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Resource Allocation Algorithm with Dynamic Subcarrier Assignment in OFDMA-based Wireless Networks

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The allocation of available resources is one of the main issues in multi-user systems. Dependence of system capacity on radio link quality is an additional obstacle of efficient resource allocation in wireless networks. Combinations of two opposite approaches – fair resource allocation and system capacity maximization are used to solve this problem in practice.

This paper proposes a resource allocation method that is primarily based on assigning almost an equal bandwidth to all users. System capacity maximization is achieved by selecting the subcarriers with the best SNR values. This algorithm was developed for orthogonal frequency division multiple access (OFDMA) wireless systems. Resource allocation is done at the subcarrier level according to the weight factor that had been calculated for each user. Frequency hopping was used to increase frequency diversity and to make the system more robust to disturbance. Frequency hopping pattern is determined dynamically on the basis of SNR value of each subcarrier.

The results of the proposed algorithm are compared with the water filling (WF) and proportional fairness (PF) methods. The influence of various data traffic classes on system throughput and resource allocation is also described.

Key words: OFDMA, QoS, Resource allocation, Subcarrier scheduling

Algoritam alokacije resursa s dinamičkim pridruživanjem podnosioca u bežičnim mrežama zasnovanim na OFDMA-u. U sustavima s više korisnika jedno od glavnih pitanja je kako podijeliti raspoložive resurse. Kod radio mreža dodatni otežavajući faktor predstavlja promjenjivost kapaciteta sustava ovisno o kvaliteti radio veze. U praksi se za raspodjelu resursa obično koriste algoritmi koji su kombinacija dvaju oprečnih pristupa, fer raspodjele resursa i maksimizacije kapaciteta sustava.

U ovom radu predložena je metoda primarno bazirana na fer raspodjeli resursa. Maksimizacija kapaciteta sustava ostvarena je odabirom podnosilaca s najboljim mogućim SNR-om. Algoritam je razvijen za sustave bazirane na OFDMA. Dodjela resursa korisnicima vrši se na razini pojedinog podnosioca prema izračunatom težinskom faktoru za svakog korisnika posebno. Kako bi se povećao frekvencijski diverziti i sustav učinio otpornijim na smetnje, uvedeno je frekvencijsko skakanje prema dinamički određenom predlošku. Predložak se formira na osnovu SNR vrijednosti određene po svakom podnosiocu.

Rezultati predloženog algoritma uspoređeni su s WF (water filling) i PF (proportional fairness) algoritmima. Prikazan je utjecaj različitih klasa prometa na prijenosni kapacitet i raspodjelu resursa sustava.

Ključne riječi: OFDMA, QoS, raspodjela resursa, raspoređivanje podnosilaca

1 INTRODUCTION

Wireless networks enable access to various data and services on the Internet. The continuous increase of multimedia content enhances the needs for higher data speed in communication channels. For this purpose, many advanced technologies are used, such as orthogonal frequency division multiple access (OFDMA), multiple-input and multiple-output (MIMO), frequency hopping (FH), adaptive modulation and coding (AMC), dynamic resource allocation [1, 2]. They strive to provide high data throughput and quality of established communications with most rational use of available transmission bandwidth.

A model of transmission communication system has been developed to increase data throughput, better exploit the available bandwidth and fairly distribute system capacity. A new resource allocation algorithm (RAA) for this model has been developed and described in this paper. It aims to provide an efficient distribution of resources with respect to Quality of Service (QoS) requirements [3, 4] for specific service classes.

There are two possible approaches of resource allocation among users – throughput maximization and fair resource allocation. The practical solutions try to provide the balance between the two. The general idea is to achieve the highest possible data throughput while keeping proportional resource allocation among users. In [5] the authors give advantage to fair allocation with additional conditions that prevent excess reduction of bandwidth efficiency. The authors suggest proportional fairness algorithm. Three algorithms are proposed by [6]. The first algorithm assigns the same capacity to each user; the second spreads different capacity proportionately with channel conditions, while the third algorithm provides equal capacity with non-adaptive slot allocation approach.

