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Policy-Based Radio Resource Management in Multicast OFDMA Systems

Vasileios D. Papoutsis

Supervisor: **Athanasia Alonistioti,** Lecturer

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ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

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ΕΠΙΒΛΕΠΟΝΤΕΣ: **Αθανασία Αλωνιστιώτη,** Λέκτορας

ΕΞΕΤΑΣΤΙΚΗ ΕΠΙΤΡΟΠΗ: **Ευστάθιος Χατζηευθυμιάδης,** Αναπληρωτής Καθηγητής

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ABSTRACT

Wireless spectral efficiency is increasingly important due to the rapid growth of demand for high data rate wideband wireless services. The design of a multi-carrier system, such as an OFDMA system, enables high system capacity suited for these wideband wireless services. This system capacity can be further optimized with a resource allocation scheme by exploiting the characteristics of the wireless fading channels. The fundamental idea of a resource allocation scheme is to efficiently distribute the available wireless resources, such as the subcarriers and transmission power, among all admitted users in the system.

Regarding the problems of resource allocation in OFDMA-based wireless communication systems, much of the research effort mainly focuses on finding efficient power control and subcarrier assignment policies. With systems employing multicast transmission, the available schemes in literature are not always applicable. Moreover, the existing approaches are particularly inaccessible in practical systems in which there are a large number of OFDM subcarriers being utilized, as the required computational burden is prohibitively high.

The ultimate goal of this Thesis is therefore to propose affordable mechanisms to flexibly and effectively share out the available resources in multicast wireless systems deploying OFDMA technology. Specifically, according to multicast system, it is assumed that both the BS and each user are equipped with a single antenna and the allocation unit is not the subcarrier, as in conventional OFDMA systems, but a set of contiguous subcarriers, which is called chunk, in order to alleviate the heavy computational burden.

An efficient algorithm is proposed whose aim is to maximize the total throughput subject to constraints on total available power, BER over a chunk, and proportional data rates constraints among multicast groups. Simulation and complexity analysis are provided to support the benefits of chunk-based resource allocation to multicast OFDMA systems with targeting proportional data rates among multicast groups.

SUBJECT AREA: Wireless Telecommunications, Multicast Systems, Radio Resource Management

KEYWORDS: multicast systems, resource allocation, OFDMA, proportional data rate constraints

ΠΕΡΙΛΗΨΗ

Η ασύρματη φασματική αποδοτικότητα είναι ένας, όλο και περισσότερο, σημαντικός παράγοντας εξαιτίας της ταχείας ανάπτυξης των ασύρματων υπηρεσιών ευρείας ζώνης. Η σχεδίαση ενός συστήματος με πολλά φέροντα, όπως είναι ένα σύστημα OFDMA, επιτρέπει στα συστήματα να έχουν υψηλή χωρητικότητα για να ικανοποιήσουν τις απαιτήσεις των υπηρεσιών ευρείας ζώνης. Αυτή η αυξημένη χωρητικότητα των συστημάτων μπορεί να βελτιστοποιηθεί περαιτέρω εκμεταλλευόμενοι καλύτερα τα χαρακτηριστικά των ασύρματων καναλιών. Η θεμελιώδης ιδέα ενός σχήματος κατανομής πόρων είναι η αποτελεσματική κατανομή των διαθέσιμων ασύρματων πόρων, όπως είναι οι υποφορείς και η ισχύς εκπομπής, μεταξύ των χρηστών του συστήματος.

Σχετικά με τα προβλήματα της κατανομής πόρων σε ασύρματα συστήματα τηλεπικοινωνιών βασισμένα στην τεχνική OFDMA, η περισσότερη έρευνα επικεντρώνεται στην αναζήτηση πολιτικών ανάθεσης υποφορέων και ισχύος. Οι διαθέσιμες τεχνικές της βιβλιογραφίας δεν μπορούν να εφαρμοστούν όπως είναι σε συστήματα πολυεκπομπής. Επιπλέον, οι υπάρχουσες τεχνικές δεν μπορούν να εφαρμοστούν αμετάβλητες σε πραγματικά συστήματα στα οποία υπάρχει μεγάλος αριθμός OFDM υποφορέων, καθώς η υπολογιστική πολυπλοκότητα είναι πολύ μεγάλη.

Ο βασικός στόχος της παρούσας διπλωματικής εργασίας είναι η πρόταση ικανών μηχανισμών κατανομής των διαθέσιμων υποφορέων σε ασύρματα συστήματα πολυεκπομπής χρησιμοποιώντας την τεχνολογία OFDMA. Πιο συγκεκριμένα, σχετικά με τα συστήματα πολυεκπομπής, θεωρούμε ότι τόσο ο σταθμός βάσης όσο και κάθε χρήστης είναι εφοδιασμένοι με μοναδική κεραία και η μονάδα κατανομής δεν είναι ο υποφορέας, όπως στα συμβατικά συστήματα OFDMA, αλλά μία ομάδα γειτονικών υποφορέων, η οποία ονομάζεται τεμάχιο, με σκοπό τη μείωση της μεγάλης υπολογιστικής πολυπλοκότητας.

Ένας αποτελεσματικός αλγόριθμος προτείνεται του οποίου ο στόχος είναι η μεγιστοποίηση του συνολικού ρυθμού μετάδοσης δεδομένων με περιορισμούς στη συνολική διαθέσιμη ισχύ, στο BER ανά τεμάχιο και στους αναλογικούς περιορισμούς μεταξύ των ρυθμών μετάδοσης δεδομένων των ομάδων χρηστών. Η προσομοίωση και η ανάλυση της πολυπλοκότητας που παρουσιάζονται, υποστηρίζουν τα πλεονεκτήματα της κατανομής πόρων σε συστήματα πολυεκπομπής OFDMA τα οποία βασίζονται σε κατανομή τεμαχίων και έχουν ως στόχο την εξασφάλιση της αναλογικότητας μεταξύ των ρυθμών μετάδοσης δεδομένων των ομάδων χρηστών.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Ασύρματες Τηλεπικοινωνίες, Συστήματα Πολυεκπομπής, Κατανομή Ραδιοπόρων

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: συστήματα πολυεκπομπής, κατανομή πόρων, OFDMA, αναλογικοί περιορισμοί δικαιοσύνης

Dedicated to my parents.

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First of all I would like to thank Dr. Eleni Patouni for her valuable help during this master thesis. Without her help, it would have been much harder to finish this thesis. Also, I wish to thank my supervisor Lecturer Athanasia Alonistioni for the opportunity she gave me to continue the research I started some years ago in the scientific area of radio resource management in OFDMA systems.

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1. INTRODUCTION

1.1 Evolution Towards 4G

The last few years have witnessed a phenomenal growth in the wireless industry, both in terms of mobile technology and its subscribers. There has been a clear shift from fixed to mobile cellular telephony, especially since the turn of the century. By the end of 2010, there were over four times more mobile cellular subscriptions than fixed telephone lines. Both the mobile network operators and vendors have felt the importance of efficient networks with equally efficient design. This resulted in Network Planning and optimization related services coming in to sharp focus. Also, powered by enabling technologies [1], such as advanced digital signal processing and very large scale integrated circuits, wireless communication systems have experienced an explosive growth in the last decades.

Cellular systems [2] are one of the most successful wireless applications, having billions of subscribers. It owes its birth to Bell Laboratories, where the cellular concept was conceived in the 1970s [3]. Due to the fact that radio signal strength weakens with distance, the limited frequency bandwidth can be spatially reused, rendering the possibility of wide coverage over a large population. A basic mobile communication system [4] consists of a base station, a mobile telephone switching office and multiple mobile units. The two communication links between a base station and multiple mobile units are known as the downlink and uplink. A downlink is a communication link from a base station to a mobile unit whereas the uplink is a communication link from a mobile unit to a base station. The communication between the mobile unit and the base station via an air interface can utilize various multiple access schemes such as OFDMA, which is discussed in next chapters.

1.1.1 1G

The first generation of cellular systems in the United States was AMPS, which was deployed in 1980s. It was commercially introduced in US in 1978, Israel in 1986, and Australia in 1987. AMPS was a pioneering technology that helped drive mass market usage of cellular technology, but it poses several limitations compared to modern standards. It was unencrypted and easily vulnerable to eavesdropping via a scanner; it was susceptible to cell phone “cloning”. In addition it adopted analog FM technology with FDMA that required significant amounts of wireless spectrum to support. Many of the iconic early commercial cell phones such as the Motorola DynaTAC Analog AMPS were eventually superseded by D-AMPS in 1990. A similar analog cellular system, named The E-TACS, was deployed in Europe. Particularly, AMPS was allocated a 40-MHz bandwidth within the 800 to 900 MHz frequency range by the FCC for AMPS. In 1988, an additional 10 MHz bandwidth, called ES was allocated to AMPS. It was first deployed in Chicago, with a service area of 2100 square miles. AMPS offered 832 channels, with a data rate of 10 kbps. Although Omni directional antennas were used in the earlier AMPS implementation, it was realized that using directional antennas would yield better cell reuse. In fact, the smallest reuse factor that would fulfill the 18db SIR using 120-degree directional antennas was found to be 7. Hence, a 7-cell reuse pattern was adopted for AMPS. Transmissions from the base stations to mobiles occur over the forward channel using frequencies between 869-894 MHz. The reverse channel is used for transmissions from mobiles to base station, using frequencies between 824-849 MHz. AMPS and TACS use the FM technique for radio transmission. Traffic is multiplexed onto an FDMA system.

1.1.2 2G

Soon the first generation of cellular systems reached its capacity (AMPS service was shut down by most North American carriers by 2008) and phased out by the second generation in the early 1990s. This differed from the previous generation by using digital instead of analog transmission, providing much higher communication capacity at an even lower cost. Also it provides fast out-of-band phone-to-network signaling. The rise in mobile phone usage as a result of 2G was explosive and during this era the advent of prepaid mobile phones took place. Specifically, in 2G low bit rate data services were supported as well as the traditional speech service. Compared to first-generation systems, 2G systems use digital multiple access technology, such as TDMA and CDMA. Consequently, compared with first-generation systems, higher spectrum efficiency, better data services, and more advanced roaming were offered by 2G systems. In Europe, the GSM was deployed to provide a single unified standard. This enabled seamless services throughout Europe by means of international roaming. GSM, uses TDMA technology to support multiple users. During its 20-year development, GSM technology has been continuously improved to offer better services in the market. New technologies have been developed based on the original GSM system, leading to some more advanced systems known as 2.5G systems.

In the United States, there were three lines of development in second-generation digital cellular systems. The first digital system, introduced in 1991, was the IS-54 (North America TDMA Digital Cellular), of which a new version supporting additional services (IS-136) was introduced in 1996. Meanwhile, IS-95 (CDMA One) was deployed in 1993 [5]. The US FCC also auctioned a new block of spectrum in the 1900 MHz band, allowing GSM1900 to enter the US market. In Japan, the PDC system, originally known as JDC was initially defined in 1990.

Since the first networks appeared at the beginning of the 1991, GSM gradually evolved to meet the requirements of data traffic and many more services than the original networks.

- GSM: The main element of this system are the BSS, in which there are BTS and BSC and the NSS, in which there is the MSC, VLR, HLR, AC and EIR. This network is capable of providing all the basic services up to 9.6kbps, fax, etc. This GSM network also has an extension to the fixed telephony network. A new design was introduced into the mobile switching center of second-generation systems. In particular, the use of BSCs lightens the load placed on the MSC found in first generation systems. This design allows the interface between the MSC and BSC to be standardized. Hence, considerable attention was devoted to interoperability and standardization in second-generation systems so that carrier could employ different manufacturers for the MSC and BSCs. In addition to enhancements in MSC design, the mobile-assisted handoff mechanism was introduced. By sensing signals received from adjacent base stations, a mobile unit can trigger a handoff by performing explicit signaling with the network.
- GSM and VAS: The next advancement in the GSM system was the addition of two platforms, called VMS and the SMSC. The SMSC proved to be incredibly commercially successful, so much so that in some networks the SMS traffic constitutes a major part of the total traffic. Along with VAS, IN also made its mark in the GSM system, with its advantage of giving the operators the chance to create a whole range of new services. Fraud management and “prepaid” services are the result of the IN service.

- GSM and GPRS: As requirement for sending data on the air-interface increased, new elements such as SGSN and GGSN were added to the existing GSM system. These elements made it possible to send packet data on the air-interface. This part of the network handling the packet data is also called the “packet core network”. In addition to the SGSN and GGSN it also contains the IP routers, firewall servers and DNS. This enables wireless access to the internet and bit rate reaching to 150 kbps in optimum conditions. The move into the 2.5G world began with GPRS. GPRS is a radio technology for GSM networks that adds packet-switching protocols, shorter setup time for ISP connections, and the possibility to charge by the amount of data sent, rather than connection time. Packet switching is a technique whereby the information (voice or data) to be sent is broken up into packets, of at most a few Kbytes each, which are then routed by the network between different destinations based on addressing data within each packet. Use of network resources is optimized as the resources are needed only during the handling of each packet. GPRS supports flexible data transmission rates as well as continuous connection to the network. GPRS is the most significant step towards 3G.
- GSM and EDGE: With both voice and data traffic moving on the system, the need was felt to increase the data rate. This was done by using more sophisticated coding methods over the internet and thus increasing the data rate up to 384 kbps. Implementing EDGE was relatively painless and required relatively small changes to network hardware and software as it uses the same TDMA frame structure, logic channel and 200 kHz carrier bandwidth as today's GSM networks. As EDGE progresses to coexistence with 3G WCDMA, data rates of up to ATM-like speeds of 2 Mbps could be available.

1.1.3 3G

Nowadays, second-generation digital cellular systems still dominate the mobile industry throughout the whole world. However, third generation (3G) systems have been introduced in the market, but their penetration is quite limited because of several techno-economic reasons. As the use of 2G phones became more widespread and people began to utilize mobile phones in their daily lives, it became clear that demand for data services (such as access to the internet) was growing. Furthermore, experience from fixed broadband services led to predictions for an ever increasing demand for greater data speeds. The 2G technology was nowhere near up to the job, so the industry began to work on the next generation of technology known as 3G.

In EDGE, high-volume movement of data was possible, but still the packet transfer on the air-interface behaves like a circuit switch call. Thus part of this packet connection efficiency is lost in the circuit switch environment. Moreover, the standards for developing the networks were different for different parts of the world. Hence, it was decided to have a network which provides services independent of the technology platform and whose network design standards are same globally. Thus, 3G was born. The ITU defined the demands for 3G mobile networks with the IMT-2000 standard. An organization called 3GPP has continued that work by defining a mobile system that fulfills the IMT-2000 standard. In Europe it was called UMTS, which is ETSI-driven. IMT2000 is the ITU-T name for the third generation system, while cdma2000 is the name of the American 3G variant. WCDMA is the air-interface technology for the UMTS. The main components includes BS or nod B, RNC, apart from WMSC and SGSN/GGSN. 3G networks enable network operators to offer users a wider range of more advanced services while achieving greater network capacity through improved spectral efficiency. Services include wide-area wireless voice telephony, video calls, and broadband wireless data, all in a mobile environment. Additional features also include HSPA data transmission capabilities able to deliver speeds up to 14.4 Mbps on the downlink and 5.8 Mbps on the uplink.

The first commercial 3G network was launched by NTT DoCoMo in Japan branded FOMA, based on W-CDMA technology on October 1, 2001. The second network to go commercially live was by SK Telecom in South Korea on the 1xEV-DO (Evolution-Data Optimized) technology in January 2002 followed by another South Korean 3G network was by KTF on EV-DO in May 2002. In Europe, the mass market commercial 3G services were introduced starting in March 2003 by 3 (Part of Hutchison Whampoa) in the UK and Italy. This was based on the W-CDMA technology. The first commercial United States 3G network was by Monet Mobile Networks, on CDMA2000 1x EV-DO technology and the second 3G network operator in the USA was Verizon Wireless in October 2003 also on CDMA2000 1x EVDO. The first commercial 3G network in southern hemisphere was launched by Hutchison Telecommunications branded as Three using UMTS in April 2003. The first commercial launch of 3G in Africa was by EMTEL in Mauritius on the W-CDMA standard. In North Africa (Morocco), a 3G service was provided by the new company Wana in late March 2006. Roll-out of 3G networks was delayed in some countries by the enormous costs of additional spectrum licensing fees. In many countries, 3G networks do not use the same radio frequencies as 2G, so mobile operators must build entirely new networks and license entirely new frequencies; an exception is the United States where carriers operate 3G service in the same frequencies as other services. The license fees in some European countries were particularly high, bolstered by government auctions of a limited number of licenses and sealed bid auctions, and initial excitement over 3G's potential. Other delays were due to the expenses of upgrading equipment for the new systems. Still several major countries such as Indonesia have not awarded 3G licenses and customers await 3G services. China delayed its decisions on 3G for many years. In January 2009, China launched 3G but interestingly three major companies in China got license to operate the 3G network on different standards, China Mobile for TD-SCDMA, China Unicom for WCDMA and China Telecom for CDMA2000.

