due to such rapid enhancements in mobile technologies, an exponentially increasing energy consumption both in the network and in the user equipment (UE)[32]-[37] is noticed, which leads towards a critical economic issue for the network operators. The network operator's operational expenditure has risen up to the half of their electricity bills[5]. Thus, an energy-efficient network is of paramount importance for the sustainability. Various wireless standards has adopted by OFDMA as one of the solution to tackle such a challange. The OFDMA system has been applied in [38]-[41], which gaves an energy-efficient solution on resource allocations. In this research, both circuit energy and transmission energy consumption is considered, and the properties of energy efficiency (EE) have been investigated and identified.

Recent research efforts on the integration and inter-operability of RATs with OFDMA have effectively improved the performance[36],[42]-[47]. According to [48]-[51], if the resources available among multiple radio access (MRA) networks are jointly and effectively utilized, a positive influence on the performance can be achieved. In particular, the concept of MRA systems is introduced, where the data stream of a UE is split into multiple sub-streams and transmitted simultaneously over multiple RATs. Some research results have been present in [52]-[56]. The RAT was selected for single transmissions schemes which are proposed in [57]-[59].

Recent researchers pay more attention on multi-RATs networks, specifically user connectivity and throughput in the single-carrier system to ensure energy-efficient design for the OFDMA system. The literature shows that the limitation on multi-carrier systems in applying energy-efficient on jointly multi-RATs wireless networks is complicated. To satisfying the QoS requirements of UE, some works have proposed resource allocation algorithms for the OFDMA system in resource allocations, such as subcarriers and powers across multiple RATs, to maximize the energy efficiency of the system[60],[61]. Several challenges and opportunities in the multi-RATs network were discussed in [60]. UE and RAT association in LTE and universal mobile telecommunications system (UMTS) based multi-RATs networks has been studied to minimize the total network energy consumption[61].

2.3 OFDMA FemtoCell Network

In order to meet the increasing demand for ubiquitous wireless coverage and high throughput, an enabling solution call FemtoCell—a dense small-cell heterogeneous network has been proposed[62],[63]. There is more active UE that can be packed into the same radio spectrum with a large number of small cells, which allows greater area spectral efficiency. The traditional site survey and network planning is no longer needed by FemtoCell, which makes it cost effectively and can be installed by end-users in a plug-and-play fashion. Indoor coverage can be improved, as a high signal-to-interference-plus-noise ratio (SINR) can be achieved, when FemtoCells lowers their transmit power.

Co-channel deployment is much more effective compared with orthogonal deployments, because it offers a higher spectral efficiency[64]-[67]. FemtoCell user equipment (FUE) uses the spectrum that is allocated to macrocell user equipment (MUE), hence making the signal interference issues arise[68],[69]. Cross-tier interference induced by FUE to MUE is limited, as the priority in accessing the underlying frequency bands is very strict. The task to manage the random and severe interference resulting from the deployment of numerous unplanned small cells remains a critical challenge.

OFDMA has been used as the air-interference technology by LTE-FemtoCell due to its flexibility in allocating the radio spectrum[70]. With OFDMA, the exclusive channel assignment helps to eliminate the intracellular interference. At any given time, only a sub-channel is assigned to at most one UE in each cell. An OFDM sub-channel can be shared by different UE from different cells as stated in co-channel deployment, which makes the problem on intercellular interference arise. The allocation of limited radio frequencies to different UE in multiple cells is another technical challenge in sub-channel assignment. An extensive study is required to address these combinational problems.

The downlink transmission of OFDMA-based FemtoCells in the joint allocation of resource blocks and transmit power was investigated in [71]. When a best-response adaptive strategy is applied, the formulated exact-potential game converge to a Nash Equilibrium is shown. As in [72], a joint sub-channel and binary power allocation algorithm was developed and only one transmitter was allowed to send signals on each sub-channel. The joint power allocation and scheduling problem in a coordinated OFDMA multicell network has been resolved in [73]-[75], they used the concept of a reference user to devise a low-complexity distributed scheme, where the weighted sum rate in the downlink of OFDMA-based heterogeneous networks was maximized. The suggested solutions in [73]-[77] are no longer applicable, if the minimum rate constraint is strictly imposed to guarantee the QoS of the preferential macrocell in such a network. There are various joint sub-channels and power allocation schemes for OFDMA FemtoCells proposed by [78] based on Lagrangian dual relaxation[76],[77]. These studies fixed the cross-tier interference from macrocell to FemtoCell, while the intra-tier inter-FemtoCell interference was ignored. This assumption helped to simplify the analysis remarkably. A computationally expensive global optimization method which may only be applicable to small-scale problems was presented by [79] where all the transmit power in an interference channel was jointly optimized. Exchanging the global network information was not easy in such a scenario, due to the random network deployment and limited backhaul capacity available for control and signaling purposes, making the existing centralized solutions in [73], [79], and [80] unsuitable to be done practically in wireless heterogeneous networks. New formulation for the downlink sub-channel and power allocation problem in an OFDMA-based heterogeneous network consisting of one macrocell and several FemtoCells is provided in this work. The network capacity of the prioritized macrocell is being protected regardless of any FemtoCell deployment. In the multiuser multicell heterogeneous network scenario, the data rate functions are highly non-convex and create challenges in managing the inter-cell interference caused by the sharing of radio spectrum among UE from different cells. The nontrivial task of assigning multiple OFDM sub-channels to individual UE in each cell to maximize the total FemtoCell throughput making the critical issue become more complicated. There is another challenge in finding an optimal solution for resource allocations with the requirement of satisfying a minimum data rate constraint for the FemtoCell.

An interactive algorithm that alternatively assigns OFDM sub-channels to UE and allocates transmit power to the base station (BS) is developed in order to solve the multi-dimensional problem. Every cell giving sub-channels to the serviced UE with the highest corresponding SINR is proved to be the optimal strategy that can solve the sub-channel assignment problems. The successive convex approximation (SCA) method[81] to solve the power allocation sub-problems is adopted, where the original highly non-convex problem will be transformed into a series of relaxed convex programs. Network setting considered in this paper is much more different from those in [80] and [82]. The digital subscriber line (DSL)[83] and multi-carrier homogeneous networks[73] make the existing solution be not directly applicable. The critical issue of interference in dense small-cell OFDMA-based heterogeneous networks with macrocell networks capacity protection is systematically addressed by adapting the SCA approach.