Diversity and AMC mode are compared in [7]. The authors have shown that higher throughput is achieved with AMC method relative to randomly distributed subcarriers. In addition to AMC and dynamic power allocation, the algorithm complexity is analysed in [8]. The advantage is given to low-complexity algorithm with suboptimal capacity redistribution. Due to higher number of non-linearly correlated variables, a heuristic algorithm with linearized variables is suggested. Such an algorithm computes faster and can be performed in real time. It is shown in the paper that such heuristic algorithms achieve similar performance with significantly lower complexity.

Unlike previously mentioned algorithms, [9] proposes the allocation algorithms with QoS and scheduling priority. The algorithm maximizes OFDM system throughput with different QoS requirements for each user. Revenue factor is used to balance between throughput and QoS. The proposed algorithm takes care of channel conditions and required data rate per user.

Priority scheduling algorithm between real time (RT) and non-real time (NRT) traffic with various QoS requirements is described [3], [4] and [10]. A similar approach of cross-layer scheduling that differentiates RT and NRT traffic is used in [11]. RT traffic is favored while assuring minimum reserved data rate for NRT traffic.

In [12] a variation of PF algorithm is described whereby the first phase achieves minimum data rate for users and the second phase applies PF algorithm. In addition, PF algorithm is considered [13] to achieve a trade-off between throughput and fairness, i.e. to decrease system throughput while improving fair resource allocation among users. Power allocation is based on water filling method.

The advantages of random FH application in OFDM within Long Term Evolution (LTE) context are analysed in [14]. The benefits of dynamic FH are compared to pseudo-random FH, assuming perfect signal measuring and no delay in signaling [15, 16].

In this paper an RAA algorithm suitable for multi-user, multi-channel and multi-service environment is developed. Compared with the aforementioned approaches, this cross-layer algorithm unites fair resource allocation to users with capacity maximization and dynamic subcarrier allocation at the subcarrier level. It also supports for adaptive modulation and coding and frequency hopping according to dynamically determined hopping pattern. The system is based on OFDM and 802.16 standard. According to the channel quality information (CQI), it dynamically selects the best available subcarriers for each user. The quality of subcarriers is determined by SNR values obtained from preambles. Due to various conditions in their micro locations, each user receives subcarriers with different signal-to-noise ratio (SNR). SNR calculation and dynamic subcarrier assignment is done for each subcarrier and each user. A modulation coded (MC) group is determined for each subcarrier. Additional frequency diversity is achieved with FH between subcarriers of the same quality to prevent system capacity degradation. Unlike other papers, FH is not limited to the pre-defined set of subcarriers only and hopping pattern is determined dynamically based on the subcarriers' quality [14-16].

The description of the model, SNR calculation per user, and the principles of subcarriers allocation are described in the second section of the paper. The proposed algorithm is elaborated in the third part. System throughput is calculated in the fourth section and the proposed RAA is compared with water filling (WF) and proportional fairness (PF) methods. The allocation between the users and total throughput are observed. A comparison is done for NRT traffic and for more realistic mixture of RT and NRT traffic. Influence of higher RT data quantity on allocation between users and overall system capacity is also analysed. Last section concludes.

2 SYSTEM MODEL

The proposed solution was developed on the basis of the 802.16 standard [17], with significant revisions and adaptations. The data streams generated for the users are transferred into transmitter where traffic data are analysed according to the defined classes and QoS. The data traffic is generally divided into RT and NRT traffic [3]. According to the IEEE 802.16 standard, Worldwide Interoperability for Microwave Access (WiMAX) QoS transport unit is defined as service flow between the mobile station (MS) and the base station (BS) [4], [11]. With LTE QoS transport unit is a bearer between use equipment (UE) and the Packet Data Network Gateway (PDN GW). In the 802.16 standard QoS scheduling types are: unsolicited grant service

(UGS), extended real-time polling service (ertPS), real-time polling service (rtPS), non-real time polling service (nrtPS), and best effort (BE). With the LTE guaranteed bit rate (GBR) mechanism functions as rtPS, while non-GBR mechanism functions as BE. There are certain differences between referred classes of RT traffic, but due to simplicity of implementation, it is assumed that the same QoS requirements are present for all RT traffic classes. The same principle is assumed for NRT traffic. Although it is possible to define five groups of data traffic in simulation, for the purpose of simplification of the LTE, only the RT and the NRT traffic groups are considered. It is also assumed that certain algorithms such as Earliest Deadline First (EDF) and Weight Fair Queue (WFQ) are applied within certain data traffic classes to respect priorities of data blocks' sending.