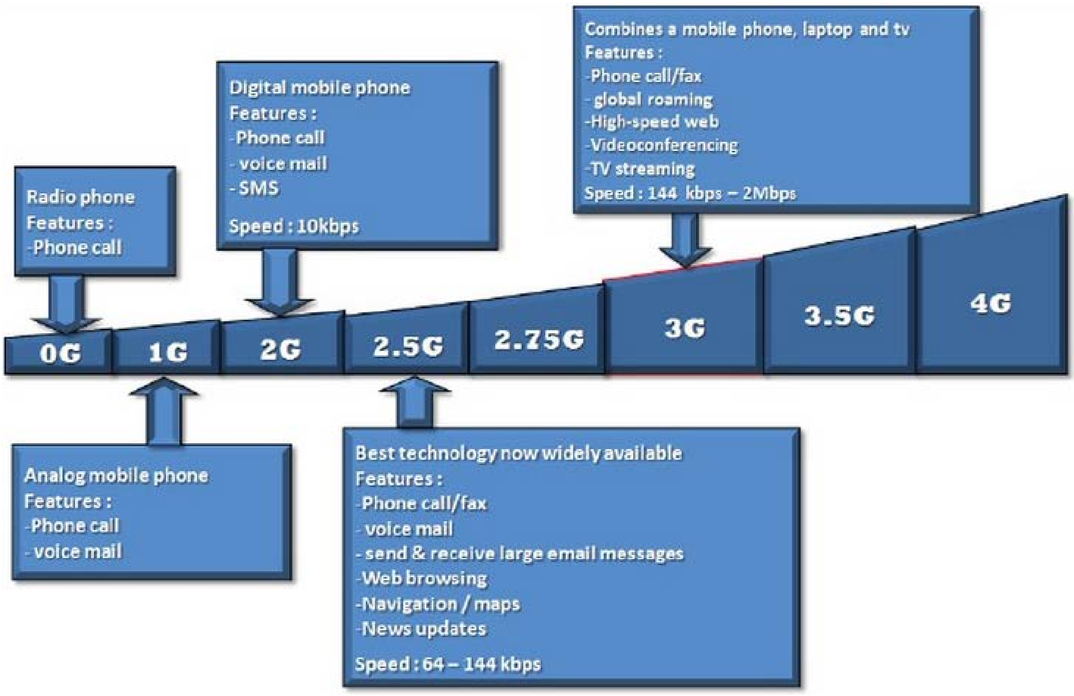

Fig. 1: Evolution of mobile communication standards.

1.1.4 4G

The emergence of new technologies in the mobile communication systems and also the ever increasing growth of user demand have triggered researchers and industries to come up with a comprehensive manifestation of the fourth generation (4G) mobile communication system [6] [7] [8]. In contrast to 3G, the new established 4G framework tries to accomplish new levels of user experience and multi-service capacity by also integrating all the mobile technologies that exist (e.g. GSM, GPRS, IMT-2000, Wi-Fi, Bluetooth). The fundamental reason for the transition to the All-IP is to have a common platform for all the technologies that have been developed so far, and to harmonize with user expectations of the many services to be provided. The fundamental difference between the GSM/3G and All-IP is that the functionality of the RNC and BSC is now distributed to the BTS and a set of servers and gateways. This means that this network will be less expensive and data transfer will be much faster. 4G makes sure that "The user has freedom and flexibility to select any desired service with reasonable QoS and affordable price, anytime, anywhere". 4G mobile communication services started in 2010 but will become mass market in about 2014-15.

IMT-Advanced 4G standards will usher in a new era of mobile broadband communications, according to the ITU-R. IMTAdvanced provides a global platform on which to build next generations of interactive mobile services that will provide faster data access, enhanced roaming capabilities, unified messaging and broadband multimedia. According to ITU, "ICTs and broadband networks have become vital national infrastructure but with an impact that promises to be even more powerful and far-reaching. These key enhancements in wireless broadband can drive social and economic development, and accelerate progress towards achieving the United Nations' Millennium Development Goals, or MDGs". The current agreements on the requirements for IMT-Advanced are:

- Peak data rate of 1 Gbps for downlink and 500 Mbps for uplink.
- Regarding latency, in the Control plane the transition time from Idle to Connected should be lower than 100ms. In the active state, a dormant user should take less than 10ms to get synchronized and the scheduler should reduce the User plane latency at maximum.
- Downlink peak spectral efficiency up to 15 bps/Hz and uplink peak spectral efficiency of 6.75 bps/Hz with an antenna configuration of 4 × 4 or less in DL and 2 × 4 or less in UL.
- The average user spectral efficiency in DL (with inter-site distance of 500m and pedestrian users) must be 2.2 bps/Hz/cell with MIMO 4 × 2, whereas in UL the target average spectral efficiency is 1.4 bps/Hz/cell with MIMO 2 × 4.
- In the same scenario with 10 users, cell edge user spectral efficiency will be 0.06 in DL 4 × 2. In the UL, this cell edge user spectral efficiency must be 0.03 with MIMO 2 × 4.
- Mobility up to 350 km/h in IMT-Advanced.
- IMT-Advanced system will support scalable bandwidth and spectrum aggregation with transmission bandwidths more than 40MHz in DL and UL.
- Backward compatibility and inter-working with legacy systems.

After completion of its Release-8 specifications, 3GPP has already planned for a work item called LTE-Advanced to meet the IMT-Advanced requirements for 4G. Also, WiMAX Forum and IEEE are also evolving WiMAX through IEEE 802.16m or WiMAX-m to satisfy 4G requirements.

1.2 Related Word

Next generation communication systems must address challenges of multimedia broadcast due to wide variations of the wireless channel, high mobility of users and limited system resources. To resolve these challenges, combinations of multicasting [28] together with OFDMA, MIMO antenna scheme, scheduling, and DRRA have been particularly identified as spectrum efficient techniques to maximize spectral utilization, minimize transmission power consumption at the base station (BS) and provide better QoE for users within the network. These technologies have been widely adopted as MBMS in few cellular standards such as IEEE802.16 (Fixed and Mobile WiMAX) and the 3GPP LTE to accommodate high speed mobility as well as support high rates for nomadic and mobile users [52].

1.2.1 OFDM

OFDM [53] [54] has developed into a popular scheme for wideband wireless digital communication used in applications such as digital television and audio broadcasting, wireless networking and broadband internet access. The primary advantage of OFDM is its ability to cope with severe wireless channel conditions such as multipath fading which exists because of the frequency-selective nature of the wireless channel. Multipath fading leads to severe intersymbol interference (ISI) in both frequency and time. OFDM shows robustness against frequency-selective fading and tolerance to ISI.

OFDM [30] uses N orthogonal subcarriers so that a high-rate data stream is split into N lower rate substreams, which are transmitted in parallel on the subcarriers. The time duration of an OFDM symbol is therefore N times longer than that of a single-carrier symbol. Because the symbol duration increases for the lower rate parallel subcarriers, the relative amount of time dispersion caused by multipath delay spread is decreased. The concept of using parallel data transmission and FDM with orthogonal spectral overlap was published in the mid-1960s [31] [32]. Some early development can be traced back in 1957, which was for bandwidth efficient transmission over telephone and HF radio channel [33]. The basic idea was to use parallel data and FDM with overlapping subcarriers to avoid the use of high-speed equalization and to combat impulsive noise and multipath distortion as well as to fully use the available bandwidth. The initial applications were in military communications, such as [33] [34] in HF military systems in the 1960s.

For a large number of subcarriers, in order to avoid the unreasonably expensive and complex sinusoid generators and coherent demodulators, the DFT was implemented in the mid-1960 in military HF radios [34]. In the early 1970s, in [35], IFFT/FFT was applied to simplify the OFDM modulation and demodulation process. IFFT/FFT is needed for a completely digital implementation so that the bank of subcarrier oscillators and coherent demodulators required by the original OFDM proposal [31] [32] can be eliminated. Rapid advances in VLSI technology make high-speed large size FFT chips commercially affordable. In 1985, OFDM was introduced for mobile wireless communications [36]. In 1990, the performance and complexity of OFDM has been studied and concluded that the time for OFDM had arrived [37]. In the 1990s, OFDM has been investigated for voice-band modems such as ADSL, HDSL, and VHDSL [38]. OFDM has also been exploited for wideband data communications over mobile radio FM channels, DAB [39], DVB [40] and HDTV [41].

A broadband wireless system with a very high data rate encounters large delay spread, and therefore, has to cope with frequency selectivity. OFDM converts a frequency-selective channel into a number of parallel frequency-flat subcarriers. The subcarriers have the minimum frequency separation required to maintain orthogonality of their corresponding time-domain waveforms yet the signal spectra associated with the different subcarriers overlap in frequency domain. The available bandwidth is hence used efficiently. If knowledge of the channel is available at the transmitter, OFDM can allocate the transmitted power on a subcarrier basis to match the channel so that the optimal BER and/or ideal water filling capacity of a frequency-selective channel can be approached. Therefore, closed-loop OFDM facilitates the utilization of the capacity or BER performance gains on frequency-selective channels.

OFDM has been exploited for several wireless standards, including IEEE 802.11a LAN standard [42] and IEEE 802.16a, MAN standard [43]. The IEEE 802.11a operates at raw data rate up to 54Mb/s with 20MHz channel spacing, thus yielding a bandwidth efficiency of 2.7 b/s/Hz. The actual throughput is highly dependent on the MAC protocol. IEEE 802.16a operates in many modes depending on channel conditions with a data rate ranging from 4.20 to 22.91Mbps in a typical bandwidth of 6MHz; the efficiency is then 0.7 to 3.82 b/s/Hz [43]. In IEEE 802.20a, OFDM has also being considered as a standard for maintaining high-bandwidth connections to users moving at speeds up to 100 km/h. OFDM is in addition being regarded as a potential candidate for 4G mobile wireless systems [44].

1.2.2 OFDMA

OFDM is not a multiple-access strategy but rather a modulation technique that creates many independent streams of data that can be used by different users. Previous OFDM systems, such as DSL, 802.11a/g, and the earlier versions of 802.16/WiMAX, use single-user OFDM: All the subcarriers are used by a single user at a time. For example, in 802.11a/g, collocated users share the 20MHz bandwidth by transmitting at different times after contending for the channel. WiMAX (802.16e-2005) takes a different approach, known as OFDMA, whereby users share subcarriers and time slots.

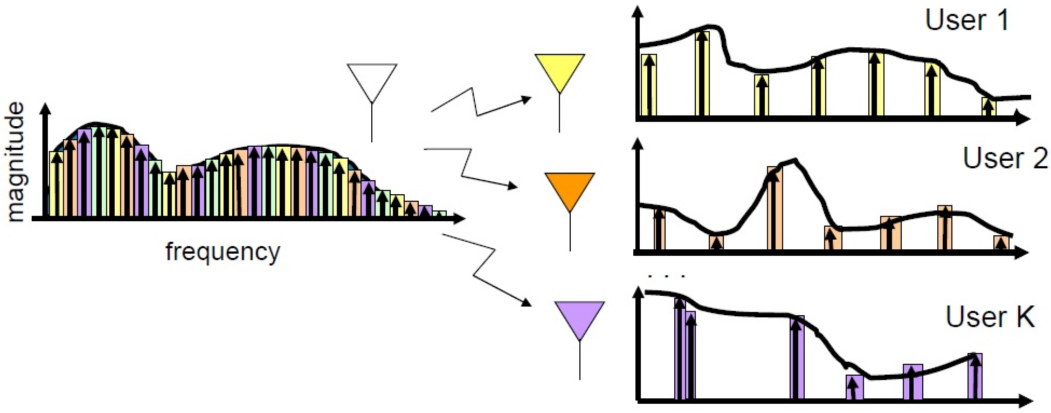

Fig. 2: Multiple Access Scheme.

As an extension, OFDM could be used not only as modulation scheme, but also as part of the OFDMA [55] scheme, which is also referred to as multiuser OFDM. OFDMA [4] is a multiuser version of the popular OFDM digital modulation scheme. In OFDMA, multiple access is achieved by first dividing the spectrum of interest into a number of subcarriers and then assigning subsets of the subcarriers to individual users, as can be seen in Fig. 2. OFDMA helps exploit multiuser diversity in frequency-selective channels, since it is very likely that some subcarriers that are “bad” for a user are “good” for at least one of the other users [56] [57]. Because of its superior performance in frequency-selective fading wireless channels, OFDMA is the modulation and multiple access scheme used in latest wireless systems such as IEEE 802.16e (Mobile WiMAX).

OFDMA is essentially a hybrid of FDMA and TDMA: Users are dynamically assigned subcarriers (FDMA) in different time slots (TDMA). The advantages of OFDMA start with the advantages of single-user OFDM in terms of robust multipath suppression and frequency diversity. In addition, OFDMA is a flexible multiple-access technique that can accommodate many users with widely varying applications, data rates, and QoS requirements. Because the multiple access is performed in the digital domain, before the IFFT operation, dynamic and efficient bandwidth allocation is possible. This allows sophisticated time- and frequency- domain scheduling algorithms to be integrated in order to best serve the user population.

The optimality of the OFDMA network is proved in [58] [59] where it is shown that the optimal policy is that each subcarrier be exclusively assigned to only one user, eliminating the ICI. In [58], the optimality of OFDMA is proved in a downlink multiuser OFDM system with adaptive QAM and independent decoding. However, the proof cannot be generalized to other modulation schemes. This generalization is shown in [59] where it is proved that the optimality of OFDMA holds for any adaptive modulation scheme which can be approximated using a convex data rate-SNR/SINR function [60].

So, the main idea of OFDMA is the distribution of the narrowband subcarriers among users depending on their channel characteristics [61], whereas, MIMO uses multiple antenna at both the transmitter and receiver to enable increased spectral efficiency for a given total transmit power by properly multiplexing parallel channels and taking advantage of antenna diversities. Similarly, scheduling and dynamic resource allocation establish management protocols to ensure fair and efficient exploitation of system resources. The transmission strength of OFDMA together with advanced antenna capabilities of MIMO allow more users to be packed into available resources in frequency and spatial domains. Combination of MIMO-OFDMA unique features has been reported to result in enhanced system total capacity [62].

MSRA is based on two types of multicast transmissions: Single-rate and multi-rate transmissions. In single-rate, the BS transmits to all users in each multicast group at the same rate irrespective of their non-uniform achievable capacities whereas in multi-rate, the BS transmits to each user in each multicast group at different rates based on what each user can handle. Until recently, single-rate scheme has been quite popular and widely accepted due to its implementation simplicity and low complexity. Multi-rate, on the other hand, has been receiving more attention lately because of necessity to achieve user throughput differentiation such that improved system spectral efficiency is attained.

MSRA is still confronted with various technical challenges. For example, in single-rate transmission, multicast services must be transmitted at a rate low enough for the least (worst or minimum) user to decode and high enough to maximally utilize system resources. Hence, the major problem is determining the most efficient single rate to transmit to each group without being insensitive to users with bad channel quality or unfair to users with high throughput potentials. Invariably, single-rate multicasting translates to trade-off between the transmission rate and system coverage.

In multi-rate transmission however, the problem is how to reduce the computational complexities, coding, and synchronization difficulties associated with transmission to multiple subgroups or individual group members. Based on these two types of multicast group rate determinations, scheduling, resource allocation and optimization can then be performed such that spectral efficiency is achieved, various network resources are optimally utilized without performance degradation and users' QoS requirements are satisfied given that they experience different channel fading dynamics.

Table 1: Notations.