A sequence of geometric programs[84] after condensing polynomials into monomial has been solved by using the arithmetic-geometric means (AGM) approximation. Upon lower-bounding the highly non-concave rate function by a concave function[83] as in the logarithmic approximation, it can be simply dealt as the standard concave maximization problems. In the difference-of-two-concave-functions (D.C.) approximation, the difference of two concave functions[85]-[87] is used to represent the data rate and a set of improved feasible solutions is generated. Previous work[88] for the case of D.C. approximation has presented the effectiveness of the SCA-based approach. Based on the SCA approach, all the three power optimization policies are established and this approach eventually converges to locally optimal transmit power solutions for any given sub-channel allotment. It ensures that the macrocell sum rate is always above a prescribed value, and the overall joint sub-channel and power algorithm is shown to converge to a local maximum[89].

Network optimization for the case of AGM approximation is performed by a central processing unit, such as for an operation, administration, and management (OAM) server is proposed in terms of algorithm implementation[90]. In distributed implementation for the proposed algorithm for the logarithmic and D.C. approximation, individual BSs will compute the optimal OFDM sub-channel and power allocations for their own servicing cells. Such distributed solutions are particularly applicable to wireless heterogeneous networks, where FemtoCells are being deployed randomly and there is no network planning process needed.

2.4 OFDMA Relay Network

With the emergence of cooperative communication which allows better throughput, energy consumption, and cell coverage for overall better performance, the combination with OFDMA seems resulting in a promising structure that offers the possibility to reach many desirable objectives for future wireless networks[91]. However, there is a need for a good design with the radio resource allocation (RRA) principles which include the coordination of power and subcarrier allocations, as well as the selection of relay. An iterative algorithm was proposed in [92] to solve the subcarrier assignment together with the relay selection and power allocation problem. The authors in [93] introduced a closed-form solution for RRA for the multi hop cooperative relay network. A threshold method was used to solve the two sub-problems: the subcarrier allocation and power allocation in [94], and the asymmetric resource allocation was studied in [95].

The RRA algorithm plays an important role in either conventional or relay-aided OFDMA systems. The authors also emphasize the necessary of careful design and the coordination of the power and subcarrier allocation, selection of relay across multiple hops, as well as the optimization of resource asymmetric between the hops. The recent works on this field usually lack of the concerns toward the selection of relays, asymmetry of the source-to-relay, as well as relay-to-destination links. Two main concerns are focused on: firstly, the consideration on the problem of asymmetric RRA. The objective is to maximize the system throughput of the source-to-destination link with limited information and various constrains. It is implemented by optimizing the set of collaborative relays and link asymmetries together with subcarrier and power allocations. Secondly, the target of the proposed scheme is to enhance the total system throughput, when only the estimated channel-state information (CSI) is available at the source and so the CSI is really needed for the resource allocation. Since the channel capacity in the presence of imperfect CSI is unknown, the conditional capacity expectation as the performance metric is applied[96]. Not all of channel-state information is perfect; most of it is not perfect. Most of the recent works assumed the perfect channel-state information to be available at the source. In [87], the system model design was proposed, where two hops were introduced. In this model, AP delivers information data to a cluster of de-code-and-forward (DF) relays in the first hop, and relays cooperate to transmit the information data to the UE in the second hop, so that the spatial diversity gain can be achieved.

In [87], it was assumed that there were total Z relays in the network, and the selected relay cluster $K=\{1, 2, \cdots, k, \cdots, K\}$ contains K potential half-duplex relays. The direct link from AP to UE is not considered due to the distance or any other obstacles especially when relays are deployed for cell extension. One of the assumptions is the transmission time for the first and second hops can be different. The data rate in the first hop is influenced by the rate of links between AP and the selected relays. An adaptive algorithm is introduced to solve the problem. The problem of the resource allocation is combinatorial in nature with its non-convex structure, however, it shows that regardless of its convexity, with the condition of time sharing, the duality gap of the optimization problem can be negligible. Therefore, it can be solved in the dual domain with the asymptotically optimal solution.

With the assumption made by the authors, when the number of subcarriers is large enough, the duality gap of the primal problem and duality function can be negligible[97]. After the comparison between the algorithms, it shows that 32 subcarriers would be large enough to make the gap be minor. This assumption is true when considering the specification of LTE, where the subcarrier’s number is much larger than 32. Thus, the problem can be solved by minimizing the dual function $g(\lambda, \mu)$. There are more than one way that can be used to minimize $g(\lambda, \mu)$ and find the dual point which is guaranteed convergence. This is due to the fact that a dual function is always convex[98]. The subgradient method in [84] derived the subgradient of $g(\lambda, \mu)$ with the optimal power allocation P^*, and the detailed algorithm can be viewed in [84].

The subgradient algorithm is guaranteed to be converged to the global optimal λ and μ. The computational complexity for the algorithm is considered polynomial with the dual variable $K+1$. By solving the three sub-problems, which are the relay set selection, subcarrier, and power and asymmetry allocations, it is believed to be able to solve the optimization problem. Since the relay selection and subcarrier allocation have been done, the time slot for the hop can be obtained by using Karush-Kuhn-Tucker (KKT) conditions[98],[99]. Even with the imperfect channel state information, by using the approximation method, the power allocation is able to be gotten. After the relay selection and subcarrier allocation have been done, the resource allocation with essential parameters also can be solved.

3. Discussion and Comparison Analysis

3.1 OFDMA Two-Tier Cellular Network

FemtoCells, which are small cells overlaying the macrocells, are able to enhance the coverage and capacity of cellular wireless networks, especially the indoor coverage. FemtoCells or FAPs, which are small and low powered base stations, are more cost-effective to be used to enhance the indoor coverage compared with macrobase stations (MBSs). FAPs are able to improve the indoor coverage by providing the radio coverage to UE. FAPs are also used to fulfill the huge demand of network capacity for the next generation cellular wireless networks. The biggest challenge in the deployment of FemtoCells over the existing macrocell networks is the spectrum allocation between FemtoCells and macrocell networks. In order to maximize the high frequency reuse efficiency, co-channel deployment is mostly chosen by wireless operators, where the FAPs and MBSs operate on the same licensed spectrum simultaneously in a universal frequency reuse fashion. However, the network performance significantly degrades due to the co-tier and cross-tier inerference in OFDMA-based two-tier cellular networks with spectrum sharing among FemtoCells and macrocells. Interference mitigation techniques must be developed to manage the radio resources of FemtoCells to achieve the QoS requirements for all the users. RRA methods for the FemtoCells and the cooperative resource allocation among the FemtoCells are used to mitigate the cross-tier and co-tier interference.