After the SNR values have been calculated and MC groups selected, the subcarriers are allocated to the users by means of RAA. The assignment of subcarriers to a particular MC group is determined according to the SNR levels shown in Table 1. SNR thresholds are set for each MC group [11] based on required bit error rate (BER). The column MC_B in Table 1, shows the number of data bits that can be sent per one subcarrier inside one WiMAX data frame in downlink communication. The quantity of sent data varies depending on the applied modulation and coding. Zero pad tail byte and redundant bits arose due to Reed-Solomon (RS) and convolution coding (CC) are added to the data. In this way created bits are modulated in symbols that fill a data frame.

The algorithm for dynamic FH is embedded in the system. FH is done if there is a free subcarrier of the same quality for an observed user. The system selects the subcarrier that was not used in the previous frame. Frequency diversity is enhanced in this way. As FH is done exclusively among the same quality subcarriers, there is no reduction in throughput and transmission rate of the system. Hopping pattern for FH is not pre-defined because it is determined dynamically based on the subcarriers' quality [14-16], [18]. The algorithm of subcarrier allocation is described in Section 3 in more details.

The data are subsequently coded, modulated, packaged and prepared for sending. The OFDMA transmission system is used with 192 data subcarriers, 8 pilots, 256-point FFTs, cyclic prefix length $\frac{1}{8}$ and channel bandwidth of 3.5 MHz. Adaptive modulation and coding is applied according to the conditions in the transmission channel. Seven MC groups are used for modulation and coding in the simulation: OFDMA with BPSK $\frac{1}{2}$, QPSK $\frac{1}{2}$, QPSK $\frac{3}{4}$, 16QAM $\frac{1}{2}$, 16QAM $\frac{3}{4}$, 64QAM $\frac{2}{3}$ and 64QAM $\frac{3}{4}$. The coding is run as Forward Error Correction (FEC), consisting of a RS outer code concatenated with a rate-compatible inner CC. After that the data pass through three independent channels until they are received by three receivers, decoded and demodulated. A non-fading, flat-fading, or dispersive multipath fading can be chosen in each of three independent transmission channels. Additive white Gaussian noise (AWGN) variance (in SNR mode) is added to the signal. An appropriate *K* factor, maximum Doppler shift, number of paths, and path gains can be changed accordingly. The data rate varies dynamically in relation to the channel conditions.

Stanford University Interim (SUI), SUI 3 channel model is used in the simulation together with the following parameters: dispersive multipath fading channel with different combinations of AWGN parameter, *K* factor 0.5, maximum Doppler shift 0.5 Hz, delay vector $[0\ 0.4\ 0.9]$ in μs and gain vector $[0\ \ -5\ \ -10]$ in dB.

To show how the proposed model works, three users are chosen for simplicity reasons. The downlink communication is analysed only in this simulation.

Perfect system synchronization is assumed. It is supposed that control bits are known to both the transmitter and the receiver. In comparison to the existing solutions, the information on signal reception from the preamble, which is needed for SNR calculation along all subcarriers, and the information on allocated subcarriers for each user have to be additionally communicated with this method.

3 PROPOSED RESOURCE ALLOCATION ALGORITHM

The proposed RAA is a two-phase algorithm. Figure 1 shows the selecting procedure of subcarriers for each user. The incoming data contain RT and NRT data traffic. In the first phase the algorithm allocates RT and, if defined, mandatory NRT (mNRT) data traffic. The resources for mNRT data are assigned to ensure that all users get minimum guaranteed bandwidth for NRT data traffic [11]. In the second phase NRT data traffic is distributed to its subcarriers up to the full system capacity. Due to stringent QoS requirements for RT traffic, the subcarriers with the best SNR values are respectively selected for each user. The assignment of better quality subcarriers to RT traffic guarantees the satisfaction of QoS requirements. The entire system capacity is enhanced in this way and the required QoS parameters (e.g. small delay, delay variation, and maximum sustained data rate) are achieved [1].

The weight factors (*W*) are direct measures of assigned throughput of a user, expressed in allocated bits' number for useful data transmission in the observed time period within a particular frame [9]. Fair resource allocation is achieved by equalizing *W*, while data rate maximization is accomplished by selecting the best subcarriers for each user.