Notation	Meaning
K	Number of users
N	Number of subcarriers
$\left\|H_{k,n}\right\|^2$	Channel gain of user k in subcarrier n
$p_{k,n}$	Transmit power allocated for user *k* in subcarrier *n*
$\frac{N_0}{2}$	AWGN power spectrum density
P_{total}	Total transmit power available at the BS
B	Total available bandwidth

In OFDMA [45], the subcarrier and the power allocation should be based on the channel conditions in order to maximize the throughput. Multiuser diversity describes the gains available by selecting a user or subset of users having "good" conditions. Adaptive modulation is the means by which good channels can be exploited to achieve higher data rates. There are a number of ways to take advantage of multiuser diversity and adaptive modulation in OFDMA systems. Algorithms that take advantage of these gains are not specified by the WiMAX standard, and all developers are free to develop their own innovative procedures. The idea is to develop algorithms for determining which users to schedule, how to allocate subcarriers to them, and how to determine the appropriate power levels for each user on each subcarrier. Referring to the downlink OFDMA system, users estimate and feedback the CSI to a centralized base station, where subcarrier and power allocation are determined according to users' CSI and the resource-allocation procedure. Once the subcarriers for each user have been determined, the base station must inform each user which subcarriers have been allocated to it. This subcarrier mapping must be broadcast to all users whenever the resource allocation changes. Typically, the resource allocation must be performed on the order of the channel coherence time, although it may be performed more frequently if a lot of users are competing for resources.

The resource allocation is usually formulated as a constrained optimization problem, to either (1) minimize the total transmit power with a constraint on the user data rate [46] [47] or (2) maximize the total data rate with a constraint on total transmit power [53] [54] [64] [65]. The first objective is appropriate for fixed-rate applications, such as voice, whereas the second is more appropriate for bursty applications, such as data and other IP applications. Therefore, we focus on the rate-adaptive algorithms, which are more relevant to WiMAX and LTE systems. We also note that considerable related work on resource allocation has been done for multicarrier DSL systems [48] [49] [50] [51]; the coverage and references in this section are by no means comprehensive. We assume that the base station has obtained perfect instantaneous channel-station information for all users. Table 1 summarizes the notation that will be used in the nest paragraphs.

1.2.2.1 Maximum Sum Rate Algorithm

In recent years, many dynamic resource allocation schemes for the unicast OFDMA systems have been developed. The objective of the MSR algorithm is to maximize the sum rate of all users, given a total transmit power constraint [45]. In [58], it is proved that the sum of the users' data rates is maximized when each subcarrier is assigned to the user with the best subcarrier gain, and power is then distributed by the water-filling algorithm [62] [63]. This strategy followed by the use of adaptive modulation [64] is known to be optimal. Also, it is optimal if the goal is to get as much data as possible through the system. The drawback of the MSR algorithm is that it is likely that a few users close to the base station, and hence having excellent channels, will be allocated all the system resources. We now briefly characterize the SINR, data rate, and power and subcarrier allocation that the MSR algorithm achieves.

Let $p_{k,n}$ denote transmit power of user k in subcarrier n. The signal-to-interference plus noise ratio for user k in subcarrier n, denoted as $SINR_{k,n}$, can be expressed as

$$SINR_{k,n} = \frac{p_{k,n}\left|H_{k,n}\right|^2}{\sum_{j=1,j\neq k}^{K} p_{j,n}\left|H_{j,n}\right|^2 + \sigma^2 \frac{B}{L}} \tag{1}$$

Using the Shannon capacity formula as the throughput measure, the MSR algorithm maximizes the following quantity:

$$\max_{p_{k,n},S_k} \left\{ \sum_{k=1}^{K} \sum_{n=1}^{N} \frac{B}{N} log_2\left(1 + SINR_{k,n}\right) \right\} \tag{2}$$

with the total power constraint

$$\sum_{\kappa=1}^{K} \sum_{n=1}^{N} p_{k,n} \leq P_{total} \tag{3}$$

The sum capacity is maximized if the total throughput in each subcarrier is maximized. Hence, the maximum sum capacity optimization problem can be decoupled into N simpler problems, one for each subcarrier. Further, the sum capacity in subcarrier n, denoted as C_n, can be written as

$$C_n = \sum_{k=1}^{K} log_2\left(1 + \frac{p_{k,n}}{P_{total,n} - p_{k,n} + \frac{\sigma^2}{h_{k,n}^2}\frac{B}{N}}\right) \tag{4}$$

where $P_{total,n} - p_{k,n}$ denotes other users' interference to user k in subcarrier n. It is easy to show that is maximized when all available power is assigned to the single user with the largest channel gain in subcarrier n. This result agrees with intuition: Give each channel to the user with the best gain in that channel. This is sometimes referred to as a “greedy” optimization. The optimal power allocation proceeds by the waterfilling algorithm, and the total sum capacity is readily determined by adding up the rate on each of the subcarriers.

1.2.2.2 Maximum Fairness Algorithm

Although the total throughput is maximized by the MSR algorithm, in a cellular system such as WiMAX or LTE, in which the pathloss attenuation varies by several orders of magnitude between users, some users will be extremely underserved by an MSR-based scheduling procedure. At the alternative extreme, the maximum fairness algorithm [65] aims to allocate the subcarriers and power such that the minimum user’s data rate is maximized. This essentially corresponds to equalizing the data rates of all users; hence the name “maximum fairness”.

The maximum fairness algorithm can be referred to as a max-min problem, since the goal is to maximize the minimum data rate. The optimum subcarrier and power allocation is considerably more difficult to determine than in the MSR case, because the objective function is not concave. It is particularly difficult to simultaneously find the optimum subcarrier and power allocation. Therefore, low-complexity suboptimal algorithms are necessary, in which the subcarrier and power allocation are done separately.

A common approach is to assume initially that equal power is allocated to each subcarrier and then to iteratively assign each available subcarrier to a low-rate user with the best channel on it [45] [65]. Once this generally suboptimal subcarrier allocation is completed, an optimum (waterfilling) power allocation can be performed. It is typical for this suboptimal approximation to be very close to the performance obtained with an exhaustive search for the best joint subcarrier-power allocation, in terms of both the fairness achieved and the total throughput.

1.2.2.3 Proportional Rate Constraints Algorithm

A weakness of the maximum fairness algorithm is that the rate distribution among users is not flexible. Furthermore, the total throughput is limited largely by the user with the worst SINR, as most of the resources are allocated to that user, which is clearly suboptimal. In a wireless broadband network, it is likely that different users require application-specific data rates that vary substantially. A generalization of the maximum fairness algorithm is a the PRC algorithm, whose objective is to maximize the sum throughput, with the additional constraint that each user’s data rate is proportional to a set of predetermined system parameters. Mathematically, the proportional data rates constraint can be expressed as

$$\frac{R_1}{\gamma_1} = \frac{R_2}{\gamma_2} = \cdots = \frac{R_K}{\gamma_K} \tag{5}$$

Where each user’s achievable data rate is

$$R_k = \sum_{n=1}^{N} \frac{B}{N} \rho_{k,n} log_2 \left(1 + \frac{p_{k,n}}{P_{total,n} - p_{k,n} + \frac{\sigma^2}{h_{k,n}^2} \frac{B}{N}} \right) \tag{6}$$

and $\rho_{k,n}$ can be the value only of either 1 or 0, indicating whether subcarrier n is used by user k. Clearly, this is the same setup as the maximum fairness algorithm if $\gamma_k = 1 \forall k$. The advantage is that any arbitrary data rates can be achieved by varying the γ_k values.

The PRC optimization problem is also generally very difficult to solve directly, since it involves both continuous variables $p_{k,n}$ and binary variables $\rho_{k,n}$, and the feasible set is not convex. As for the maximum fairness case, the prudent approach is to separate the subcarrier and power allocation and to settle for a near-optimal subcarrier and power allocation that can be achieved with manageable complexity. In [65], fairness in the resource allocation is incorporated through maximizing the minimum data rate among users. In [66] [67], a proportional fairness criterion that is determined by the system QoS guarantees is employed. In [66], an iterative method for root finding of nonlinear equation is used which is complex and time consuming. In [67], a low complexity noniterative data rate adaptive resource allocation scheme is proposed that linearizes the power allocation problem and yields higher sum of the users' data rates than [66]. The algorithms of [66] [67] impose a ratio $(\gamma_1 : \gamma_2 : \ldots : \gamma_K)$ among the data rates of the users that is determined by the system QoS guarantees. By setting $(\gamma_1 : \gamma_2 : \ldots : \gamma_K = 1 : 1 : \ldots : 1)$, the proportional fairness criterion reduces to that of [65]. In [68], the subcarrier allocation algorithm is based on prioritizing the most sensitive user in the system, and the variance of the subcarrier gains for each user is used to define the sensitivity of the user to the subcarrier allocation. In [69], a joint subcarrier and power allocation algorithm is proposed which is based on [65].

1.2.2.4 Other Approaches in Literature

In [70] [71], the fulfillment of every user's data rate constraints is guaranteed, and in [72], the proposed algorithms ensure a fair resource allocation in terms of the number of subcarriers with affordable data rates. However, in [72], the proportional data rate constraint is not applied, and an equal number of subcarriers is assigned to each user with the magnitude of the channel frequency responses being the only factor for determining the subcarrier allocation. In [73], the sum of the users' data rates is maximized with long-term access proportional fairness which means that every user has the same average channel access probability, and proportional data rate constraint is not applied too. Finally, in [74], the sum of the users' data rates is maximized but the resource allocation unit is not the subcarrier, as in previous algorithms [58] [19]-[29], but a time/frequency unit (slot), in accordance with WiMAX systems.

1.2.3 Multicast Resource Allocation

While a huge plethora of literature exists on scheduling and DRA in unicast multiuser OFDM systems as surveyed in [75] [76], works on multicast scheduling and resource allocation (MSRA) are just beginning to emerge in broadband wireless systems. Authors of [77] [15] examined single-rate multiple multicast groups within a single cell while [78] [79] investigated multiple multicasts with multi-rate transmissions. All these algorithms consider different performance metrics and constraints. Of particular challenge is the resulting optimization problem of multiple antenna complexities at both the BS and individual users. Specifically, [14] [80] are among the few works investigating MIMO techniques in multicast. In [81], total power consumption is minimized while in [82], a low-complexity algorithm is proposed which improves the downlink system throughput. In addition, in [83], the power control and bit-loading problems are addressed for both maximizing total throughput and guaranteeing proportional fairness. Furthermore, in [84], minimum number of subcarriers is guaranteed to individual multicast groups.

Finally, in [85], average BER constraint and in [86], a survey of resource allocation algorithms for multicast OFDMA systems is introduced.

1.2.4 Chunk Allocation

In order to mitigate the overhead and complexity, a set of contiguous subcarriers is properly grouped into one chunk and chunk-based resource allocation [87] [88] [85] [89]-[92] is carried out. In [88] [89], chunks are allocated to users according to their average SNR within each chunk, in contrast to [87] [85] [90]-[92], where BER constraint is ensured within each chunk. Finally, in [87] [88], chunk-based resource allocation is applied not only to the single antenna scenario but also to the multiple antennas.

1.3 Motivation and Thesis Outline

1.3.1 Motivation

In recent years [9], wireless multimedia applications like multi-party video conferences, Video on Demand, or on-line mobile gaming pose overwhelming demands for high data rates and need to support large number of users with flexible QoS and real-time requirements. This fact has led to an explosive surge in mobile and wireless communication systems development. These demands and requirements on the communication infrastructure are anticipated to be more intense in the future as more military applications and commercial services become more prevalent. Of particular interest are certain applications which require transmission to selected groups of users that naturally lend themselves towards multicasting. Also, a large part of the content in these applications is common information required by a group of users. For instance, geographic information updates such as traffic reports, local news, weather forecast, stock prices and location-based adverts. Multimedia entertainments such as IPTV, mobile TV, video conferencing, and other multimedia services, which currently account for one-third of mobile internet market, are some of the disruptive innovations that can be deployed using multicast technology [10]-[16]. Since there is no substitute for intelligent deployment and utilization of finite resources, hence, when multiple users within the same or adjacent cell require same content, multicasting allows such users to form groups and share allocated resources as illustrated in Fig. 3. The idea further maximizes spectral efficiency and minimizes transmission power consumption at the base station while also maximally utilizing the limited system resources [13]. This is in contrast to unicast transmissions where users cannot share resources and as many transmissions as number of users are required for full cell coverage. Hence allowing multiple users to share the same network resources (wired network resource or radio resource) via Multicast/Broadcast is highly attractive in providing current and future wireless multimedia services.

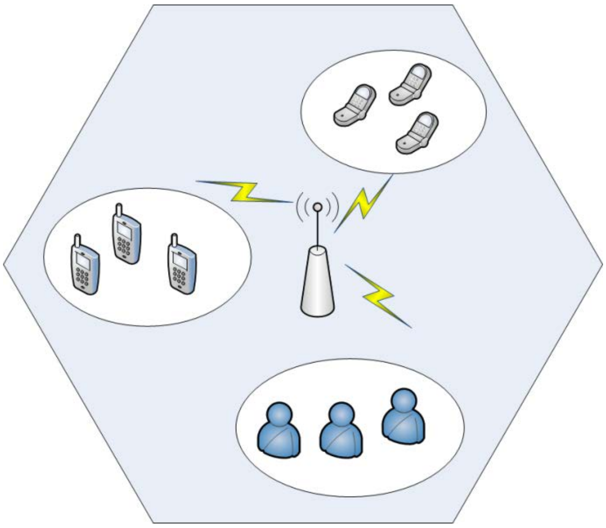

Fig. 3: Multicast system where multiple users share allocated system resources requesting same service. The users may not be in the same location.

Broadcast and multicast are the two modes of PTM communications. In Broadcast, the same content is delivered to all receivers within the transmission range from the sender. Known examples are radio and TV services, which are broadcasted over the air (either terrestrial or via satellite) and over cable networks. In Multicast, on the other hand, each content are solely delivered to users who have joined a particular multicast group. Normally, a multicast group is a group of users interested in a certain kind of content, for example, sports, news, cartoons. A multicast- enabled network ensures that the content is solely distributed over those links that are serving receivers which belong to the corresponding multicast group. In large scale networks like the Internet, the available content to be delivered are so diversified and the content senders and intended receivers are distributed so far apart that broadcast is nearly impossible. Hence multicast is the main concern of this thesis.

Basically, wireless multicast can be done in either infrastructure-based mobile networks or Ad-Hoc mobile networks. In infrastructure-based networks like GSM and UMTS, MTs communicate with a BS connecting to backbone networks, which can help one MT to communicate with any other MT, fixed phone or Internet server anywhere. An ad-hoc network is a self-organized network made up of a group of wireless mobile hosts [17], where each host has to forward data for others due to the limited transmission range of each mobile host. Such types of networks are usually designed for specific purpose, e.g., the battlefield networks, sensor networks, whereas the wireless multimedia content requiring multicast is usually provided by servers located in infrastructure-based networks. That is, this thesis only covers wireless multicast in infrastructure-based networks.

Wireless multicast has been drawing a lot of attention from both industry and academia, i.e., UMTS MBMS is a framework designed by the 3GPP to extend IP multicast to current 3G mobile networks [18] [19]. However, there are still many open issues to solve in both the fixed backbone part and the radio cell part in order to fully adopt multicast in mobile networks. In the backbone side, the problems posed by mobility include: (a) the movement of the multicast source, if the content sender is also a MT; (b) the movement of the multicast group members, thus the multicast routing topology (namely the multicast tree) needs to be reconfigured quickly; (c) data transmission reliability during hand-over, to avoid packet drop or enable lost data recovery; (d) signaling overhead due to frequently changed multicast tree topology and membership. In the radio cell side, challenges are mainly upon the radio resource management.

RRM is the system level control of radio transmission characteristics in wireless communication systems [20]. RRM includes strategies and algorithms controlling transmit power, channel allocation, handover criteria, modulation schemes, error-control-coding schemes [21]. The objective is to utilize the limited radio spectrum resources and radio network infrastructure as efficiently as possible. RRM considers multi-user system capacity issues, rather than just point-to-point link capacity.

The two important resources in wireless communication [22] are the available spectrum over which all the users' signals may occupy, and the transmitted power budget. While more and more users desire to utilize the system, the actual system resources remain limited and thus making the resource allocation problem a very critical and challenging one. In literature, there are two key approaches to share out the available resources in wireless communication systems: i) fixed resource allocation, and ii) dynamic resource allocation. A fixed allocation scheme, such as TDMA or FDMA, essentially assigns an independent dimension (time slots or frequency subchannels) to each individual user in a static manner. However, in a frequency selective fading environment there are time slots or subchannels left unused because these experience highly deep fade and therefore are not power efficient to carry any information bit. As the allocation is fixed regardless of the current channel condition while the fundamental characteristic of wireless links is being varying, a preset resource distribution algorithm is certainly not optimal. On the contrary, a dynamic resource allocation method adaptively shares out the available dimensions to the users according to their respective channel conditions, and thus takes full advantage of channel diversity among users in different locations. This kind of diversity, commonly known as the "multiuser diversity", stems from independent pathloss and fading of different users. In a particular time slot or subchannel, although a certain user may be in deep fade, it is unlikely that all other users also experience bad channel conditions since fading parameters of different users are mutually independent. That time slot or subchannel is therefore not wasted as in the fixed allocation, but can be assigned to the users with good wireless links. By utilizing the available channel state information and also exploiting the multiuser diversity, adaptive resource distribution schemes can help to substantially enhance the system performance.