Even though the centralized interference management in two-tier cellular networks with OFDMA is able to yield optimal/near-optimal performance, however, with the computational complexity issue, it is impractical to apply in the real world. Distributed interference management in a two-tier cellular network with OFDMA is easier and practical to be implemented compared with centralized solution interference management, but it losts the superiority of centralized scheme. Therefore, in order to obtain optimal/near optimal performance but with less computational complexity, a semi-distributed interference scheme is proposed. The proposed semi-distributed interference management scheme is based on joint clustering and resource allocations for FemtoCells.

3.2 OFDMA Multi-RATs Network

OFDMA has been adopted in various wireless standards networks including 3GPP-LTE, wireless local area network (WLAN), and the worldwide interoperability for microwave access (WiMAX) technologies. Besides that, the energy and transmission energy consumption need to be consideration in the OFDMA system, and the properties of the energy efficiency have been investigated. Through the growing concern about the energy consumption, the considered of the energy-efficient has been designed in the multi-RAR network. A study has been conducted to minimize the energy consumption in the total network by the user and RAT association in LTE and UMTS. Moreover, the energy-efficient parallel transmission scheme is proposed to find the extremely traffic splitting to maximize the system energy efficiency by using the point-to-point scenario with single carrier-based multiple RATs. The energy-efficient relaying scheme in a cooperative multi-RATs network is proposed for switched-RAT. The multi-RATs network focuses on the user connectivity and the throughput in a single carrier system. The energy-efficient design for OFDMA has been mainly confined to a single RAT network. However, there is limited work on energy-efficient design jointly considering a multi-carriers system in a multi-RATs wireless network.

Besides, the energy efficiency maximization for multiuser downlink OFDMA cellular networks with user cooperation has been proposed to jointly optimize the power and subcarrier allocations and relay selection considering QoS providing to users. Furthermore, the energy-efficient design in OFDMA multi-RATs networks is becoming increasingly important. The near-optimal resource allocation strategies address the energy-efficient resource allocation (e.g., subcarriers and powers) for OFDMA systems in a multi-RATs network in order to maximize the system energy efficiency, while satisfying the QoS requirements of UE. And the system model in the multi-RATs network is also proposed to optimize the problem. In the system description of a single cell OFDMA based multi-RATs network, each RAT is assumed frequency synchronization. And the channel gain at each subcarrier in each RAT is to remain a constant during the time of interest. Since different RATs operate at different frequencies, the heterogeneous network is assumed and there is no interference between the RATs. Besides that, also assume a central control unit performs multi-radio resource management (MRRM) and facilitates parallel transmission among the RATs. For the parallel transmission, the desired data can be split into multiple sub-streams for multiple RATs to transmit simultaneously, the data to each multimode UE (MMU) transmitted from multiple RATs can be recovered.

Therefore, the maximum of energy efficiency can be achieved by jointly optimizing the set of active RATs and subcarrier assignment for the given RATs. There are some solutions requiring the exhaustively search for over-all possible combinations to the active RATs and corresponding resource allocations. Besides that, the RAT selection is on the large time scale based on the average of daily traffic load profile and obtained from long-term observations. It can be concluded that, through the investigation of energy-efficient resource allocations for the downlink OFDMA-based multi-RATs network, different RATs operate with different system configurations.

3.3 OFDMA FemtoCell Network

The FemtoCell has been used as a solution to meet the increasing demand for the ubiquitous wireless network coverage and higher throughput. In FemtoCell networks, numbers of small cells enable more active UE, which can be packed into one given area of the same radio spectrum. This has enabled a greater area spectral efficiency. FemtoCells are highly cost-effectively as the network planning process and traditional site survey are no longer needed. FemtoCell's transmit power can be lowered and a better SINR can be archived because of the close transmitter-receiver proximity.

A joint sub-channel and power allocation algorithm for the downlink deployment of an OFDMA mixed FemtoCells network has maximized the total throughput of all FUE while the network capacity is protected. The algorithm using an iterative approach where the transmit power of BS and OFDM sub-channels is alternatively assigned and optimized. OFDMA is a flexible technology, therefore, it has been used as an air-interface technology for FemtoCells. The intracellular interference is eliminated because of the exclusive channel assignment. Exclusive channel assignment defines that at any given time, there is only a sub-channel allotted to one UE. The iterative scheme can be used to solve the joint power allocation problem and the scheduling problem in the coordinated OFDMA multicell network. A low complexity distributed scheme can maximize the weighted sum rate in downlink, but it will affect the QoS of the preferential macrocell.

A new formulation has been proposed, which considers both downlink sub-channel and power allocation problems in the OFDMA-based heterogeneous network. This OFDMA-based heterogeneous network consists of one macrocell and several FemtoCells. These formulas protect the network capacity of the prioritized macrocell. But the FemtoCell deployment is not considered. The sharing of radio spectrum among the UE from different cells makes the management of intercellular interference more complicated. And it is critical to maximize the throughput of each cell. It is difficult to manage this problem as the minimum data rate needs to be ensured. An iterative formula has been proposed to solve the problems, which alternatively assigns OFDM sub-channels to UE and allocates the power to transmit. To overcome the problem of power allocations, a successive convex approximation (SCA) method has been used. By using SCA, the nonconvex problem is transformed into a series of relaxed convex programs.

The arithmetic-geometric mean (AGM) approximation can help to solve the problem, which relates to the geometric programs. AGM helps to condense a polynomial into a monomial. The SCA approach is effective in solving the data rate problem. It eventually converges to the local optimal transmit power solutions for any sub-channel. It not only ensures the macrocell sum rate above a prescribed value, but also overall joints the sub-channel and power allocation algorithm, and converges to a local maximum.

3.4 OFDMA Relay Network

In the relay network, the joint optimization problem for RRA can be solved by addressing the opportunistic selection of collaborative relays, allowing different durations between the two hops, the subcarriers and power allocation aiming to maximize the expected system throughput. A proper resource allocation scheme that allows imperfect CSI for different hops is able to significantly increase the cell-edge throughput. The set of collaborative relays and link asymmetries together with subcarrier and power allocations can be optimized by using the proposed solutions. The RRA needs to be designed carefully. The selection of relays across the different hops and the resources asymmetric optimization between the hops can be ensured by carefully design and coordination of the power and subcarrier allocations.