Table 1. MC groups parameters

SNR	MC group	MC_B (data bits)	Zero pad tail byte	Number of bits after RS and CC coding	Bits per symbol	Number of symbol per frame
(6, 11]	1 (BPSK 1/2)	88	8	192	1	192
(11, 12]	2 (QPSK 1/2)	184	8	384	2	192
(12, 14]	3 (QPSK 3/4)	280	8	384	2	192
(14, 15]	4 (16QAM 1/2)	376	8	768	4	192
(15, 19]	5 (16QAM 3/4)	568	8	768	4	192
(19, 25]	6 (64QAM 2/3)	760	8	1152	6	192
(25, ∞)	7 (64QAM 3/4)	856	8	1152	6	192

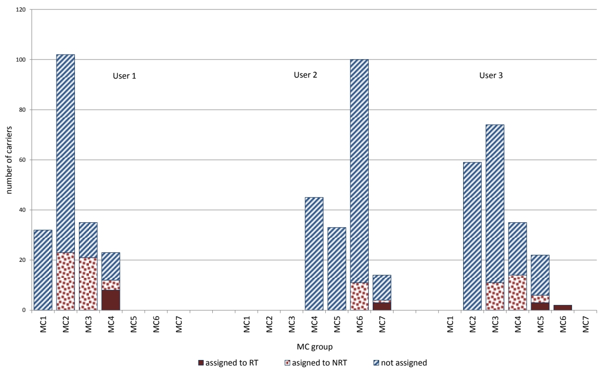

Fig. 1. RT and NRT data traffic across MC groups for each user

If the Ws are equal, the advantage is given to the user with higher MC group, if applicable. An additional diversity in frequency domain is achieved by checking the previous constellation vector of subcarriers. In case of the same Ws and the same MC groups, allocation of the same subcarriers from the previous allocation cycle to the same users is avoided as much as possible. Thereby the effect of FH is created.

The applied algorithm assigns a subcarrier X_k, ($k = (1, 2, ..., M)$, where M is the number of data subcarriers) to user U_j, ($j = (1, 2, ..., N)$, where N is number of users). The logic of the algorithm is described as follows:

1. it is examined how many users h from N fulfils the following two conditions:
    - a user has data for transmission
    - a user has free and usable subcarriers
2. if $h = 0$, the algorithm ends
3. if $h = 1$, subcarriers for specific user are assigned for data transmission until there are either free subcarriers or data
4. if $h \geq 2$, subcarriers are allocated according to the following rules:

    a) the subcarrier X_k will be assigned to the user U_j, if the user U_j has the smallest W: $W_j = \min\{W_1, ..., W_N\}$. W_1 , ..., W_N, are weight factors for users U_1, ..., U_N. The subcarriers are allocated to this user until the upper condition is valid. The algorithm is subsequently repeated;

    b) if there are L users, where $L = (1, 2, ..., N)$, with the same factor W, the subcarrier X_k would be allotted to the user U_j for which X_k has the highest MC group. Function G determines the user U_j with highest MC group for the observed subcarrier X_k.

    $$G(X_k(U_j)) = \max\{G(X_k(U_1)), ..., G(X_k(U_L))\}$$

    MC groups are assigned according to Table 1.

After defined criteria in subcarrier allocation are fulfilled, additional FH requirements for subcarriers' allocation applied are:

- if users have the same MC group and different subcarriers, a subcarrier is assigned to the first registered user in the system who has not got the same subcarrier in the previous allocation cycle.

  If the decision is not made, it is checked whether there are more subcarriers with the same MC group. In such case, the following subcarriers in a raw are taken and previous allocation cycle is checked to avoid the repetitive allocation of the same subcarrier to the same user.

  If the decision has still not been made, a subcarrier is added according to the registration order in the system;

- if users have the same MC group and the same subcarriers, the previous allocation cycle is checked. The subcarrier is allocated to the user that has not had it in the previous cycle.

In described method throughput maximization is achieved by allocating the best subcarriers first, and fair resource allocation between the users is accomplished by equaling overall allocated capacity inside the frame. The assignment of better quality subcarriers to RT traffic guarantees QoS requirements' satisfaction [19].

4 SIMULATION RESULTS

The system needs to be overloaded to show the efficiency of proposed RAA. With insufficient system load, the RAA cannot show its full functionality because the algorithm is not crucial for subcarriers' allocation.