Though the problems of multicast on the wired network part have been investigated extensively [21] [23]-[29], the challenges on the air interface part have not been discussed thoroughly. Multicast problems on the air interface are as interesting as those in the wired network part, and the reason is two-fold:

- Multicasting in air interface is very challenging since the wireless transmission is highly error-prone due to different fading phenomena and user mobility. The radio resources from a transmitter serving its receivers have to be limited to control the interferences to receivers served by other transmitters. Even though the radio resource management approaches have been fully developed for Unicast mobile receivers, they may not be the right solutions for multicast mobile users.
- The wireless transmission is broadcasting in its nature; therefore the multicasting on the air interface can utilize such nature to save the scarce radio resource. In the infrastructure-based networks today such as UMTS, the downlink radio resource (from base station to mobile terminals) is "scarce" due to the limitation enforced by the interference problem. By multicasting the same content in a common channel to multiple receivers rather than unicasting via multiple channels, not only radio resources are saved but also the interferences among multiple channels are reduced.

Therefore, this thesis focus on the wireless multicast performance optimization on the air interface with RRM approaches.

1.3.2 Thesis Outline

This Thesis consists of four chapters whose contents and contributions are briefly described in this section.

This first chapter is the introductory chapter of the Thesis. First, a brief history of cellular systems and then the motivation of this work are introduced. Two key technologies are adopted; OFDM and OFDMA which are also the key technologies of 4G. In OFDMA there are three main algorithms for solving the problem of resource management, i.e. the maximum sum rate algorithm, the maximum fairness algorithm and the proportional rate constraints algorithm. Finally, a section with the related work is presented.

In the second chapter, the system model and problem formulation are introduced. First, main aspects of wireless channel are shown and related work for policy based systems is introduced. In this thesis, resource allocation is performed in a channel-aware concept and channel is known not only to transmitter abut also to receiver. Finally, MSRA performance metrics and tradeoffs along with the multicast system model are introduced.

In the third chapter, the proposed algorithm is introduced. Also, complexity and simulation analysis are provided to enhance its contribution.

The last chapter summarizes the main results obtained in this thesis and concludes this work.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1 Wireless Channel Dynamism

Propagation over wireless channel weakens, delays, and deteriorates transmitted signals randomly [93]. Expansion of wireless networks over urban areas necessitates NLOS transmission, where a transmitted signal passes several obstructions on its way to a wireless receiver. When a signal is propagated in NLOS conditions, random phenomena, such as, reflection, refraction, diffraction, absorption, or scattering deteriorate the signal and result in multiple reception of the signal with different delays and strength. The wireless channel impairments can be categorized to the following phenomena and effects:

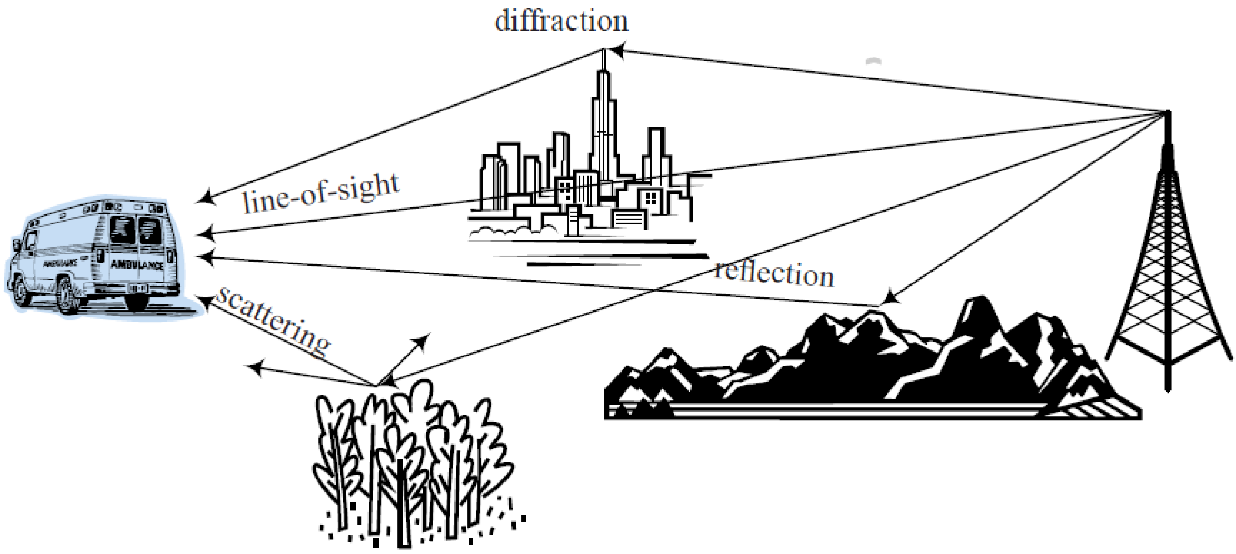

Fig. 4: Multipath channel.

- Noise: AWGN is the main impairment in any communication channel. AWGN has a constant spectral density, so it affects broadband signals more than narrow-band signals. As AWGN is additive, it can be formulated by simple and tractable mathematical models.
- Shadowing: Large obstacles in the propagation path, such as buildings and moving objects, shadow the signal transmission. Although, radio waves propagate around such blockages via diffraction but the power loss drops severely. Shadowing phenomenon causes slow variations of a transmitted signal with respect to the signal duration. So shadowing is sometimes referred to as slow fading in the literature.
- Pathloss: A signal power decays in the communication path as the distance increases. Pathloss depends on the environment of traversing signals and is inversely proportional to square carrier frequencies. Broadband signals experience significant pathloss. In addition, pathloss is worse in NLOS than the LOS transmission. Pathloss is a large-scale fading type because its effects are dominant in extended geographical networks.
- Multipath Fading: Large variations in received signal envelope occurred by propagating the transmitted signal via diffraction, scattering, and reflection, as it is shown in Fig. 4, is characterized as multipath fading. The variation of the amplitude of the received signal affected by multipath fading may be very large even over very small distances or small durations. Multipath propagation causes

frequency selective fading and ISI. The frequency selectivity results from destructive interference of transmitted signal with itself due to multipath reflections. A frequency selective fading channel cause deep fading in some frequency components of the transmitted signal. The locations of the deep fades may change because the interference pattern changes with reflectors movement or changes. ISI happens due to the signal propagation through different paths and concurrent receptions of different transmitted signals. In a NLOS environment, time dispersion of a multiple propagated signal causes it to arrive at the receiver during the next symbol period reception. ISI is a big concern for broadband signal transmission, because the symbol length is short in time and a small delay cause ISI. Traditionally, ISI is overcome by equalization, but it is computationally hard when number of transmitted signals increases.

- Doppler Shift: Time selectivity caused by the relative motion between a transmitter and receiver results in carrier frequency dispersion called Doppler shift. Doppler shift phenomenon depends on movement speed and carrier frequency. Doppler shift reduces SNR and can make carrier recovery and synchronization more difficult for broadband signals. Doppler shift is a main concern for OFDM based networks, since it can corrupt the orthogonality of the OFDM subcarriers named ICI.
- Interference: It is the conflict produced when two or more users transmit on the same frequency band. Frequency reuse, which allows users to share available bandwidth and improve spectrum utilization, may cause signals from different users to interfere with each other. Interference limits the capacity and coverage of wireless networks.

Typically, the broader is the signal; the worse is the wireless channel impacts. Broadband wireless networks need to be designed to cope with these large and rapid variations in received signal strength. There is no unique solution to all these impairments. However, OFDM is a popular choice for mitigating most of these deficits, because it exploits wireless channel fluctuations and multichannel transmission flexibility for efficient transmission of broadband signals.

Signal impairment is a major problem resulting from rapid wireless channel variations, multipath propagation and fading of transmitted signals. Likewise, the mobility of users and attributes of the surrounding terrain make the wireless link to vary considerably in frequency, time and space for all users especially in urban areas where multicast is considerably beneficial. This channel diversity of users can be adapted to assign subcarriers, modulation, coding rate, and transmit power to users based on their instantaneous channel experiences. Hence, we can ensure that the most efficient transmission mode is always employed in each subcarrier regardless of the wireless channel quality. For example, in WiMAX, 64QAM $\frac{2}{3}$ coding rate having high spectral efficiency may be used when the mobile nodes are close to the BS and the link is good but BPSK $\frac{1}{2}$ coding rate having poor spectral efficiency but good BER is used when the MS is far from BS and link is bad. In multicast systems, the use of aggressive modulation is complicated due to channel disparity of users; hence, little progress has been achieved in this avenue.

2.2 Policy-Based System

The complex environment of future networks consisting [94] of new technologies and services and terminals with variant requirements increases the complexity of uniform and efficient management. Specifically, the network and service co-management of such a complex network environment sets high automation and efficiency requirements not satisfied by the current management frameworks. In addition, the current static network management solutions lack the flexibility required by the new situation and are not cost effective either, as a large number of management entities are scattered along the network.

Policy based management is built upon the concept of high level business goals and policy rules. A policy can be defined as a set of rules which express how to reach a desired (network or service) behavior [95]. The policy translation process (widely known as “policy refinement”) defined as the translation of high level policies to low level policies is realized by a framework which translates the high level business goal imposed by the operator into low level policy rules which can be enforced on a set of network elements.

A variety of policy translation frameworks have been proposed so far, some of which are surveyed in [96]. In general, the translation frameworks can be classified based on their proposed methodologies to: Goal-oriented policy refinement, Classification-based policy refinement, Ontology-based policy refinement, Prescription-based policy refinement and Case-based policy refinement. The most typical of each category are described in the following paragraphs.

The study [97] relies on Goal-oriented policy refinement, which use the KAOS [98] formalization technology to perform goal elaboration. A set of domain-specific and domain-independent elaboration patterns defined in [99] are used to refine a goal into sub-goals which prove to be logically contained by the original goal. The proposed refinement method makes use of the KAOS goal elaboration method [100] in combination with modal logic and related proofs. In [101] a policy refinement method is presented based on goal requirement and modal checking technologies. Initially KAOS goal elaboration method is used to derive the low-level goals, and then system trace executions aimed at fulfilling low-level goals are obtained using Linear-Time Model Checking methodology.

The study in [103] utilizes classification-based policy refinement, in which classification of statistical data is used in order to refine the policies. This approach proposes deriving policy bounds on low-level metrics so that high-level goals are met. The main steps of policy refinement comprises the a) Test and Development Phase, where the test environment records values for the low level system attributes by placing workloads on the system, b) Classification Phase where a classification algorithm is applied on the dataset and the useful policies are derived, c) Policy Derivation and Refinement Phase, in which policies are derived from the output of the classification phase.

According to Ontology-based refinement, ontologies are used to describe concepts and the relationship among them. Some researchers use OWL [104] to describe the policy in their policy refinement methods. An ontology-based policy refinement using SWRL rules is proposed in [105]. Authors propose a methodology in which policies in each level are described by OWL while OWL links with rules in SWRL are used to allow the data interchange between the different levels. In [102], the SEMPR is proposed which is an architecture that uses Web services and automatic Web services composition as a complementary technique to policy translation.

A policy refinement approach based on prescription and ontology is presented in [107]. Relying on ontologies and prescriptions, the policy elaboration engine transforms the abstract policy into specific or enforceable policies. When an abstract policy is inserted into the policy elaboration engine, the engine will choose one prescription which has the same policy signature as the abstract policy. Then, a policy elaboration plan is automatically produced according to the prescription and the conditions in each elaborated branch.

In [106], which belong to the case-based refinement category, authors propose three approaches for policy transformation: static rule transformation, policy table lookup and case-based reasoning. The third one, which is the most dynamic, uses a case-based reasoning approach, in which the transformation module uses the knowledge acquired from the behaviors of the system in the past to predict its present and future behavior(s).

The majority of the aforementioned policy translation studies concentrate on translating a business goal into a set of low level policies which are generated from scratch. This approach, although general enough, lacks practical feasibility as it requires the operator to provide a vast quantity of information which is very difficult or even impossible to collect. The aforementioned translation frameworks do not take into consideration the actual intention of the operator (e.g. QoE, Energy efficiency).

In addition, the use of OWL/SWRL for the policy translation ensures a high degree of automation, interoperability with different information models and bidirectional translation (which is supported only by [105] as well), while the translation engine can be easily implemented and executed by general purpose semantic engines.

2.3 Channel-Aware Resource Allocation

In wireless communications, CSI refers to known channel properties of a communication link. This information describes how a signal propagates from the transmitter to the receiver and represents the combined effect of, for example, scattering, fading, and power decay with distance. The CSI makes it possible to adapt transmissions to current channel conditions, which is crucial for achieving reliable communication with high data rates in multi-antenna systems.

CSI needs to be estimated at the receiver and usually quantized and communicated back to the transmitter (although reverse-link estimation is possible in TDD systems). Therefore, the transmitter and receiver may have different CSI. The CSI at the transmitter and the CSI at the receiver are sometimes referred to as CSIT and CSIR, respectively.

There are basically two levels of CSI, namely instantaneous CSI and statistical CSI. Instantaneous CSI (or short-term CSI) means that the current channel conditions are known, which can be viewed as knowing the impulse response of a digital filter. This gives an opportunity to adapt the transmitted signal to the impulse response and thereby optimize the received signal for spatial multiplexing or to achieve low bit error rates. Statistical CSI (or long-term CSI) means that a statistical characterization of the channel is known. This description can include, for example, the type of fading distribution, the average channel gain, the line-of-sight component, and the spatial correlation. As with instantaneous CSI, this information can be used for transmission optimization.

The CSI acquisition is practically limited by how fast the channel conditions are changing. In fast fading systems where channel conditions vary rapidly under the transmission of a single information symbol, only statistical CSI is reasonable. On the other hand, in slow fading systems instantaneous CSI can be estimated with reasonable accuracy and used for transmission adaptation for some time before being outdated.

In practical systems, the available CSI often lies in between these two levels; instantaneous CSI with some estimation/quantization error is combined with statistical information.

Adaptive resource allocation is based on few assumptions: firstly, it is assumed that nodes can perfectly estimate and feedback their CSI to the BS. Secondly, CSI is always available to the BS before the commencement of each transmission. Thirdly, channel is slow-fading, meaning that the channel condition does not change during each OFDM symbol transmission block to avoid allocating resources based on obsolete CSI. While these assumptions are required to investigate system performance; they however do not offer realistic view of practical wireless systems. Practically, perfect CSI is hardly ever available at the BS due to channel prediction error, quantization error, feedback overhead, and channel feedback delay which is due to variation of the wireless link after estimation [108]. This delay often nullifies the validity of the estimates and degrades system performance.

The need for perfect CSI is even more apparent in channel-aware MSRA algorithms since the BS often utilizes knowledge of the channel condition for transmissions. BS would require frequent updates of the channel information for efficient resource allocation and optimal utilization. This frequent feedback requirement imposes significant load and complexity on the system since multiple multicast groups within a single cell may use large number of aggregate subcarriers. Therefore, channel estimation techniques that reduce feedback overhead have been studied in [109] [110]. More specifically, [109] investigated the sufficiency of partial CSI in maintaining certain performance level and [110] considers the impact of delayed feedback channel on system throughput and shows that predictive coding can be used to mitigate effect of outdated CSI.

2.4 MSRA Performance Metrics & Tradeoffs

The principle of multicast communication hinges on how to achieve intra/inter multicast group rate balance (or fairness) and compromise. There are two major conflicting fairness criteria in the literature depending on various perspectives. First equality based fairness should be mentioned; this notion proposes that all users expect equal rates or resource shares. Secondly, proportional fairness where each user receives allocation based on their potential capabilities. Since fairness and throughput maximization have always been two conflicting issues of concern in resource allocation problems, trade-off (compromise) or proportionality should always obtain good performance. Although these issues have enjoyed tremendous research attention for conventional unicast systems in recent years, more investigation is still required for multicast systems. MSRA algorithms are classified into three main categories depending on their features.