All the fundamental properties: the resource allocation for the relays, link asymmetry, selection of the relay, and imperfection in CSI are considered. The total system throughput can be enhanced only if the estimated CSI is available at the source. The direct link from the source to destination is not considered because the relays are deployed for extending the cell coverage. Furthermore, a subcarrier allocation scheme and a relay selection method have been proposed, which allows a set of relays to obtain the best data rate for the link selected. In this method, the power is allocated to the source and relays under per-node constraints, which is more effective than only considering the sum of the whole system power. The comparison analysis of resource allocations in OFDMA based networks is shown in Table 1.

4. Future Trends of OFDMA Based Networks

The rapid development of mobile communications makes the services diversified and it demands a higher requirement on the system bandwidth and the data transfer rate to support high data rate wireless multimedia services, while the traditional cellular network has been unable to meet the needs of the high speed rate and the high quality of service. Among the OFDMA based networks:

Table 1: Comparison analysis of resource allocations in OFDMA based networks

Network	Strength	Weakness
OFDMA cellular network	• Enhance coverage and capacity of cellular wireless network • Increase spectrum efficiency • Improve indoor coverage • Cost effective • Energy-efficient • Fulfill the rising demand with the limited resources • Improve QoS and data rate of mobile data traffic	• Management of both the cross-tier and co-tier interference o Centralized solution ▪ Impractical due to computational complexity o Distributed solution ▪ Lack of superiority of centralized schemes • Spectrum allocations between FemtoCell and macrocell networks • No two FemtoCells in the same cluster on the same sub-channel • Multiple user corporative OFDMA system is hard to solve • Cost effective issue, when the solution does not meet requirement • Not effective to use macro base station to improve network coverage as it is costly
OFDMA multi-RATs network	• Improve the energy consumption in both network and user equipment with RAT network	• Limitation and complicated on multi- carrier system to applying energy-efficiently with jointly multi-RATs wireless networks
OFDMA FemtoCell network	• Increasing demand for ubiquitous wireless coverage and high throughput • Offer a higher spectral efficiency	• Improve indoor coverage as high signal to interference-plus-noise-ration, the FemtoCell need lower their transmit power
OFDMA relay network	• Reduce or cancel channel noise and multipath effect • Better throughput • Better energy consumption • Cell coverage for overall better performance	• Need for a good design in RRA principles which include the coordination of power and subcarrier allocations, as well as selection of relay

1) two-tier cellular network, 2) multi-RATs technology, 3) FemtoCell network, and 4) relay network, the combination of the relay and OFDMA is a trend of future mobile communications networks. This is because the entire bandwidth is split into a plurality of parallel carriers which can reduce the influence of frequency selective fading in the broadband system and improve the spectrum utilization by eliminating inter-symbol interference. Introducing the technologies of OFDMA and relays to the system at the same time can provide better flexibility for the resource allocation, for example, using subcarrier allocations, scheduling, and power control to obtain multi-dimension diversity gains.

The next-generation wireless communication technology standards such as LTE-A and WiMAX both use this potential relay network architecture based on the OFDMA technology introducing the relay station to assist the BS to complete the data communication. On the other hand, OFDMA is the evolution of OFDM which is treated as the technical basis of the fourth generation mobile communication standard and has become a mainstream choice. Introducing relay stations can effectively expand the cell coverage, improve the users' QoS in the cell edge and the system throughput. Meanwhile, because of the ability of anti-multipath, it improves the system's spectral efficiency and the flexible allocation of resources. Besides that, the relay as one of the essential techniques in the future network has lower arrangement and maintenance costs. And integrating relay nodes into traditional cellular networks can overcome the near-far effect in the wireless communication system due to the scarcity of frequency resources. The future mobile communication will use the carrier higher than 2 GHz which can improve the performance of the future network.

At the energy crisis today, energy-saving emission reduction and promoting green communications are major problems for the communication industry to face. But the power and signaling overhead brought by relay stations is inevitable. Therefore, it is meaningful to do research on the resource allocation problem of the mobile relay system, especially the system energy efficiency problem. Thus, thr research aiming at the problem of resource allocation and intending to increase the system performance through improving the algorithm of resource allocations in OFDMA systems will be highly demanded in the near future in the current research of resource management that mainly focus on three aspects, namely, the resource control, resource allocation, and resource scheduling.

5. Conclusions

Most of the broadband cellular wireless network organizations are planning to deploy green OFDMA in their daily operations to seek the benefits provided by the OFDMA technology. The green OFDMA technique is designed in such a way that it matches with the organizations' requirements, allowing high data rate transmissions with an energy-efficient mechanism. The resource allocations in OFDMA sub-channels from subcarriers are an important concept in OFDMA systems to mitigate the inter-cell interference and cope with network traffic and channel fluctuations in space and time. Some studies have been done on dynamic resource allocations in various OFDMA networks such as cellular, multi-RATs, FemtoCells, and relay networks to address the energy constraint, computational complexity, and sub-channel assignment problems. In this paper, we have provided the basic definition of OFDMA and highlighted various issues related to resource allocations for OFDMA based networks. Furthermore, we presented some discussion and comparison analysis, and future trends were also discussed.

References

[1] Z. Chang, T. Ristaniemi, and Z.-S. Niu, "Radio resource allocation for collaborative OFDMA relay networks with imperfect channel state information," *IEEE Trans. on Wireless Communications*, vol. 13, no. 5, pp. 2824-2835, May 2014.

[2] H. Ekstrom, A. Furuskar, J. Karlsson, M. Meyer, J. Torsner, and M. Wahlqvist, "Technical solution for the 3G long-term evoluation," *IEEE Communications Magazine*, vol. 44, no. 3, pp. 38-45, Mar. 2006.

[3] M. S. Gast, *802.11 Wireless Networks*, 2st ed. Boston: O'Reilly Publications, April 2005.

[4] S. Srikanth, V. Kumaran, and M. C. Murugesapandian. Orthogonal frequency division multiple access: Is it the multiple access system of the future? [Online]. Available: http://www.au-kbc.org/comm/Docs/Tutorils/OFDMA_BCW_cv6.pdf

[5] The 3rd Generation Partnership Project. (March 2010). Telecommunication management; Study on energy savings management (ESM). *Sophia-Antipolis Cedex, France, Tech. Rep. TR 32.826*. [Online]. Available: http://www.3gpp.org/ftp/Specs/html-info/32826.htm

[6] G.-Y. Li, Z.-K. Xu, G. Xiong, C.-Y. Yang, Y. Chen, and S.-G. Xu, "Energy-efficient wireless communications: Tutorial, survey, open issues," *IEEE Trans. Wireless Communications*, vol. 18, no. 6, pp. 28-35, Dec. 2011.