Minimum bit quantity that needs to be transmitted in each data downlink frame is defined for RT traffic to fulfill QoS requirements for this data class. If this condition is not satisfied, because of poor channel conditions, the simulation is interrupted. Minimum Qos requirements are not obtained. Furthermore it is possible to define minimum quantity of NRT traffic (mNRT) that needs to be transmitted in each frame. The quantity of remaining NRT traffic to be transferred in the frame is determined by the remaining capacity of the frame with respect to fair allocation among the users. The NRT data that are not transferred in the current frame are put into a buffer to be transferred in the subsequent frames.

If the conditions in the transmission channels are the same for all users, the fair allocation of total system capacity is assumed. Hence, resource allocation and system capacity with different channel quality are observed in the proposed, water filling (WF) and proportional fairness (PF) method [6].

4.1 Calculating system throughput

The system capacity can be calculated in the following way. Assume that Z_i is the number of subcarriers of certain MC group. The variable MC denotes MC group, $i = 1, 2, ..., 7$.

$$Z_i = \sum_{k=1}^{M} 1_{(\mathrm{MC}=i)}$$

$$1_{(\mathrm{MC}=i)} = \begin{cases} 1, & \mathrm{MC} = i \\ 0, & \mathrm{MC} \neq i \end{cases}.$$

The transmission system capacity C that is assigned to the user U_j is calculated as the number of bits that a user U_j can transfer in one frame:

$$C_{U_j} = \sum_{i=1}^{7} Z_{\mathrm{ji}}\, \mathrm{MC}_{B_i}.$$

Z_{ji} is the number of subcarriers of certain MC group for user U_j. $\mathrm{MC}_{\mathrm{Bi}}$, $i = 1, 2, ..., 7$, is the number of bits transferred by certain MC group according to the Table 1.

The system transmission capacity of the frame is calculated as:

$$C_{\mathrm{FRAME}} = \sum_{j=1}^{N} C_{U_j}.$$

If $M = 192$, $N = 3$, in the simulation sample, transmission capacity of one frame equals:

$$\begin{aligned} C_{\mathrm{FRAME}} &= \sum_{j=1}^{3} C_{U_j} \\ &= \sum_{j=1}^{3}\sum_{i=1}^{7} Z_{\mathrm{ji}}\, \mathrm{MC}_{B_i} \\ &= \sum_{j=1}^{3}\sum_{i=1}^{7} \left(\sum_{k=1}^{192} 1_{(\mathrm{MC}=i,j)} \right) \mathrm{MC}_{B_i}. \end{aligned}$$

If F_t stands for duration of one frame, throughput T_R equals:

$$T_R = \frac{C_{\mathrm{FRAME}}}{F_T}.$$

4.2 Resource allocation among users in proposed, WF and PF method

Resource allocation for the proposed method with different SNR values in users' transmission channels is illustrated in Fig. 2. The comparison with PF and WF method is done on 10-frame basis and full system load. For algorithm testing purpose, the simulation was run for two different cases, i.e. for RT traffic only and for RT and NRT traffic. In the first case the incoming data contain NRT traffic only. Due to simulating large differences in quality of the transmission channel between the users, average SNR values are set to 15, 19 and 30. The SNR value of 15 has been taken because the quality of the transmission channel worsens significantly below this threshold while BER falls below defined 10^{-5}. For SNR values below 15, the algorithm cannot ensure uniform resource allocation between the users. As it can be seen from Fig. 2, the applied algorithm ensures fair resource allocation among the users even if the differences in quality of the communication channel are substantial. The curves for all users overlap along the entire observed area.