- Strict Throughput Maximization (STM): Without consideration for fairness, STM is often utilized in multiple multicast resource allocation problems where inter-group competitive coexistence must be well managed to achieve optimal system spectral efficiency. STM is an overtly optimistic approach which is totally inapplicable in intra-group because it selects rate of user with highest channel gain as the group’s transmission rate which undoubtedly would result in absolute intra-group resource starvation. On the other hand, STM has been shown to attain significant capacity gains for inter-group resource allocation because it allocates the best resource in time, frequency, and spatial domains to groups with the best potential to maximize total system capacity [82] [74] [111]. However, the gain comes at the expense of groups composed of sizeable number of users experiencing poor channel quality.
- Max-Min Fairness (MMF): In multicast-enabled systems, MMF attempts to rectify fairness deprivation in STM by giving priority to minimum users/groups to realize their maximum achievable rates. In [112] [113] the threshold is defined as

average (AVG) group throughput. Both schemes then traded-off LCG users and full system coverage. To achieve higher system capacities, the system is then optimized in favor of the AVG users. An improvement to both schemes could be to give the LCGs higher priority in the next time slots when their channel gains might have improved. Consequently, LCGs would experience temporary service failure instead of denial-of-service as in the case when they are totally given up. In MMF-based MSRA algorithms, each iteration maximizes the threshold-rate by allocating resources to users to achieve their highest possible rates until pareto optimality is attained - this is a state at which there is no other way to improve allocation of system resources to threshold user without decreasing allocation of other users. Hence, MMF-based MSRA algorithm is a pessimistic approach to provide guaranteed reliable multicast transmissions to all users.

- Proportional Throughput with Fairness (PTF): Absolute fairness leads to drastic reduction in aggregate throughput. Strict throughput results in zero tolerance for weak multicast groups. However, proportional fairness is a compromise-based approach which attempts to simultaneously balance group aggregate throughput while preventing resource starvation and providing fair QoS to all groups. In [114], an elegant tradeoff factor approach is employed to manipulate proportionality between fairness and total system capacity. Results show high capacity gain with good fairness performance, however, unicast system was considered. A more related study conducted in [112] [115] considers multiple multicast groups scheduling in TDMA-based cellular data networks and proposed two algorithms optimized for intra-group PTF and inter-group PTF. In the inter-group PTF scheme, the BS dynamically selects multicast group such that the summation of $log(T_g)$ for all multicast group is maximized, where $log(T_g)$ is the group throughput for multicast group g. These algorithms are particularly interesting if we note that a system may achieve high spectral utilization, yet, a number of users still experience resource starvation. In such cases, the efficiency of the system results from users with good channel quality.

2.5 Multicast System Model

Consider a single-cell downlink OFDMA transmission with one BS, N subcarriers, and K active users, each equipped with a single receive antenna. We denote as B the overall available bandwidth, P_{tot} the total transmit power and N_0 the one-sided power spectral density of additive white Gaussian noise. In addition, $g_{k,n} = D_k^{-\alpha}\left|h_{k,n}\right|^2$ is the channel gain of user k to subcarrier n, where $D_k^{-\alpha}$ is the path loss with D_k being the distance of user k from BS and α being the path loss exponent. Moreover, $h_{k,n}$ is the complex Gaussian distributed frequency response between user k and subcarrier n and its magnitude, $\left|h_{k,n}\right|$, follows Rayleigh distribution with $\mathbb{E}\left[\left|h_{k,n}\right|^2\right] = 1$.

In our case, K users are grouped to G multicast groups in a way that the sum, over all groups, of the within-group sums of user-to-group-centroid distances is minimized as can be seen in Fig. 5. Assume that each user receives one traffic flow at a time; hence, it belongs only to one multicast group. Clearly, all users belong to set $K = \bigcup_{g=1}^{G} K_G$, and $|K| = \sum_{g=1}^{G}\left|K_g\right|$, where K_g denotes the user set of multicast group g and $|\cdot|$ is the cardinality of a set. It is further assumed that the channel conditions remain unchanged during the allocation period. This assumption is particularly valid for slowly varying channels, where the channel gains do not vary too significantly over time, for example, in high-data-rate systems and/or environments with reduced degrees of mobility.

An attractive feature of wireless multicast [84] is that multicast data can be transmitted from the BS to multiple mobile users only through a single transmission. However, while all users within a multicast group receive the same rate from the BS, the main issue arises from the mismatch data rates attainable by individual users of that group, whose link conditions are typically asymmetric. If the BS transmits at a rate higher than the maximum rate that a user can handle, then that user cannot decode any of the transmitted data at all. Therefore, a conventional approach is to transmit at the lowest rate of all the users within a group, which is determined by the user with the worst channel condition [82]. This assures that the multicast services can be provided to all the subscribed users. On one hand, as all the multicast users within a group receive the same data rate from the BS, the total sum rate is scaled by the group size, which is effectively the number of active users of that group. On the other hand, the lowest transmit rate typically decreases as the number of users increases, since it is based on the least capable user. However, the conventional multicast transmission scheme is indeed both practical and beneficial, particularly with the use of multicarrier transmission, as in OFDM-based wireless networks.

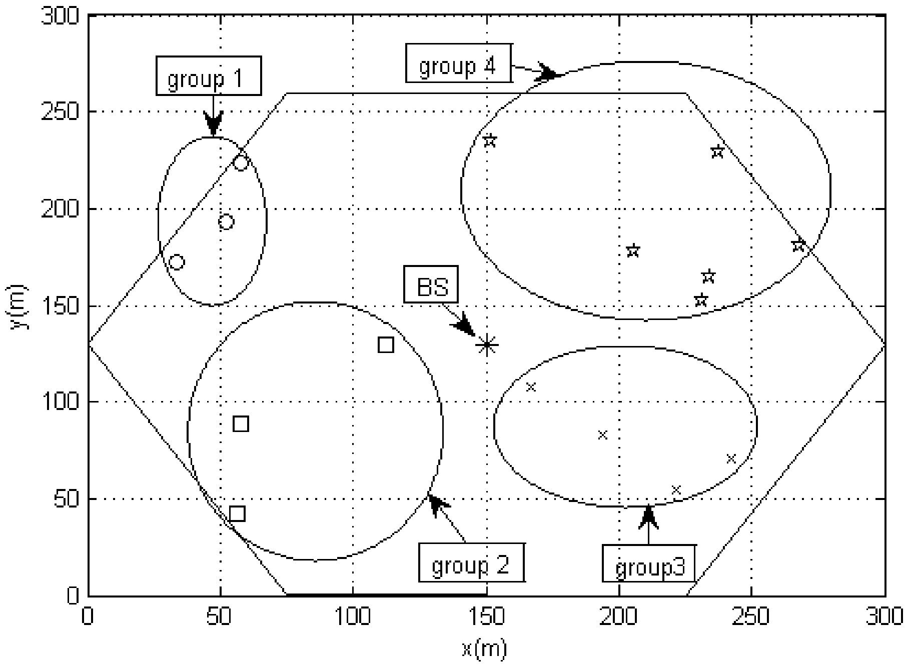

Fig. 5: Hexagonal cell with $T = 4$ distributed antennas, $R = 150$m cell radius, $K = 16$ users, and $G = 4$ multicast groups.

Although it is possible to adopt other techniques (for instance, exploiting the hierarchy in multicast data together with the assumption of multi-description coding [83]) to overcome the issue of data rate mismatch in wireless multicast, such solutions are out of the scope of this thesis. Since the channel quality of every user in a multicast group may be very different, BS is enforced to transmit at the lowest data rate of all users within each group, which is determined by the user with the smallest channel gain. Thus, the equivalent channel gain of multicast group g in subcarrier n is given below:

$$a_{g,n} = \min_{k \in K_g} g_{k,n}. \tag{7}$$

For any multicast group [90] [92], the channel fading factors of contiguous subcarriers in an OFDMA system are highly correlated in the broadband wireless channel. If a proper number of contiguous subcarriers are grouped into one chunk and the entire chunk is allocated to only one multicast group, the complexity and signaling overhead for resource allocation can be reduced. Under a BER constraint, the chunk-based allocation scheme is considered in this thesis to guarantee that the average BER within a chunk is smaller than the BER constraint (or threshold) in downlink OFDMA transmission.

In chunk-based resource allocation in the downlink OFDMA system, the downlink channel conditions of all subcarriers are estimated by multicast groups through pilot bits (channels). The channel estimates within a chunk for all multicast groups are fed back periodically to the BS through uplink transmission. The resource allocation is performed in the BS under the constraint of the total downlink transmit power P_{tot}. In each resource allocation instant, the BS allocates chunks and number of bits per symbol among multicast groups according to the estimated channel conditions of all multicast groups. When allocating chunks, one chunk is allocated only to one user according to the channel conditions of multicast groups on the chunk. In order to allocate a proper number of bits per symbol under a given BER constraint, and the transmit power constraint, QAM is adopted for each chunk by selecting proper modulation level according to the instantaneous channel condition of the allocated multicast group on the chunk. For each multicast group, the modulation levels are assumed to be the same for all subcarriers within a chunk. Hence, the number of bits allocated to a subchannel is the same for all subcarriers within a chunk. The information of chunk assignment and selected modulation levels is fed forward from the BS to each active multicast group for data recovery through downlink control signaling. After modulation, the modulated data in all chunks are input to IFFT and a guard interval is added to each OFDM symbol after the parallel-to-serial data processing. Afterwards, the OFDMA data are transmitted to the broadband wireless channel. At the receiver, first of all, the guard interval is removed from the received data and FFT is carried out. Then, the chunk channel conditions are estimated. In addition, the data on allocated chunks are demodulated according to the chunk allocation and the modulation results provided by the BS. Finally, recovered data are obtained.

As it is said above, $L-ary$ QAM is adopted as the modulation scheme and L takes values from the modulation level set

$$L = \{0, 2^2, 2^4, \dots, 2^b, \dots, 2^B\}, \tag{8}$$

where b stands for the number of bits in the QAM. When $b = 0$, modulation level is zero and no transmission is made. When $b = B$, transmission rate is B and system achieves the highest modulation level (2^B). Assuming $SNR_{g,n} = \frac{p_{g,n} T_s a_{g,n}}{N_0}$, where $p_{g,n}$ is the allocated power to group g in subcarrier n and T_s is the symbol duration, $BER_{g,n}$ of multicast group g in subcarrier n can be approximated as in [90] $BER_{g,n} = 0.2exp\left(-\frac{1.6SNR_{g,n}}{l_{g,n}-1}\right)$, where $l_{g,n} \in L$ is the QAM modulation level of multicast group g in subcarrier $n.$ Thus, sum data rate of multicast group g in subcarrier n is $r_{g,n} = |K_g| log_2(l_{g,n})$.

In real systems, multicast groups experience almost the same channel gain in contiguous subcarriers, as can be seen in Fig. 6. As the coherence bandwidth, f_c, usually exceeds the subcarrier bandwidth, considering the correlation between neighboring subcarriers to reduce system overhead, N subcarriers are grouped into C chunks, where $\mathrm{C} = \frac{N}{N'}$ is assumed to be integer and N' is the number of contiguous subcarriers per chunk. It is also assumed that $\tilde{l}_{g,c} = l_{g,cN'+n'}$, where $n' = 0,1,\dots,N'-1$ and $\tilde{l}_{g,c}$ is the modulation level determined for ,multicast group g in chunk c. Thus, sum data rate of multicast group g in chunk c is $\tilde{r}_{g,c} = |K_g| log_2(\tilde{l}_{g,c})$.

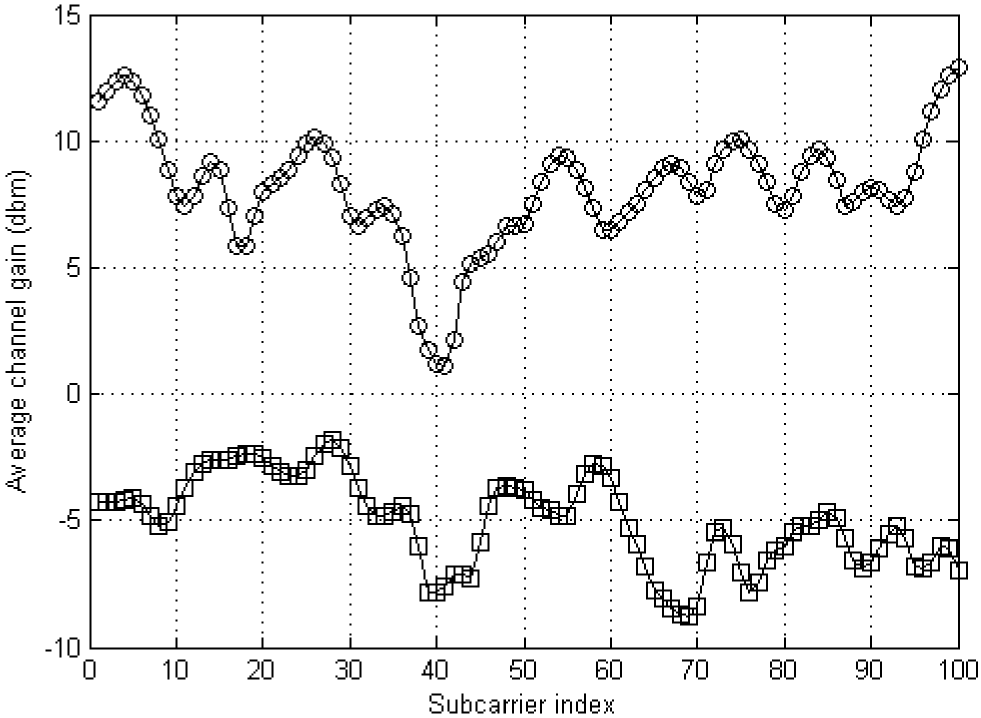

Fig. 6: Average channel gain of contiguous subcarriers of two multicast groups.

In this thesis, three classes of multicast groups are taken into account [116]: gold, silver and bronze multicast groups. Such solution deals with the different levels of multicast groups' QoS, improving the system performance. In our approach these different QoS levels appear to the different BER constraints.

By applying the conclusion above, the optimization problem is formulated as

$$\max_{\rho_{g,c}\tilde{r}_{g,c}} \sum_{g=1}^{G} \sum_{c=1}^{C} \rho_{g,c}\tilde{r}_{g,c}, \tag{9}$$

subject to

$$\rho_{g,c} \in \{0,1\}, \quad \forall g = 1,2,\dots,G, \quad \forall c = 1,2,\dots,C, \tag{10}$$

$$\sum_{g=1}^{G} \rho_{g,c} = 1, \quad \forall c = 1,2,\dots,C, \tag{11}$$

$$\overline{BER}_{g_1,c} \leq BER_1, \quad \forall g_1 \in G_1, \quad \forall c = 1,2,\dots,C, \tag{12}$$

$$\overline{BER}_{g_2,c} \le BER_2, \quad \forall g_2 \in G_2, \quad \forall c = 1,2,\dots,C, \tag{13}$$

$$\overline{BER}_{g_3,c} \le BER_3, \quad \forall g_3 \in G_3, \quad \forall c = 1,2,\dots,C, \tag{14}$$

$$\sum_{g=1}^{G}\sum_{n=1}^{N} p_{g,n} = P_{tot}\,, \tag{15}$$

$$\tilde{R}_1 : \tilde{R}_2 : \dots : \tilde{R}_G = \gamma_1 : \gamma_2 : \dots : \gamma_G, \tag{16}$$

where in (10) $\rho_{g,c}$ is the chunk allocation indicator such that $\rho_{g,c} = 1$ if chunk c is allocated to multicast group g; otherwise $\rho_{g,c} = 0$, $\forall g$, $\forall c$. Constraint (11) restricts the assignment of each chunk to only one multicast group. In addition, constraints (12),(13),(14), and (15) are the average BER and total power constraints, respectively. Average BER constraints are different in the three multicast group classes. BER_1 is the BER constraint of gold multicast groups, BER_2 is the BER constraint of silver multicast groups and BER_3 is the BER constraint of bronze multicast groups. Also, G_1, G_2, G_3, are the gold, silver and bronze multicast groups, respectively. Finally, in (16), $\{\gamma_g\}_{g=1}^{G}$ are the proportional data rate constraints. In (12),(13),(14), average BER of multicast group g over chunk c is

$$\overline{BER}_{g,c} = \frac{1}{N'} \sum_{n=cN'}^{(c+1)N'-1} 0.2exp\left(-\frac{1.6SNR_{g,n}}{l_{g,n}-1}\right), \tag{17}$$

and in (16) sum data rate of multicast group g is

$$\tilde{R}_G = \sum_{c=1}^{C} \rho_{g,c}\, \tilde{r}_{g,c}. \tag{18}$$

3. PROPOSED ALGORITHM AND SIMULATION RESULTS

3.1 Proposed Algorithm

A low complexity approach for the resource allocation problem (9)-(16), which adopts uniform power distribution among subcarriers, as it yields marginal performance difference compared to water-filling [58], is introduced in this section.