[7] E. Hossain, D. I. Kim, and V. K. Bhargava, *Cooperative Cellular Wireless Networks*. Cambridge: Cambridge University Press, 2011.

[8] Z. Hasan, H. Boostanimehr, and V. K. Bhargava, "Green cellular networks: A survey some research issues and challenges," *IEEE Communications Surveys & Tutorials Home*, vol. 13, no. 4, pp. 524-540, Nov. 2011.

[9] J. N. Laneman, D. N. C. Tse, and G. W. Wornell, "Cooperative diversity in wireless networks: Efficient protocols and outage behavior," *IEEE Trans. on Information Theory*, vol. 50, no. 12, pp. 3062-3080, Dec. 2004.

[10] R. Pabst, B. H. Walke, and D. C. Schultz, "Relay-based deployment concepts for wireless and mobile broadband radio," *IEEE Communications Magazine*, vol. 42, no. 9, pp. 80-89, Sep. 2004.

[11] Y. Yang, H. Hu, J. Xu, and G. Mao, "Relay technologies for WiMax and LTE-advanced mobile systems," *IEEE Communications Magazine*, vol. 47, no. 10, pp. 100-105, Oct. 2009.

[12] K. T. K. Cheung, S. Yang, and L. Hanzo, "Achieving maximum energy-efficiency in multi-relay OFDMA cellular networks: A fractional programming approach," *IEEE Trans. on Communications*, vol. 61, no. 7, pp. 2746-2757, Jul. 2013.

[13] D. W. K. Ng and R. Schober, "Cross-layer scheduling for OFDMA amplify-and-forward relay networks," *IEEE Trans. on Vehicular Technology*, vol. 59, no. 3, pp. 1443-1458, Mar. 2010.

[14] A. Sendonaris, E. Erkip, and B. Aazhang, "User cooperation diversity. Part I. System description," *IEEE Trans. on Communications*, vol. 51, no. 11, pp. 1927-1938, Nov. 2003.

[15] M. Nokleby and B. Aazhang, "User cooperation for energy-efficient cellular communications," in *Proc. of IEEE Intl. Conf. on Communications*, Cape Town, 2010, pp. 1-5.

[16] A. Doufexi and S. Armour, "Design considerations and physical layer performance results for a 4G OFDMA system employing dynamic subcarrier allocation," in *Proc. of IEEE 16th Intl. Symposium on Personal, Indoor and Mobile Radio Communications*, Berlin, 2005, pp. 357-361.

[17] X. Deng and A. M. Haimovich, "Power allocation for cooperative relaying in wireless networks," *IEEE Communications Letters*, vol. 9, no. 11, pp. 994-996, Nov. 2005.

[18] M. S. Alam, J. W. Mark, and X. Shen, "Relay selection and resource allocation for multi-user cooperative OFDMA networks," *IEEE Trans. on Wireless Communications*, vol. 12, no. 5, pp. 2193-2205, May 2013.

[19] C.-Y. Wong, R.-S. Cheng, K. B. Lataief, and R. D. Murch, "Multiuser OFDM with adaptive subcarrier, bit, power allocation," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 10, pp. 1747-1758, Oct. 1999.

[20] W. Dang, M. Tao, H. Mu, and J. Huang, "Subcarrier-pair based resource allocation for cooperative multi-relay OFDM systems," *IEEE Trans. on Wireless Communications*, vol. 9, no. 5, pp. 1640-1649, May 2010.

[21] S. Mallick, R. Devarajan, M. Rashid, and V. K. Bhargava, "Resource allocation for selective relaying based cellular wireless system with imperfect CSI," *IEEE Trans. on Communications*, vol. 61, no. 5, pp. 1822-1834, May 2013.

[22] K. Vardhe, D. Reynolds, and B. D. Woerner, "Joint power allocation and relay selection for multiuser cooperative communication," *IEEE Trans. on Wireless Communications*, vol. 9, no. 4, pp. 1255-1260, Apr. 2010.

[23] D. W. K. Ng, E. S. Lo, and R. Schober, "Wireless information and power transfer: Energy efficiency optimization in OFDMA systems," *IEEE Trans. on Wireless Communications*, vol. 12, no. 12, pp. 6352-6370, Dec. 2013.

[24] G. Miao, N. Himayat, Y. Li, and D. Bormann, "Energy-efficient design in wireless OFDMA," in *Proc. of IEEE Intl. Conf. on Communications*, Beijing, 2008, pp. 3307-3312.

[25] Z. Hasan, G. Bansal, E. Hossain, and V. K. Bhargava, "Energy-efficient power allocation in OFDM-based cognitive radio systems: A risk-return model," *IEEE Trans. on Wireless Communications*, vol. 8, no. 12, pp. 6078-6088, Dec. 2009.

[26] G. Miao, N. Himayat, and Y. Li, "Energy-efficient link adaptation in frequency-selective channels," *IEEE Trans. on Communications*, vol. 58, no. 2, pp. 545-554, Feb. 2010.

[27] T. Zahir, K. Arshad, A. Nakata, and K. Moessner, "Interference management in FemtoCells," *IEEE Communications Surveys and Tutorials*, vol. 15, no. 1, pp. 293-311, Feb. 2013.

[28] N. Saquib, E. Hossain, L. B. Le, and D. I. Kim, "Interference management in OFDMA FemtoCell networks: Issues and approaches," *IEEE Wireless Communications*, vol. 19, no. 3, pp. 86-95, Jun. 2012.

[29] X. Li, L. Qian, and D. Kataria, "Downlink power control in co-channel macrocell FemtoCell overlay," in *Proc. of the 43rd Annual Conf. on Information Sciences and Systems*, Baltimore, 2009, pp. 383-388.

[30] G. Cao, D. Yang, X. Ye, and X. Zhang, "A downlink joint power control and resource allocation scheme for co-channel macrocell-FemtoCell networks," in *Proc. of IEEE Wireless Communications and Networking Conf.*, Cancun, 2011, pp. 281-286.

[31] F. Cao and Z. Fan, "Power loading and resource allocation for FemtoCells," in *Proc. of IEEE Vehicular Technology Conf.*, Budapest, 2011, pp. 1-5.