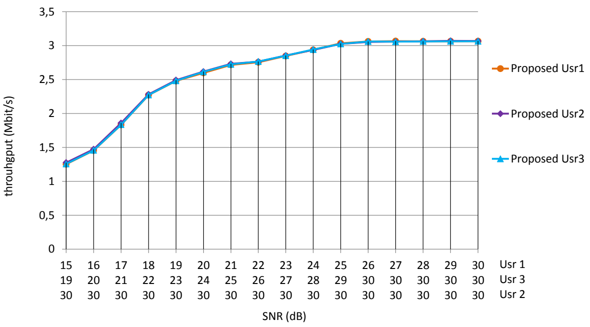

Fig. 2. Resource allocation for the proposed method - NRT data

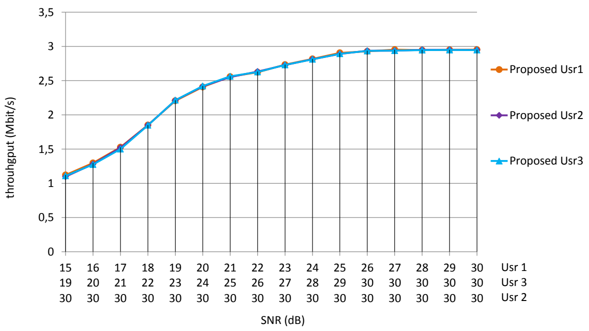

Fig. 3. Resource allocation for the proposed method - RT and NRT data

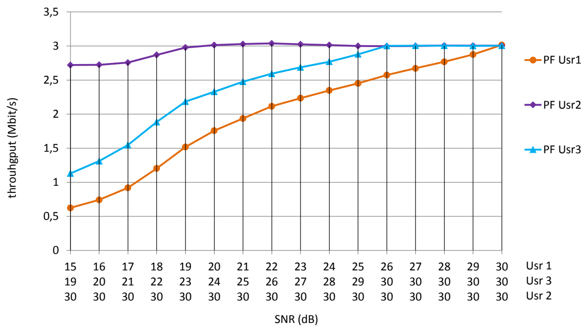

Fig. 4. Resource allocation for the PF method - NRT data

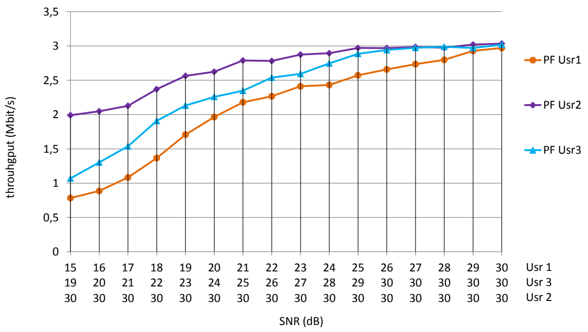

Fig. 5. Resource allocation for the PF method - RT and NRT data

Figure 3. depicts the second case when RT traffic is added to NRT traffic, which is a more realistic situation. After adding RT traffic (4000 bits), mandatory part of NRT traffic (1000 bits), and other NRT traffic up to the full capacity of a frame, resource allocation remains unchanged with minor decrease in transmitted bit quantity per user. The throughput decrease is a consequence of fewer possible combinations for subcarriers' allocation due to prioritizing mandatory traffic (two-phase algorithm).

The simulation with the same data and under the same conditions has been conducted to compare the proposed method with PF and WF methods. Proportional subcarriers' allocation has been done with the PF method. Every third subcarrier is allocated to each user. MC group has been selected based on SNR value calculation for each subcarrier. As evidenced in Fig. 4, in PF method fair resource allocation depends exclusively on the difference in quality of the assigned subcarriers. The bigger the difference in quality of the transmission channel the larger the difference in distributed capacity to the users.

If mandatory traffic is added (RT = 4000 bits, mNRT = 1000 bits, with NRT traffic up to the full capacity of a frame) Fig. 5 shows that distributional curves preserve their shape with slightly more uniform allocation. The latter is a consequence of mandatory traffic allocation requirement to all users in the first phase of algorithm.

Figure 6 shows resource allocation between users under the WF method. The subcarriers are assigned only to the user who has the highest SNR value. The balanced resource allocation is possible only at high SNR values (SNR 26 30 30). SNR value and the apportioned MC group are selected in the same way as with the previously described methods.

When RT and mNRT traffic are added (Fig. 7), the curves do not fall to zero value. Rather, they stay at the minimum defined mandatory traffic (RT + mNRT = 5000 bits) that reduces the difference in data allocation between the users.