1) Initialization:
   - Set $\tilde{R}_g = 0$, $\forall g = 1,2,\dots,G$.
   - Set $\rho_{g,c} = 0$, $\forall g = 1,2,\dots,G$, $\forall c = 1,2,\dots,C$.
   - Set $o_c = 0$, $\forall c = 1,2,\dots,C$.
   - Set L according to (8).
   - Compute $a_{g,n}$, according to (7), $\forall g = 1,2,\dots,G$, $\forall n = 1,2,\dots,N$.
2) For $c = 1,2,\dots,C$:
   - Calculate $\overline{BER}_{g,c}$, $\forall g = 1,2,\dots,G$, according to (17).
   - Find multicast group g^* and $\tilde{l}_{g^*,c} \in L$ so that $\overline{BER}_{g^*,c} \leq BER_1$ or $\overline{BER}_{g^*,c} \leq BER_2$ or $\overline{BER}_{g^*,c} \leq BER_3$ and $\frac{\tilde{R}_{g^*}}{\gamma_{g^*}} \leq \frac{\tilde{R}_g}{\gamma_g}$, $\forall g = 1,2,\dots,G$. $\tilde{R}_g$ is calculated according to (18).
   - If multicast group g^* is found:
     - Set $\rho_{g^*,c} = 1$ and calculate $\tilde{R}_{g^*}$ according to (18).
   - Else
     - Set $o_c = 1$, which means an outage is occurred.

In initialization step, the vectors keeping the sum data rate of each multicast group, $\tilde{R}_g$, and outage, o_c, and chunk allocation indicator, $\rho_{g,c}$, are initialized. In addition, modulation level set L is the set and the equivalent channel gain, $a_{g,n}$ is computed. This step requires constant time for the initialization of the aforementioned structures and $O(GN)$ for the computation of $a_{g,n}$. Then for each chunk c, average BER, $\overline{BER}_{g,c}$, is calculated, a procedure that requires $O(GC)$ for all chunks. Also, multicast group, g^*, and QAM modulation level of multicast group g^* in chunk c, $l_{g^*,c} \in L$, are found guaranteeing $\overline{BER}_{g^*,c} \leq BER_1$, or $\overline{BER}_{g^*,c} \leq BER_2$ or $\overline{BER}_{g^*,c} \leq BER_3$ and the fraction of average data rate to proportional data rate constraint of multicast group g^*, $\frac{\tilde{R}_{g^*}}{\gamma_{g^*}}$, is minimum. If there is no such multicast group, outage occurs and chunk c remains unallocated. Thus, it requires $O(GC)$ time and the overall complexity of the proposed algorithm is $O(GN + GC)$. It is easily observed that the proposed algorithm becomes more complex in conventional OFDMA systems where subcarrier allocation is applied instead of chunk allocation $(N > C)$, or when the system is unicast, i.e., $G = K$.

3.2 Simulation Results

In this section, the performance of the proposed algorithm is evaluated using simulation. A hexagonal cell [87] [117] of radius $R = 150$m with $K = 20$ number of users, $N = 1024$ number of subcarriers, $BER_1 = 10^{-3}$, $BER_2 = 10^{-2}$, $BER_3 = 5 \cdot 10^{-2}$ and total bandwidth $B = 100$MHz is considered as it is shown in [87] [117]. Then, the frequency separation between two contiguous subcarriers is $\Delta f = \frac{B}{N} = \frac{100MHz}{1024} = 97.6$KHz. Users are placed uniformly [85] [87] to the cell area at distances larger than 15m from BS and, as in [85] [87], $\frac{p_{g,n}T_s}{N_0} = 23.2$dB. Also, the coherence bandwidth, f_c, is the same for all users and for simplicity one value is examined, namely $f_c = 1.95$MHz. Table 2 summarizes the aforementioned simulation variables. In addition, the broadband channel is frequency selective and independent for all users. Correspondingly, the correlation coefficient between any two subcarriers, e.g. n_1, n_2, of any user k, is the same for all users and is given below as in [90]

$$\begin{aligned}\rho_{k,n_1,n_2} = \mathbb{E}\{h^*_{k,n_1} h_{k,n_2}\} &= \frac{1}{\sqrt{1 + \left(\frac{|f_{k,n_1} - f_{k,n_2}|}{f_c}\right)^2}} \\ &= \frac{1}{\sqrt{1 + \left(\frac{(n_1 - n_2)\Delta f}{f_c}\right)^2}}\end{aligned} \tag{19}$$

In (19), $(\cdot)^*$ stands for complex conjugate and f_{k,n_1}, f_{k,n_2} are frequencies of subcarriers n_1, n_2 of user k, respectively. Finally, path loss exponent is $a = 3$ and the results are averaged over 10^2 different topologies and over 10^2 channel realizations.

Table 2: Simulation variables.

Notation	Meaning
$K = 20$	Number of users
$N = 1024$	Number of subcarriers
$BER_1 = 10^{-3}$	BER of gold multicast group
$BER_2 = 10^{-2}$	BER of silver multicast group
$BER_3 = 5 \cdot 10^{-2}$	BER of bronze multicast group
$\Delta f = 97.6$KHz	Frequency separation between two contiguous subcarriers
$B = 100$MHz	Total available bandwidth
$f_c = 1.95$MHz	Coherence bandwidth

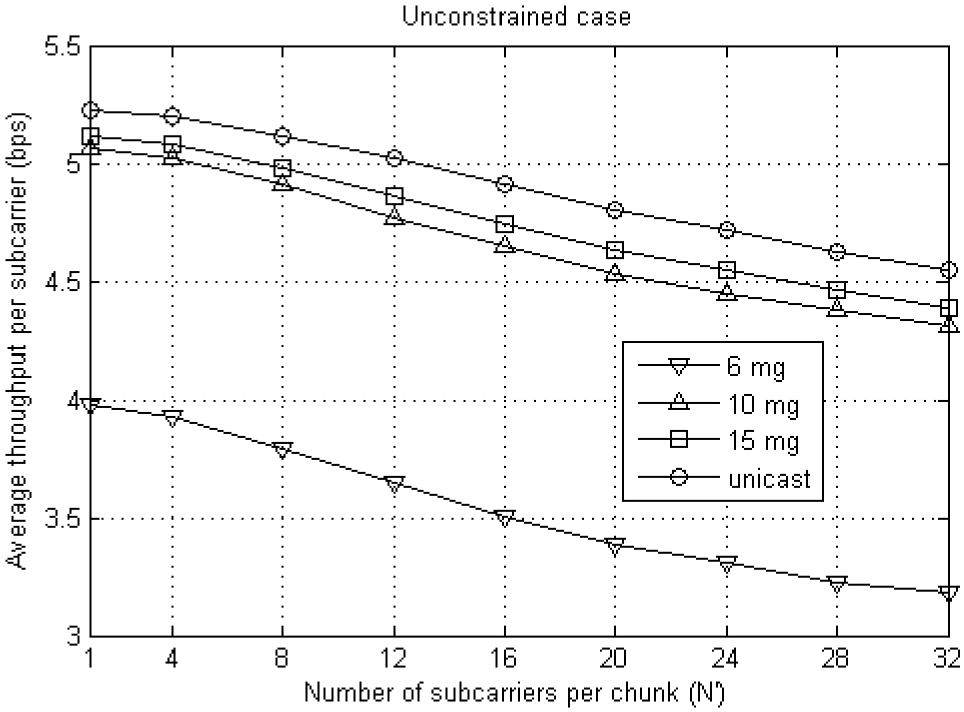

Fig. 7: Unconstrained case: Average throughput per subcarrier vs number of subcarriers per chunk; mg stands for multicast group.

For each topology, multicast groups have been assigned a set of proportional constants $\{\gamma_g\}_{g=1}^{G}$. It is assumed that these constants follow the probability mass function [88]

$$p_{\gamma_g} = \begin{cases} 1 & with\ probability\ 0{,}5 \\ 2 & with\ probability\ 0{,}3 \\ 4 & with\ probability\ 0{,}2 \end{cases} \tag{20}$$

which also indicates the gold, silver and bronze multicast groups, i.e., $p_{\gamma_g} = 4$ indicates gold multicast groups, $p_{\gamma_g} = 2$ indicates silver multicast groups and $p_{\gamma_g} = 1$ indicates bronze multicast groups. In the figures below, bandwidth ratio [90] is defined as the ratio of chunk bandwidth to channel coherence bandwidth, and it is used to show the effect of the ratio of the two bandwidths on the average throughput, i.e. $\frac{N'\Delta f}{f_c}$.

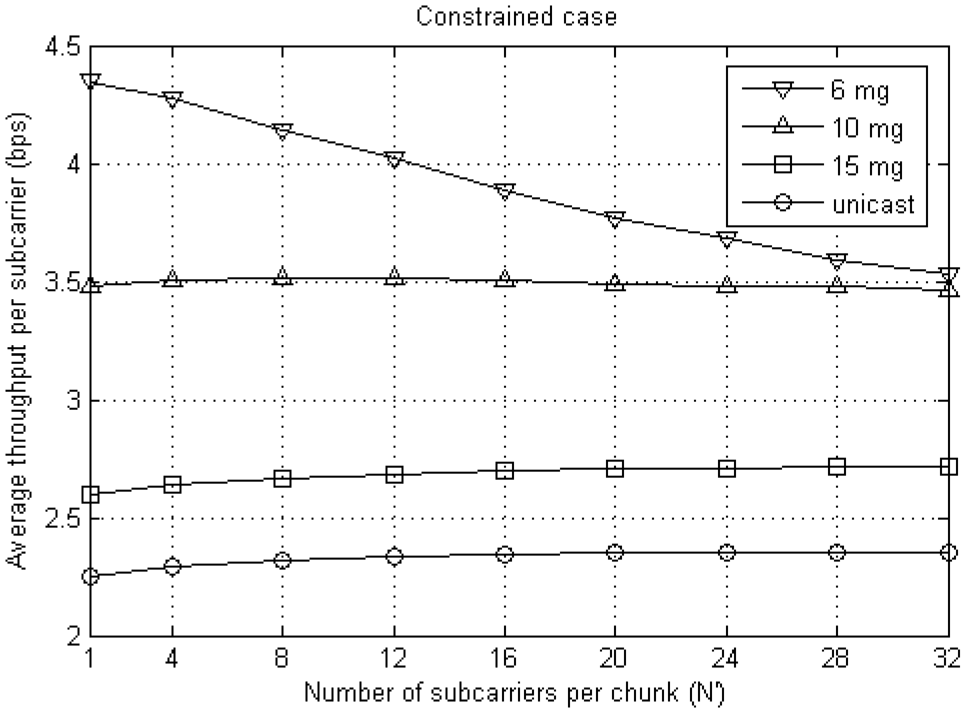

Fig. 8: Constrained case: Average throughput per subcarrier vs number of subcarriers per chunk; mg stands for multicast group.

In Fig. 7 and Fig. 8, the average throughput of the unconstrained case [85] and proposed algorithm (constrained case), respectively, are shown as a function of subcarriers per chunk, N', and number of multicast groups G. In Fig. 9 and Fig. 10, the average throughput of the unconstrained case [85] and proposed algorithm (constrained case), respectively, are shown as a function of bandwidth ratio and number of multicast groups G. In Fig. 7 and Fig. 9, it can be seen that in the unconstrained case as the number of multicast groups G increases, average throughput increases too; this is justified since the system exploits better the benefits of multiuser diversity. However, increasing G or decreasing N' leads also to increase in the complexity of the proposed algorithm. In addition, the performance of [85] is superior to the performance of the proposed algorithm as it targets sum data rate maximization with average BER constraints guaranteeing no proportional fairness at all between multicast groups' average data rates. On the other hand, in Fig. 8 and Fig. 10, as the number of multicast groups, G, increases, average throughput decreases as in that case proportional data rate constraints are better guaranteed because the system exploits multiuser diversity more efficiently.

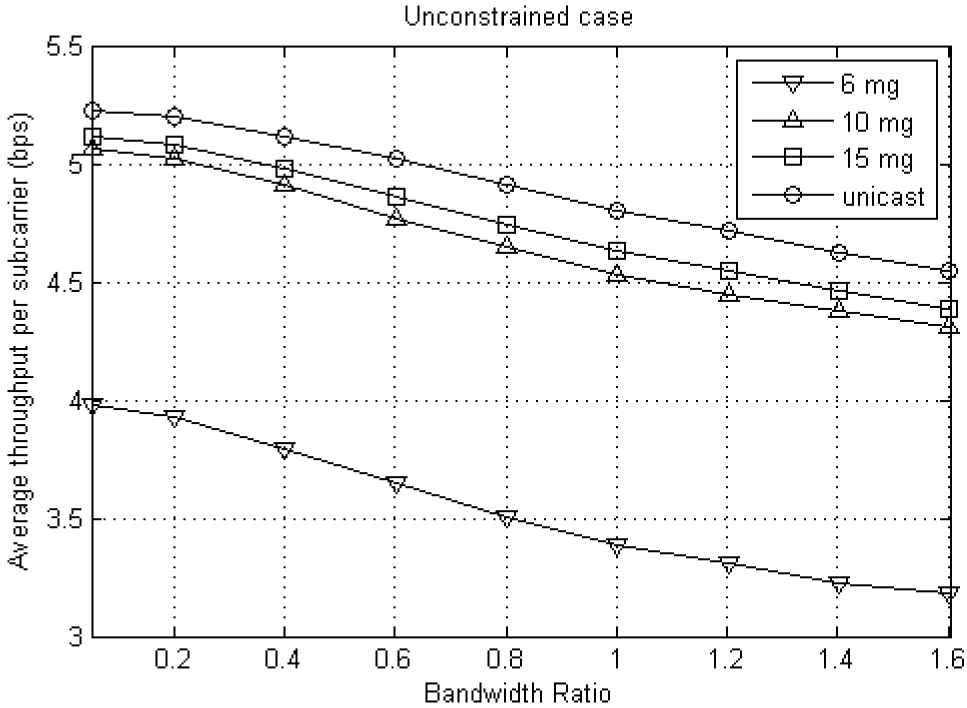

Fig. 9: Unconstrained case: Average throughput per subcarrier vs bandwidth ratio; mg stands for multicast group.

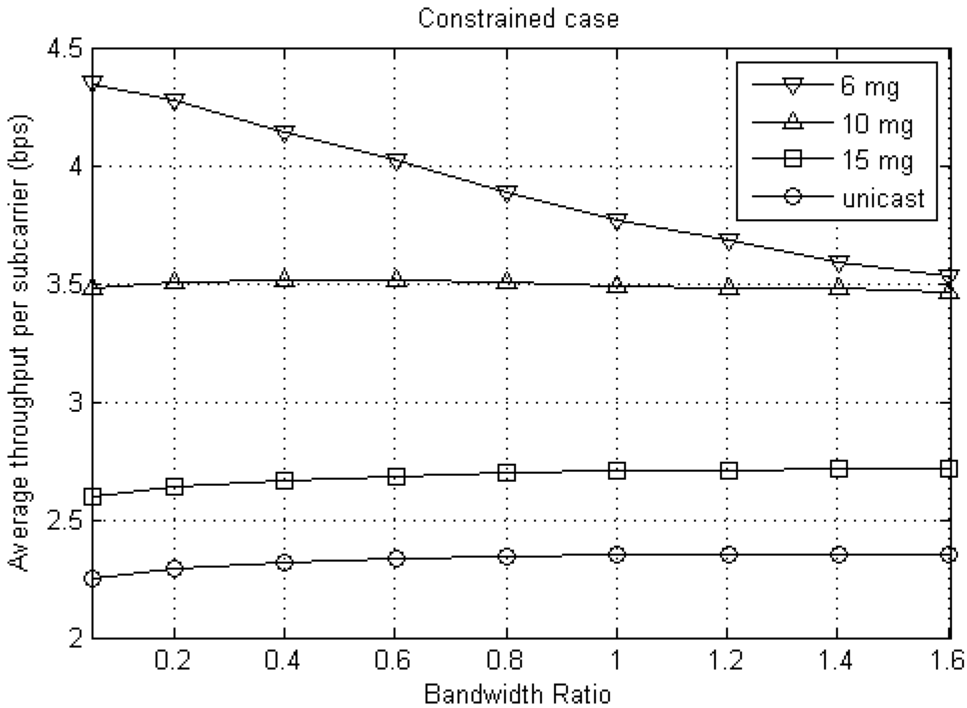

Fig. 10: Constrained case: Average throughput per subcarrier vs bandwidth ratio; mg stands for multicast group.