[32] Y. Chen, S. Zhang, S. Xu, and Y. G. Li, "Fundamental trade-offs on green wireless networks," *IEEE Communications Magazine*, vol. 49, no. 6, pp. 30-37, June 2011.

[33] G. Miao, N. Himayat, Y. G. Li, and A. Swami, "Cross-layer optimization for energy-efficient wireless communications: A survey," *Wireless Communications and Mobile Computing*, vol. 9, no. 4, pp. 529-542, Apr. 2009.

[34] Y. G. Li, Z. Xu, C. Xiong, C. Yang, S. Zhang, Y. Chen, and S. Xu, "Energy-efficient wireless communications: Tutorial, survey, and open issues," *IEEE Communications Magazine*, vol. 18, no. 6, pp. 28-35, Dec. 2011.

[35] D. Feng, C. Jiang, G. Lim, L. J. Cimini, G. Feng, and Y. G. Li, "A survey of energy-efficient wireless communications," *IEEE Communications Surveys & Tutorials*, vol. 15, no. 1, pp. 167-178, Feb. 2013.

[36] M. Ismail and W. Zhuang, "Network cooperation for energy saving in green radio communications," *IEEE Wireless Communications*, vol. 18, no. 5, pp. 76-81, Oct. 2011.

[37] D. Astely, E. Dahlman, G. Fodor, S. Parkvall, and J. Sachs, "LTE release 12 and beyond," *IEEE Communications Magazine*, vol. 51, no. 7, pp. 154-160, Jul. 2013.

[38] G. Miao, N. Himayat, and G. Y. Li, "Energy-efficient link adaptation in frequency-selective channels," *IEEE Wireless Communications*, vol. 58, no. 2, pp. 545-554, Feb. 2010.

[39] R. S. Prabhu and B. Daneshrad, "An energy efficient waterfilling algorithm for OFDM systems," in *Proc. of IEEE*

Intl. Conf. on Communications, Cape Town, 2010, DOI: 10.1109/ICC.2010.5502818

[40] C. Isheden and G. P. Fettweis, "Energy-efficient multi-carrier link adaptation with sum rate-dependent circuit power," in *Proc. of IEEE Intl. Conf. on Communications*, Cape Town, 2010, DOI: 10.1109/GLOCOM.2010.5683700

[41] C. Xiong, Y. G. Li, S. Zhang, Y. Chen, and S. Xu, "Energy-efficient resource allocation in OFDMA networks," *IEEE Trans. on Communications*, vol. 60, no. 12, pp. 3767-3778, Dec. 2012.

[42] C. Xiong, Y. G. Li, S. Zhang, Y. Chen, and S. Xu, "Energy- and spectral efficiency tradeoff in downlink OFDMA networks," *IEEE Wireless Communications*, vol. 10, no. 1, pp. 3874-3886, Nov. 2011.

[43] J. Luo, R. Mukerjee, M. Dillinger, E. Mohyeldin, and E. Schulz, "Investigation of radio resource scheduling in WLANs coupled with 3G cellular network," *IEEE Communications Magazine*, vol. 41, no. 6, pp. 108-115, Jun. 2003.

[44] R. Ferrus, O. Sallent, and R. Agusti, "Interworking in heterogeneous wireless networks: Comprehensive framework and future trends," *IEEE Wireless Communications*, vol. 17, no. 2, pp. 22-31, Apr. 2010.

[45] S. Yeh, S. Talwar, G. Wu, N. Himayat, and K. Johnsson, "Capacity and coverage enhancement in heterogeneous networks," *IEEE Wireless Communications*, vol. 18, no. 3, pp. 32-38, Jun. 2011.

[46] N. Niebert, A. Schieder, H. Abramowicz, C. Prehofer, and H. Karl, "Ambient network: An architecture for communication networks beyond 3G," *IEEE Wireless Communications*, vol. 12, no. 2, pp. 14-21, Apr. 2004.

[47] E. Gustafsson and A. Jonsson, "Ambient network: An architecture for communication networks beyond 3G," *IEEE Wireless Communications*, vol. 10, no. 1, pp. 49-55, Feb. 2003.

[48] A. Furuskar and J. Zander, "Multiservices allocation for multi-access wireless systems," *IEEE Wireless Communications*, vol. 4, no. 1, pp. 174-184, Jan. 2005.

[49] P. Magnusson, F. Berggren, I. Karla, R. Litjens, F. Meago, H. Tang, and R. Veronesi, "Multi-radio resource management for communication networks beyond 3G," in *Proc. of IEEE the 62nd VTC-2005-Fall*, 2005, pp. 1653-1657.

[50] S. Merlin, N. Vaidya, and M. Zorzi, "Resource allocation in multi-radio multi-channel multi-hop wireless networks," in *Proc. of the 27th Conf. on Computer Communications*, Phoenic, 2008, DOI: 10.1109/INFOCOM.2008.110

[51] J. Acharya and R. D. Yates, "Dynamic spectrum allocation for uplink users with heterogeneous utilities," *IEEE Trans. on Wireless Communications*, vol. 8, no. 3, pp. 1405-1413, Mar. 2009.

[52] Y. Choi, H. Kim, S.-W. Han, and Y. Han, "Joint resource allocation for parallel multi-radio access in heterogeneous wireless networks," *IEEE Wireless Communications*, vol. 9, no. 11, pp. 3324-3329, Nov. 2010.

[53] Y. Choi, Y. Lee, and J. M. Cioffi, "Optimization of cooperative interoperability in heterogeneous networks with cognitive ability," *IEEE Communications Letter*, vol. 15, no. 11, pp. 1178-1180, Nov. 2011.

[54] A. Bazzi, G. Pasolini, and O. Andrisano, "Multiradio resource management: Parallel transmission for higher throughput?" *EURASIP J. Advances in Signal Processing*, vol. 2008, 2008, DOI: 10.1155/2008/763264

[55] J. Miao, Z. Hu, K. Yang, C. Wang, and H. Tian, "Joint power and bandwidth allocation algorithm with QoS support in heterogeneous wireless networks," *IEEE Communications Letters*, vol. 16, no. 4, pp. 479-481, Apr. 2012.

[56] M. Ismail, A. Abdrabou, and W. Zhuang, "Cooperative decentralized resource allocation in heterogeneous wireless access medium," *IEEE Trans. on Wireless Communications*, vol. 12, no. 2, pp. 714-724, Feb. 2013.