4.3 Overall throughput for the proposed, PF and WF method

Figure 8 compares the total system throughput for three users by applying the proposed, WF and PF method. WF

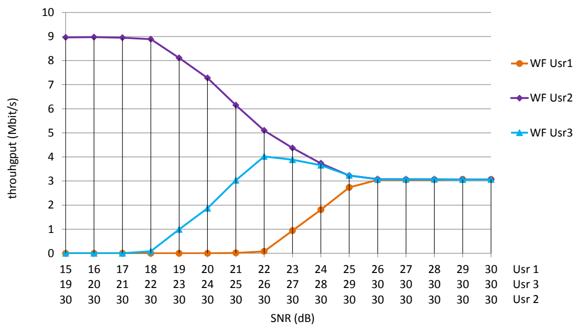

Fig. 6. Resource allocation for water filling method - NRT data

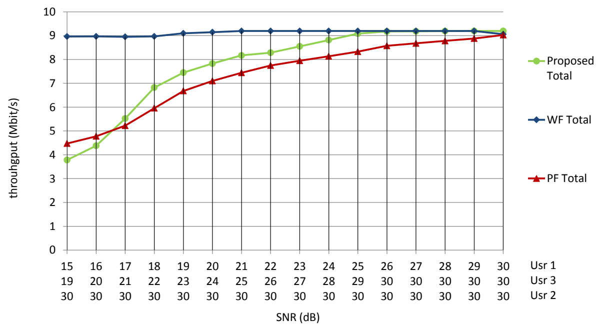

Fig. 8. Overall throughput for the proposed, WF and PF algorithm - NRT data

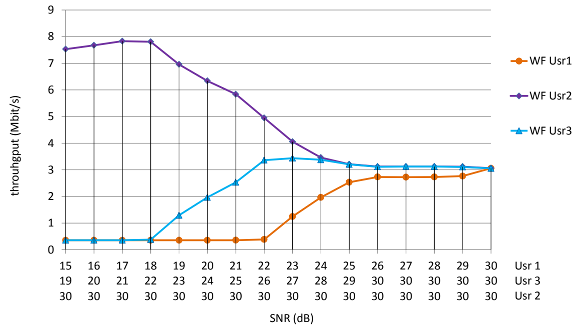

Fig. 7. Resource allocation for water filling method - RT and NRT data

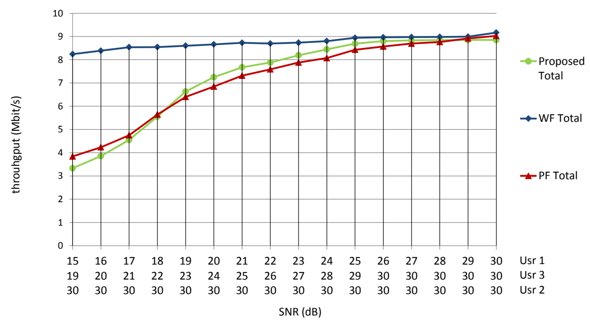

Fig. 9. Overall system throughput for the proposed, WF and PF algorithm - RT and NRT data

ensures the maximum system throughput all the time but with disproportional resource allocation between the users. PF provides higher system throughput than the proposed method at lower SNR values but with worse, unequal resource allocation between the users. The proposed method shows smaller system throughput at lower SNR values because the resources are taken from the users with better SNR values and allocated to the users with worse SNR levels to preserve uniform resource allocation between the users.

Figure 9 illustrates total system throughput for all three methods under RT and mNRT traffic. As expected, the system throughput in all methods is smaller compared to the results of the simulation obtained with NRT traffic data only. It is because the number of possible subcarriers for allocation is fewer in the two-phase algorithm application. Furthermore, forcing subcarriers' allocation to users with the worse transmission channel in the first algorithm phase is necessary to ensure mandatory traffic transmission to all users.

All simulations are conducted assuming the full system load with NRT traffic or by adding smaller quantity of mandatory traffic (10% at low SNR levels) that the proposed system, due to total capacity of a frame, can compensate for.

Figure 10 illustrates an extreme situation of the proposed method application with high RT traffic quantity (23000 bits - 60% of the total data traffic at low SNR values) added to the user with the worst channel quality (user 1). Other users have been allocated NRT traffic only.

The applied algorithm consumes the majority of resources while trying to ensure mandatory traffic transmission (for user 1). The rest of the system capacity is equally distributed among other users, namely user 2 and user 3 (their curves overlap). At lower SNR values resource allocation to all users is not proportional as the available resources within the frame are not sufficient. As a consequence, the total throughput of the system transferring large quantity of RT traffic (red line) is constantly lower, while it has been considerably reduced at low SNR levels compared to NRT data transfer only (light green line).