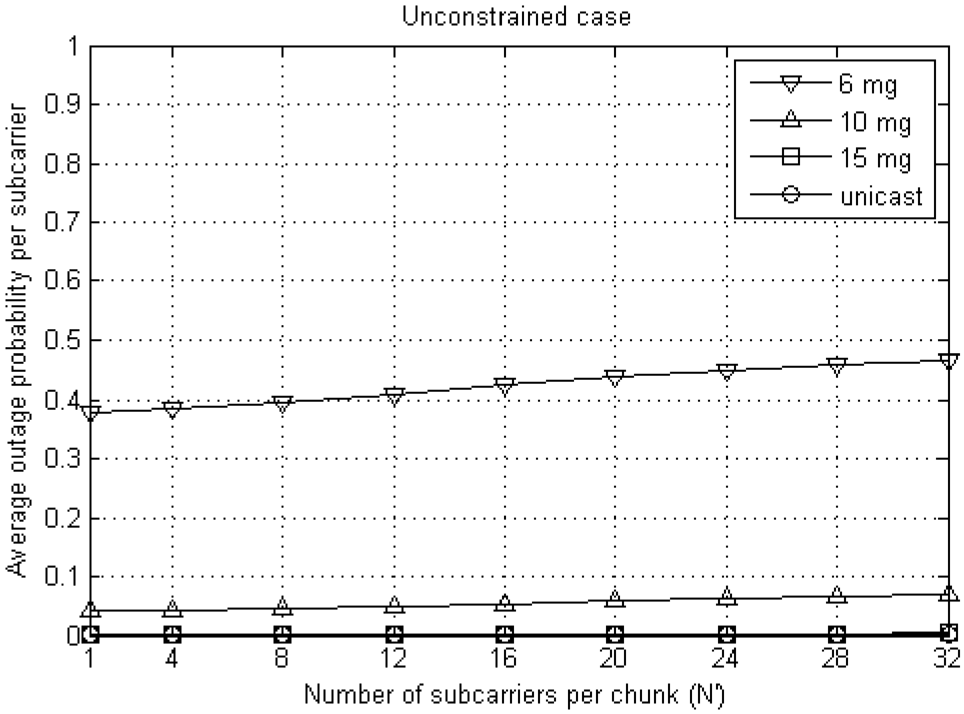

Fig. 11: Unconstrained case: Average outage probability per subcarrier vs number of subcarriers; mg stands for multicast group.

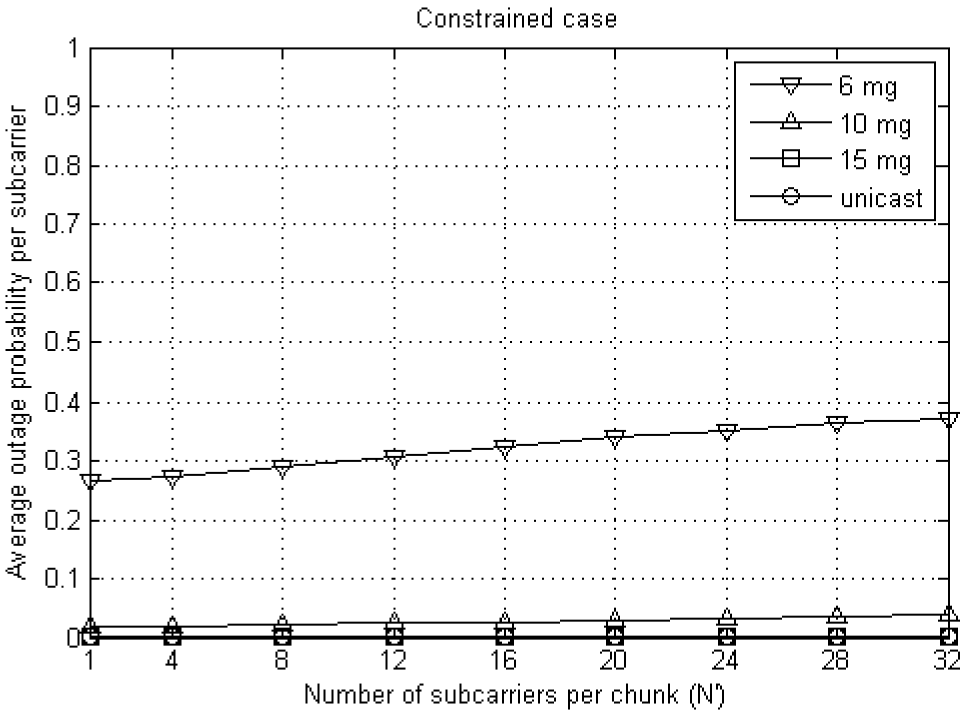

Fig. 12: Constrained case: Average outage probability per subcarrier vs number of subcarriers; mg stands for multicast group.

In Fig. 11 and Fig. 12 the average outage probability of the unconstrained case [85] and proposed algorithm (constrained case), respectively, are shown as a function of subcarriers per chunk, N', and number of multicast groups G. In addition, in Fig. 13 and Fig. 14 the average outage probability of the two cases are shown as a function of bandwidth ratio and number of multicast groups G. In all cases average outage probability is robust to the number of contiguous subcarriers per chunk as it can be seen only a small variation in average outage probability as N' increases. In addition, as the number of G, increases, average outage probability decreases because multiuser diversity is better exploited. The ratio of chunk bandwidth to the coherence bandwidth can be used as a parameter in the BER-based chunk allocation scheme. Small ratio means that the chunk bandwidth is much smaller than the coherence bandwidth, and the increasing slope of average outage probability is smaller. Finally, in constrained case average outage probability is smaller than unconstrained case.

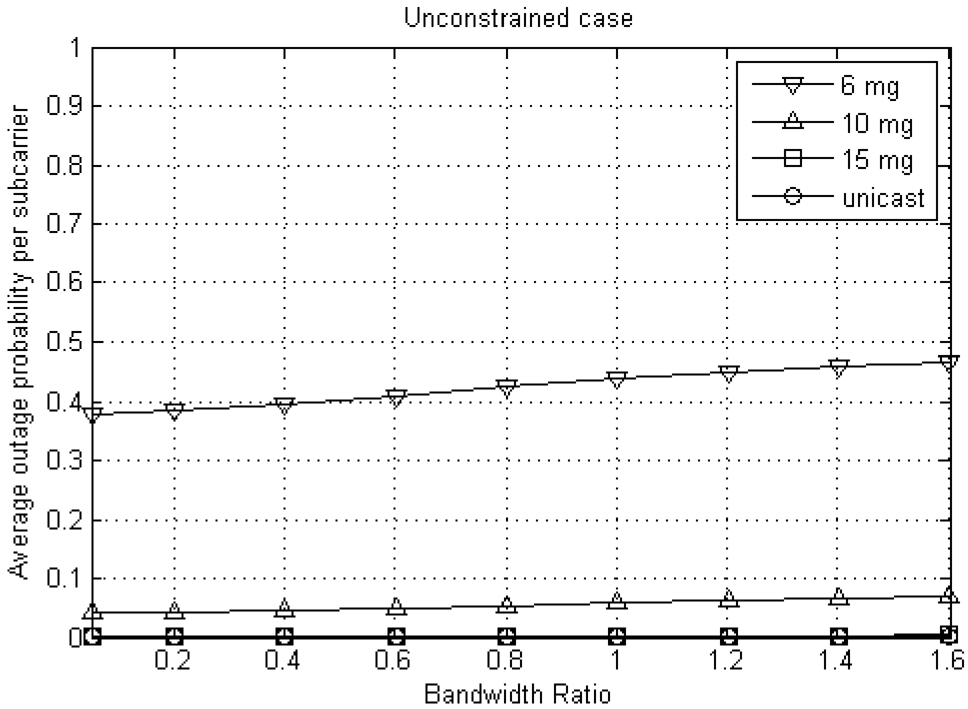

Fig. 13: Unconstrained case: Average outage probability per subcarrier vs bandwidth ratio; mg stands for multicast group.

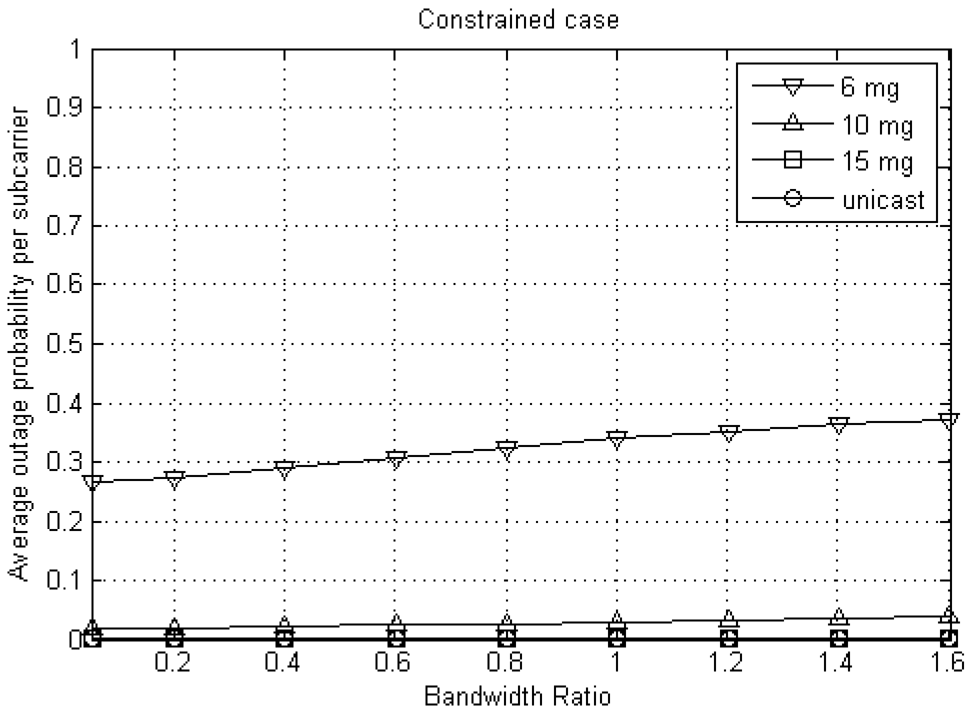

Fig. 14: Constrained case: Average outage probability per subcarrier vs bandwidth ratio; mg stands for multicast group.

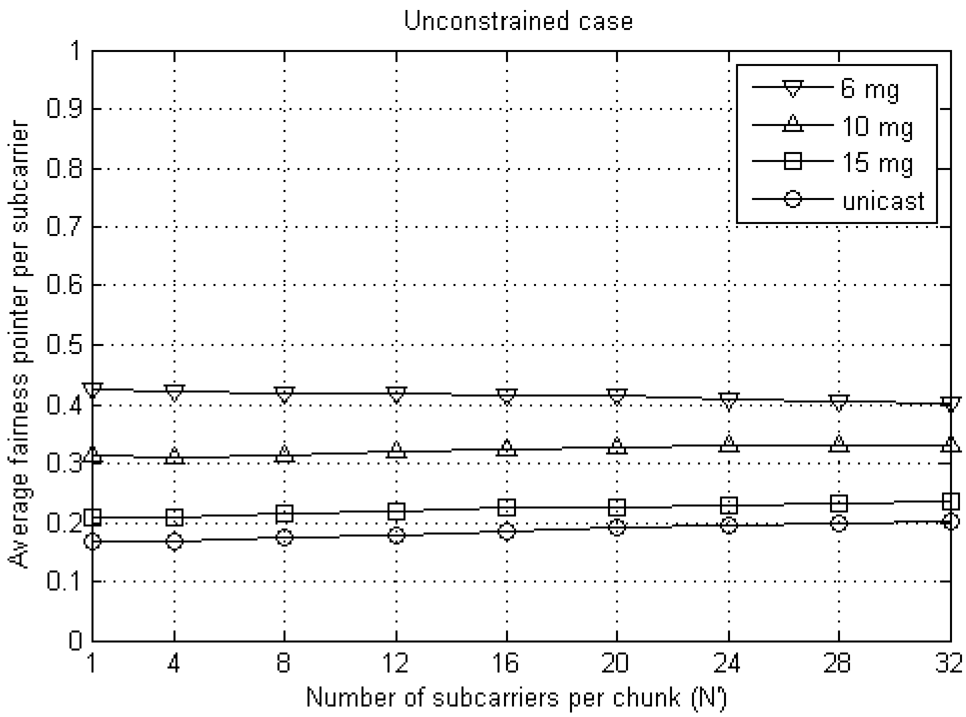

Fig. 15: Unconstrained case: Average fairness pointer per subcarrier vs number of subcarriers per chunk; mg stands for multicast group.

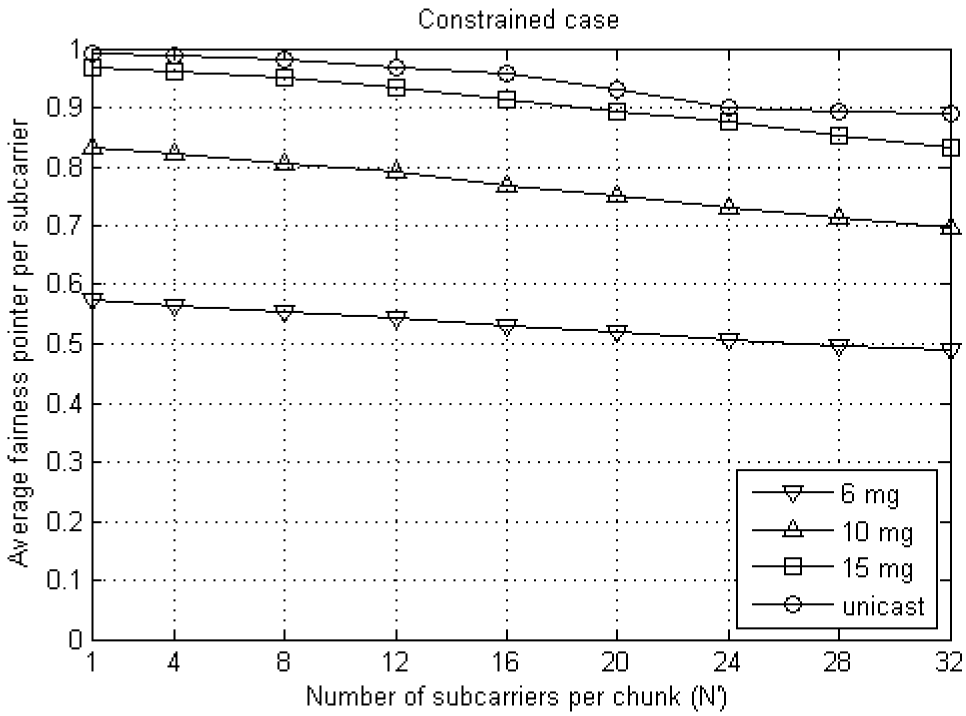

Fig. 16: Constrained case: Average fairness pointer per subcarrier vs number of subcarriers per chunk; mg stands for multicast group.