[57] K. Khawam, M. Ibrahim, J. Cohen, S. Lahoud, and S. Tohme, "Individual vs. global radio resource management in a hybrid broadband network," in *Proc. of IEEE Intl. Conf. on Communications*, Kyoto, 2011, pp. 1-6.

[58] F. Moety, M. Ibrahim, S. Lahoud, and K. Khawam, "Distributed heuristic algorithms for RAT selection in wireless heterogeneous networks," in *Proc. of IEEE Wireless Communications and Networking Conf.*, Shanghai, 2012, pp. 2220-2224.

[59] Y. Wu, H. Viswanathan, T. Klein, M. Haner, and R. Calderbank, "Capacity optimization in networks with heterogeneous radio access technologies," in *Proc. of IEEE Globe Telecommunications Conf.*, Kathmandu, 2011, pp. 1-5.

[60] S. Navaratnarajah, A. Saeed, M. Dianati, and M. A. Imran, "Energy efficiency in heterogeneous wireless access networks," *IEEE Wireless Communications*, vol. 20, no. 3, pp. 37-43, Oct. 2013.

[61] E. Pollakis, R. L. G. Cavalcante, and S. Stanczak, "Enhancing energy efficient network operation in multi-RAT cellular environments through sparse optimization," in *Proc. of IEEE 14th Workshop on Signal Processing Advances in Wireless Communications*, Darmstadt, 2013, pp. 260-264.

[62] V. Chandrasekhar, J. G. Andrews, and A. Gatherer, "Femtocell networks: A survey," *IEEE Communications Magazine*, vol. 46, no. 9, pp. 59-67, Sept. 2008.

[63] C. Patel, M. Yavuz, and S. Nanda, "FemtoCells [industry perspectives]," *IEEE Wireless Communications*, vol. 17, no. 5, pp. 6-7, Oct. 2010.

[64] J. Andrews, H. Claussen, M. Dohler, S. Rangan, and M. Reed, "FemtoCells: Past, present, and future," *IEEE Journal of Selected Areas in Communications*, vol. 30, no. 3, pp. 497-508, Apr. 2012.

[65] G. de la Roche, A. Valcarce, D. Lopez-Perez, and J. Zhang, "Access control mechanisms for FemtoCells," *IEEE Communications Magazine*, vol. 48, no. 1, pp. 33-39, Jan. 2010.

[66] M. Yavuz, F. Meshkati, S. Nanda, A. Pokhariyal, N. Johnson, B. Raghothaman, and A. Richardson, "Interference management and performance analysis of UMTS/HSPA+ FemtoCells," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 102-109, Sept. 2009.

[67] J.-H. Yun and K. Shin, "Adaptive interference management of OFDMA FemtoCells for co-channel deployment," *IEEE Journal of Selected Areas in Communications*, vol. 29, no. 6, pp. 1225-1241, June 2011.

[68] V. Chandrasekhar, J. G. Andrews, T. Muharemovic, and Z. Shen, "Power control in two-tier FemtoCell networks,"

IEEE Trans. on Wireless Communications, vol. 8, no. 8, pp. 4316-4328, Aug. 2009.

[69] D. Lopez-Perez, I. Guvenc, G. de la Roche, M. Kountouris, T. Quek, and J. Zhang, "Enhanced intercell interference coordination challenges in heterogeneous networks," *IEEE Wireless Communications Magazine*, vol. 18, no. 3, pp. 22-30, Jun. 2011.

[70] D. Lopez-Perez, A. Valcarce, G. de la Roche, and J. Zhang, "OFDMA FemtoCells: A roadmap on interference avoidance," *IEEE Communications Magazine*, vol. 47, no. 9, pp. 41-48, Sep. 2009.

[71] L. Giupponi and C. Ibars, "Distributed interference control in OFDMA based FemtoCells," in *Proc. of the 21st Annual IEEE Intl. Symposium on Personal, Indoor and Mobile Radio Communications*, Instanbul, 2010, pp. 1201-1206.

[72] J. Kim and D.-H. Cho, "A joint power and subchannel allocation scheme maximizing system capacity in indoor dense mobile communication systems," *IEEE Trans. on Vehicular Technology*, vol. 59, no. 9, pp. 4340-4353, Nov. 2010.

[73] L. Venturino, N. Prasad, and X. Wang, "Coordinated scheduling and power allocation in downlink multicell OFDMA networks," *IEEE Trans. on Vehicular Technology*, vol. 58, no. 6, pp. 2835-2848, Jul. 2009.

[74] T. Wang and L. Vandendorpe, "Iterative resource allocation for maximizing weighted sum min-rate in downlink cellular OFDMA systems," *IEEE Trans. on Signal Processing*, vol. 59, no. 1, pp. 223-234, Jan. 2011.

[75] K. Son, S. Lee, Y. Yi, and S. Chong, "REFIM: A practical interference management in heterogeneous wireless access networks," *IEEE Journal of Selected Areas in Communications*, vol. 29, no. 6, pp. 1260-1272, Jun. 2011.

[76] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization of multicarrier systems," *IEEE Trans. on Communications*, vol. 54, no. 7, pp. 1310-1322, Jul. 2006.

[77] H. Zhang, W. Zheng, X. Chu, X. Wen, M. Tao, A. Nallanathan, and D. Lopez-Perez, "Joint subchannel and power allocation in interference limited OFDMA FemtoCells with heterogeneous QoS guarantee," in *Proc. of IEEE Global Telecommunication. Conf.*, Anaheim, CA, 2012, pp. 4794-4799.

[78] L. Li, C. Xu, and M. Tao, "Resource allocation in open access OFDMA FemtoCell networks," *IEEE Wireless Communications Letter*, vol. 1, no. 6, pp. 625-628, Dec. 2012.

[79] L. Qian, Y. Zhang, and J. Huang, "MAPEL: Achieving global optimality for a non-convex wireless power control problem," *IEEE Trans. Wireless Communications*, vol. 8, no. 3, pp. 1553-1563, Mar. 2009.

[80] H. H. Kha, H.-D. Tuan, and H. H. Nguyen, "Fast global optimal power allocation in wireless networks by local D.C. programming," *IEEE Trans. Wireless Communications*, vol. 11, no. 2, pp. 510-515, Feb. 2012.

[81] B. R. Marks and G. P. Wright, "A general inner approximation algorithm for nonconvex mathematical programs," *Operations Research*, vol. 26, no. 4, pp. 681-683, 1978.

[82] M. Chiang, C. W. Tan, D. P. Palomar, D. O'Neill, and D. Julian, "Power control by geometric programming," *IEEE Trans. on Wireless Communications*, vol. 6, no. 7, pp. 2640-2651, Jul. 2007.

[83] J. Papandriopoulos and J. S. Evans, "SCALE: A low-complexity distributed protocol for spectrum balancing in multiuser DSL networks," *IEEE Trans. on Information Theory*, vol. 55, no. 8, pp. 3711-3724, Aug. 2009.

[84] S. Boyd and L. Vandenberghe, *Convex Optimization*, London: Cambridge University Press, 2004.

[85] H.-D. Tuan, S. Hosoe, and H. Tuy, "D.C. optimization approach to robust controls: The optimal scaling value problem," *IEEE Trans. on Automatic Control*, vol. 45, pp. 1903-1909, Sep. 2000.

[86] M. Frank and P. Wolfe, "An algorithm for quadratic programming," *Naval Research Logistics*, vol. 3, no. 1-2, pp. 95-110, 1956.

[87] Z. Chang, T. Ristaniemi, and Z. S. Niu, "Radio resource allocation for collaborative OFDMA relay networks with imperfect channel state information," *IEEE Trans. on Wireless Communications*, vol. 13, no. 5, pp. 2824-2835, May 2014.

[88] S. Sadr, A. Anpalagan, and K. Raahemifar, "Radio resource allocation algorithms for the downlink of multiuser OFDM communication systems," *IEEE Communications Surveys Tutorials*, vol. 11, no. 3, pp. 92-106, Aug. 2009.

[89] *Wireless LAN Medium Access Control and Physical Layer Specifications: High-speed Physical Layer in the 5 GHz Band*, IEEE 802.11 Standard, Sep. 1999.

[90] *IEEE Standard for Local and Metropolitan Area Networks Part 16: Air Interface*, IEEE Standard 802.16-2011, Jun. 1998.

[91] X. J. Li, B. C. Seet, and P. H. J. Chong, "Multihop cellular networks: Technology and economics," *Computer Networks.*, vol. 52, no. 9, pp. 1825-1837, June 2008.

[92] T. C. Y. Ng and W. Yu, "Joint optimization of relay strategies and resource allocation in cooperative cellular networks," *IEEE Journal of Selected Areas in Communications*, vol. 25, no. 2, pp. 328-339, Feb. 2007.

[93] S.-K. Kim, X. Wang, and M. Madihian, "Optimal resource allocation in multi-hop OFDMA wireless networks with cooperative relay," *IEEE Trans. on Wireless Communications*, vol. 7, no. 5, pp. 1833-1838, May 2008.

[94] M. Tang, X. Wang, Y. Wang, and J. Liao, "Dynamic resource allocation with threshold in OFDMA-based relay networks," in *Proc. of 2010 IEEE Vehicular Technology Conf.*, Taipei, 2010, pp. 1-5.

[95] N. Zhou, X. Zhu, and Y. Huang, "Optimal asymmetric resource allocation and analysis for OFDM-based multi-destination relay systems in the downlink," *IEEE Trans. on Vehicular Technology*, vol. 60, no. 3, pp. 1307-1312, Mar. 2011.

[96] M. Medard, "The effect upon channel capacity in wireless communications of perfect and impefect knowladge of the channel," *IEEE Trans. on Vehicular Technology*, vol. 46, no. 3, pp. 933-946, May 2000.

[97] W. Yu and R. Lui, "Dual methods for nonconvex spectrum optimization in multicarrier system," *IEEE Trans. on*

Communications, vol. 54, no. 7, pp. 1310-1322, Jul. 2006.

[98] R. Jain, "Channel models: A tutorial," present at WiMAX Forum AATG, Feb. 2007.

[99] W. Dang, M. Tao, H. Mu, and J. Huang, "Subcarrier-pair based resource allocation for cooperative multi-relay OFDM systems," *IEEE Trans. on Wireless Communications*, vol. 9, no. 5, pp. 1640-1649, May 2010.

Adnan Shahid Khan received his B.S. (Hons), master, and Ph.D. degrees in networks with Universiti Teknologi Malaysia (UTM), Johor Bahru, Malaysia in 2005, 2008, and 2012, respectively. And he completed his postdoctoral research in 2013 also in networks with UTM. He is currently a senior lecturer at the Faculty of Computer Science and Information Technology, Universiti Malaysia Sarawak (UNIMAS), Sarawak, Malaysia. His research interest includes network and network security in wireless communication.

Johari Abdullah is currently serving as the Dean of the Faculty of Computer Science & IT, UNIMAS, and he is also a senior lecturer with the Faculty. He received his Ph.D. degree in computing science from Newcastle University, Newcastle, UK, his master degree in IT from Queensland University of Technology, Brisbane, Australia, and the B.S. degree in computer science from Universiti Putra Malaysia, Kuala Lumpur, Malaysia.

Dr. Abdullah was the advisor and content talent for the Malaysia MOOC initiative in 2014 and 2015. His interests in ICT are wide and include web system design and development, system architect, problem solving using tools such as TRIZ, ICT education for children and youth through scratch and computer science unplugged, and also open source system and software. His research interests involve trusted web services, open source software and services, web-based application and services, and computational thinking.

Halikul Lenando is currently a senior lecturer and the Head of the Department of Computer Systems and Communication Technologies, Faculty of Computer Science and Information Technology, UNIMAS. He obtained his Ph.D. degree in mobile communications from Cardiff University, Cardiff, UK in June 2012. His research interests include mobile peer to peer (MP2P) network communications which focus on the network protocols and data dissemination in opportunistic networks. He is also involved actively in the mobile sensor networks communication research group in the faculty. Currently, he is also involved in research with the Center of Excellence in Rural Informatics (CoERI) under Network Communication Infrastructure Team.

Jambli Mohamad Nazim was born in Sarawak, Malaysia in 1976. He received the B.I.T. degree from the UNIMAS, Malaysia in 2001, the M.S. degree from the Griffith University, Queensland, Australia in 2003, and the Ph.D. degree from Newcastle University, Newcastle, UK in 2014, all in computer science and information and communication technologies. He is currently a senior lecturer at the Department of Computer System and Communication Technologies, UNIMAS. His research interests include mobile ad-hoc and wireless sensor networks, vehicular ad-hoc and sensor networks, and energy-efficient routing protocols.