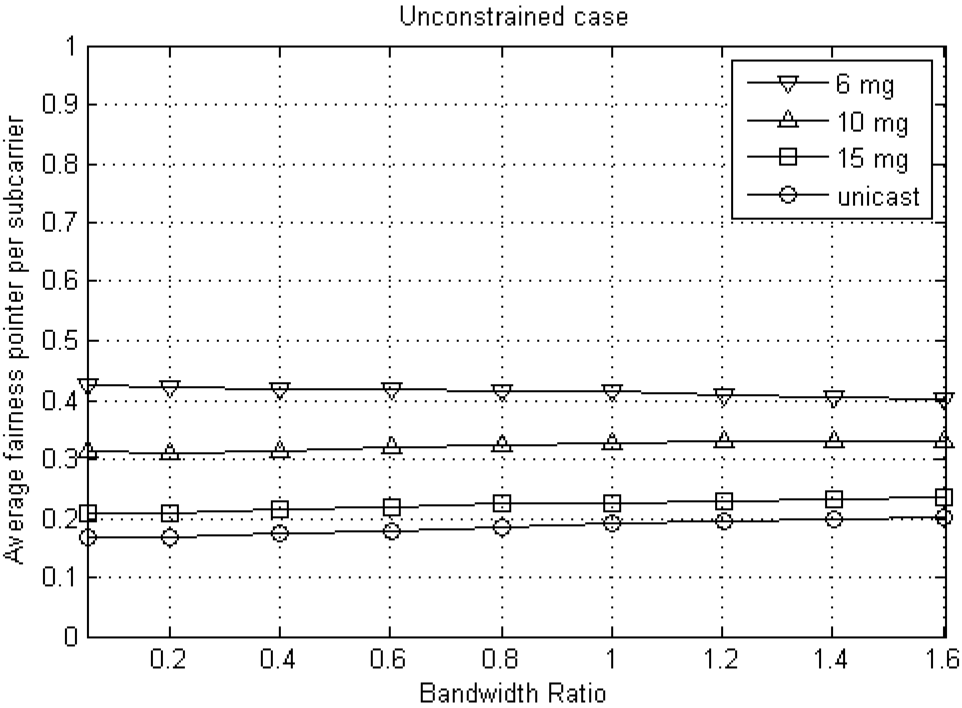

Fig. 17: Unconstrained case: Average fairness pointer per subcarrier vs bandwidth ratio; mg stands for multicast group.

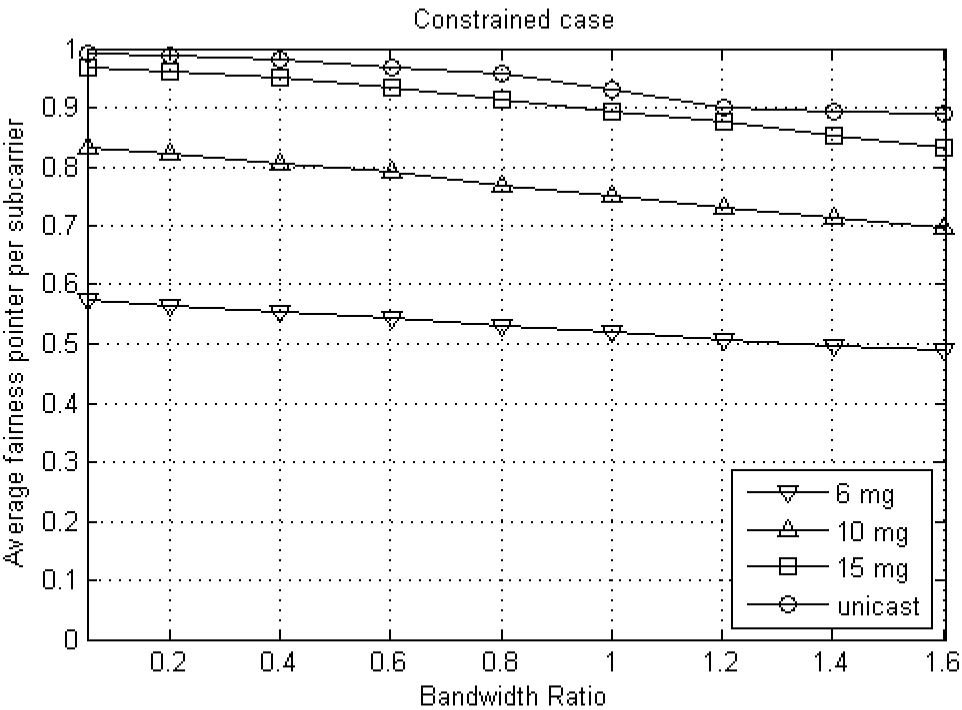

Fig. 18: Constrained case: Average fairness pointer per subcarrier vs bandwidth ratio; mg stands for multicast group.

In Fig. 15 and Fig. 16 the average fairness pointer per subcarrier of the unconstrained case [85] and proposed algorithm (constrained case), respectively, are shown as a function of subcarriers per chunk, N', and number of multicast groups G. In addition, in Fig. 17 and Fig. 18 the average fairness pointer per subcarrier of the unconstrained case [85] and proposed algorithm (constrained case), respectively, are shown as a function of bandwidth ratio and number of multicast groups G. Fairness pointer is defined as

$$F_p = \frac{\left(\sum_{g=1}^{G} \frac{\tilde{R}_g}{\gamma_g}\right)^2}{G \sum_{g=1}^{G} \left(\frac{\tilde{R}_g}{\gamma_g}\right)^2}, \tag{21}$$

where F_p is a real number in the interval $(0, 1]$ with the maximum value of 1 for the case that the achieved data rate proportions among multicast groups are the same as the predetermined set $\{\gamma_g\}_{g=1}^{G}$. Employing the algorithm for the unconstrained case, no guarantees are provided for the fairness between multicast groups' data rates and all algorithms experience almost the same fairness pointer regardless of the number of subcarriers per chunk. In addition, as the number of multicast groups increases, the proposed algorithm distributes the sum data rate very well among multicast groups, very close to the defined data rate constraints.

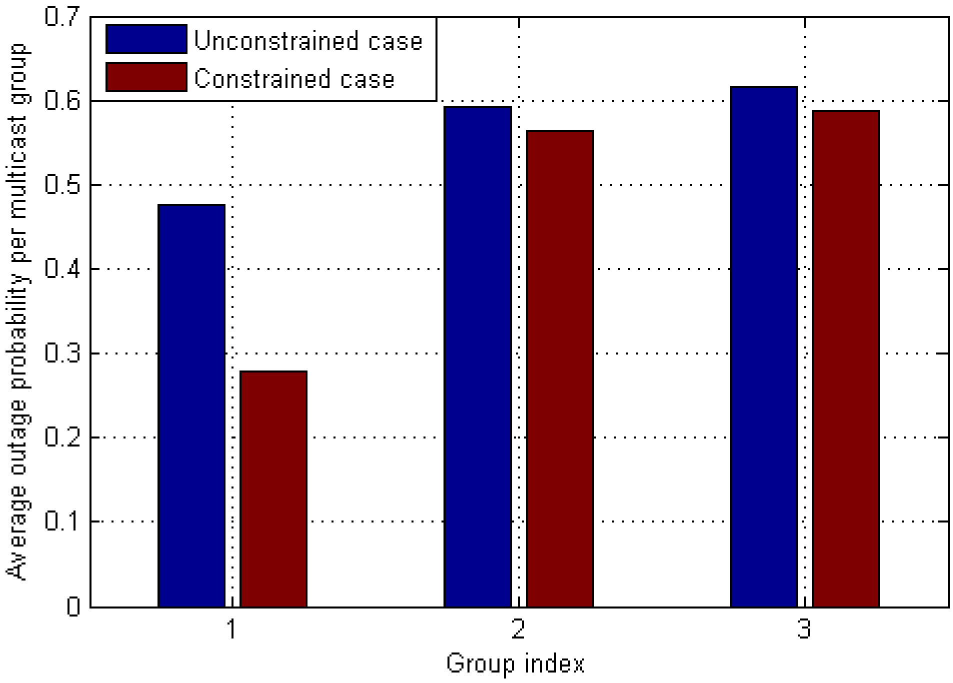

Fig. 19: Average outage probability per multicast group vs group index when there are three multicast groups present in the system.

In Fig. 19 and Fig. 20, the average outage probability per multicast group is shown as a function of group index when there are available three multicast groups and six multicast groups, respectively. It can be seen that in the constrained case average outage probability is smaller compared to the constrained case. This happens mainly because multiuser diversity is exploited better.

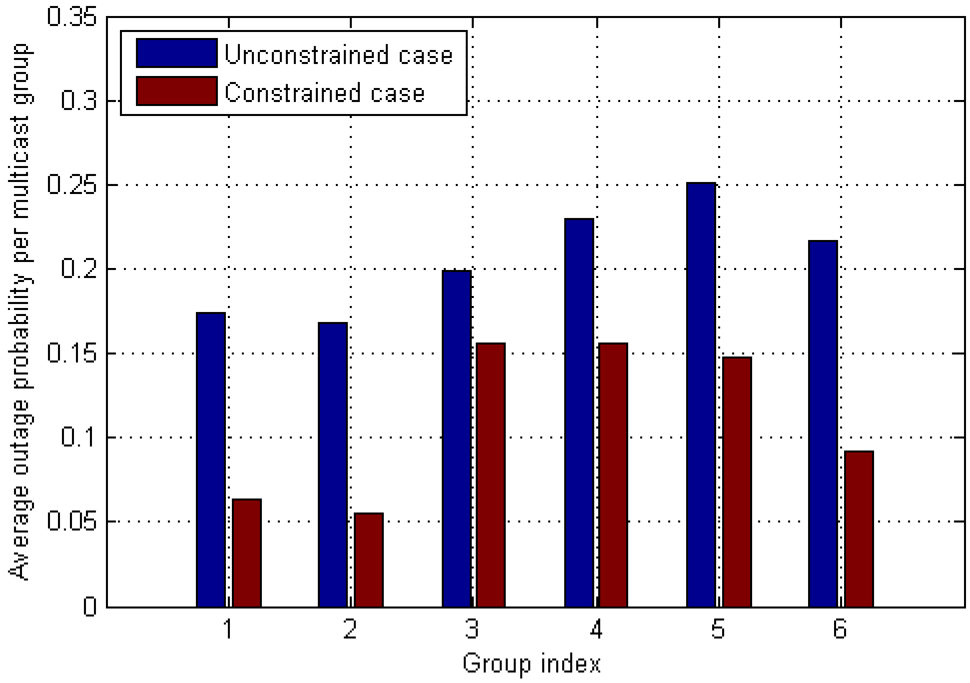

Fig. 20: Average outage probability per multicast group vs group index when there are six multicast groups present in the system.

4. CONCLUSION AND FUTURE WORK

Much of the existing work, relating to the problem of resource allocation in multicast OFDMA wireless systems, focuses on finding efficient chunk assignment guaranteeing BER below a predetermined level and proportional data rates among multicast groups. The present work has been compared to the unconstrained case [85] when only average BER is guaranteed. As can be seen in the simulation results, when the proposed algorithm is applied, while average data rate decreases compared to [85], average outage probability decreases too and average fairness among multicast groups is much higher than the unconstrained case.

This thesis consisted of four chapters. The first chapter was the introductory chapter of the Thesis where a brief history of cellular systems, the motivation of this work and the related work were introduced. In the second chapter, the system model and problem formulation were mainly introduced while in the third chapter, the proposed algorithm and simulation results were introduced. Finally, this last chapter summarizes the main results obtained in this thesis and concludes this work.

The future work in our research includes the extension of our scientific work to cover not only the single-cell scenario but also cover a multicellular environment. In that case co-channel interference and possible coordination between the BSs of different cells should be taken into account.

TERMINOLOGY MATRIX

English Term	Greek Term
Chunk	Τεμάχιο
Wideband	Ευρεία ζώνη
Capacity	Χωρητικότητα
Resource allocation	Κατανομή πόρων
Subcarrier	Υποφορέας
Multicast systems	Συστήματα πολυεκπομπής
Computational complexity	Υπολογιστική πολυπλοκότητα

ACRONYMS

TDMA	Time Division Multiple Access
GSM	Global System for Mobile Communications
FDMA	Frequency Division Multiple Access
CDMA	Code Division Multiple Access
AMPS	Advanced Mobile Phone Systems
FM	Frequency Modulation
E-TACS	European Total Access Communication System
D-AMPS	Digital AMPS
FCC	Federal Communications Commission
ES	Expanded Spectrum
SIR	Signal to Interference Ratio
GPRS	General Packet Radio Service
WCDMA	Wideband Code Division Multiple Access
FDD	Frequency Division Duplex
TDD	Time Division Duplex
QoS	Quality of Service
PTM	Point To Multipoint
UMTS	Universal Mobile Telecommunications Systems
MT	Mobile Terminal
BS	Base Station
MBMS	Multimedia Broadcast and Multicast Service
3GPP	Third Generation Partnership Project
OFDMA	Orthogonal Frequency Division Multiple Access
MIMO	Multiple Input Multiple Output
DRRA	Dynamic Radio Resource Allocation
QoE	Quality of Experience
LTE	Long Term Evolution
OFDM	Orthogonal Frequency Division Multiplexing
ICI	Intracell Interference
QAM	Quadrature Amplitude Modulation
MSRA	Multicast Scheduling and Resource Allocation
DRA	Dynamic Resource Allocation
BER	Bit Error Rate

SNR	Signal to Noise Ratio
BPSK	Binary Phase Shift Keying
MS	Mobile Station
NLOS	Non Line of Sight
LOS	Line of Sight
AWGN	Additive White Gaussian Noise
ISI	Intersymbol Interference
CSI	Channel State Information
STM	Strict Throughput Maximization
MMF	Max-Min Fairness
AVG	Average
LCG	Least Channel Gain
PTF	Proportional Throughput with Fairness
FDM	Frequency Division Multiplexing
HF	High Frequency
DFT	Discrete Fourier Transform
IFFT	Inverse Fast Fourier Transform
FFT	Fast Fourier Transform
VLSI	Very Large Scale Integration
ADSL	Asymmetric Digital Subcarrier Loop
HDSL	High-bit-rate Digital Subscriber Line
VHDSL	Very High-speed Digital Subscriber Line
DAB	Digital Audio Broadcasting
DVB	Digital Video Broadcasting
HDTV	High Definition Television
MAN	Metropolitan Area Network
MAC	Medium Access Control
MSR	Maximum Sum Rate
PRC	Proportional Rate Constraints
OWL	Web Ontology Language
SWRL	Semantic Web Rule Language
CSIT	Channel State Information for Transmitter
CSIR	Channel State Information for Receiver
JDC	Japanese Digital Cellular

PDC	Personal Digital Cellular
BTS	Base Tranceiver Station
BSC	Base Station Controllers
NSS	Network Switching Subsystem
MSC	Mobile Switching Center
VLR	Visitor Location Register
HLR	Home Location Register
AC	Authentication Center
EIR	Equipment Identity Register
BSS	Base Station Subsystem
VAS	Value Added Services
VMS	Voice Mail Service
SMSC	Short Message Service Center
IN	Intelligent Services
SGSN	Servicing GPRS
GGSN	Gateway GPRS
DNS	Domain Name Servers
EDGE	Enhanced Data rates in GSM Environment
ITU	International Telecommunication Union
3GPP	3rd Generation Partnership Project
RNC	Radio Network Controller
WMSC	Wideband CDMA Mobile Switching Center
HSPA	High Speed Packet Access
DL	Downlink
UL	Uplink

APPENDIX I: COMPLEXITY OF BASIC ALGORITHMS

Algorithmic complexity is concerned about how fast or slow particular algorithm performs. Complexity is defined as a numerical function $T(n)$ - time versus the input size n. $T(n)$ depend on the implementation. A given algorithm takes different amounts of time on the same inputs depending on such factors as: processor speed, instruction set, disk speed, brand of compiler and etc. The way around is to estimate efficiency of each algorithm asymptotically. Time $T(n)$ is measured as the number of elementary "steps" (defined in any way), provided each such step takes constant time.

The goal of computational complexity is to classify algorithms according to their performances. The time function $T(n)$ is represented using the "big-O" notation to express an algorithm runtime complexity. For example, the following statement

$$T(n) = O(n^2) \tag{22}$$

says that an algorithm has a quadratic time complexity. For any monotonic functions $f(n)$ and $g(n)$ from the positive integers to the positive integers, it is said that $f(n) = O(g(n))$ when there exist constants $c > 0$ and $n_0 > 0$ such that

$$f(n) \leq c \cdot g(n), \text{ for all } n \geq n_0 \tag{23}$$

Intuitively, this means that function $f(n)$ does not grow faster than $g(n)$, or that function $g(n)$ is an upper bound for $f(n)$, for all sufficiently large $n \to \infty$

<u>Constant Time: $O(1)$</u>

An algorithm is said to run in constant time if it requires the same amount of time regardless of the input size. Examples:

- array: accessing any element
- fixed-size stack: push and pop methods
- fixed-size queue: enqueue and dequeue methods

<u>Linear Time: $O(n)$</u>

An algorithm is said to run in linear time if its time execution is directly proportional to the input size, i.e. time grows linearly as input size increases. Examples:

- array: linear search, traversing, find minimum
- ArrayList: contains method
- queue: contains method

<u>Logarithmic Time: $O(log\, n)$</u>

An algorithm is said to run in logarithmic time if its time execution is proportional to the logarithm of the input size. Example:

- binary search

Quadratic Time: $O(n^2)$

An algorithm is said to run in logarithmic time if its time execution is proportional to the square of the input size. Examples:

- bubble sort, selection sort, insertion sort

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