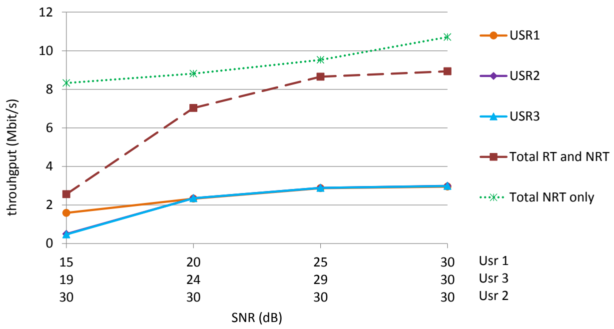

Fig. 10. Resource allocation in the proposed method when high quantity of RT traffic is assigned to the user with the worst transmission channel quality

5 CONCLUSION

Resource allocation and the overall system throughput are compared for the proposed method, WF and PF algorithm at different SNR levels in users' transmission channels. The proposed method ensures fair resource allocation between all users in wider SNR area with varying conditions in the transmission channel. However, increased resource allocation fairness causes smaller total system throughput at lower SNR values.

In case of RT and mNRT traffic transmission, the total system throughput has been reduced due to two-phase algorithm application. Forced allocation of the subcarriers to the users with mandatory traffic decreases overall system throughput as well.

REFERENCES

[1] T.-M. Wu, "Dynamic and Fair Resource Allocation Algorithm for OFDM Systems", *IEEE Communications Letters*, vol. 11, no. 12, pp. 931-933, Dec. 2007.

[2] D. Xenakis, D. Tsolkas, N. Passas, N. Alonistioti, L. Merakos, "Dynamic resource allocation in adaptive wireless OFDMA systems", *Wireless Communications and Mobile Computing*, vol. 12, no 11, pp. 985-998, 2012.

[3] T. Ali-Yahia, A.-L. Beylot, and G. Pujolle, "Radio Resource Allocation in Mobile WIMAX Networks Using Service Flows", presented at the 18th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications (PIMRC), Athens, Greece, 3-7 Sept, 2007.978-1-4244-1144-3.

[4] J. F. Borin and N. L. S. da Fonseca, "Scheduler for IEEE 802.16 Networks", *IEEE Communications Letters,* vol. 12, no. 4, pp. 274-276, April 2008.

[5] A. Biagioni, R. Fantacci, D. MArabissi and D. Tarchi, "Adaptive Subcarrier Allocation Schemes for Wireless OFDMA Systems in WiMAX Networks", *IEEE Journal on Selected Areas in communications*, vol. 27, no.2, pp. 217-225, Feb. 2009.

[6] D. Marabissi, D. Tarchi, R. Fantacci, and A. Biagioni, "Adaptive Subcarrier Allocation Algorithms in Wireless OFDMA Systems", in *Proc. IEEE ICC*, Beijing, pp. 3383-3387, 2008.

[7] S.K. Kim and C.G. Kang, "Throughput Analysis of Band AMC Scheme in Broadband Wireless OFDMA System", In vol. 3 proceedings of the *IEEE Wireless Communications and Networking Conf. (WCNC)* Las Vegas, NV, pp. 1305-1310, April 2006

[8] S. M. Alavi, C. Zhou, and Y. Cheng, "Low Complexity Resource Allocation Algorithm for IEEE 802.16 OFDMA System", presented at the IEEE ICC, Dresden, Germany, Jun 14-18, 2009.

[9] F. R. Farrokh, M. Olfat, M. Alasti, and K. J. R. Liu, "Scheduling Algorithms for Quality of Service Aware OFDMA Wireless Systems", presented at the IEEE GLOBECOM conf., Dresden, Germany, vol. 4, pp. 2689-2693, 2004.

[10] L. Wan, W. Ma and Z. Guo, "A Cross-layer Packet Scheduling and Subchannel Allocation Scheme in 802.16e OFDMA System", In *IEEE Wireless Communications and Networking Conf. (WCNC) Proceedings ,* Kowloon, pp.1865-1870, March 2007

[11] T. A. Yahiya, A.-L. Beylot, and G. Pujolle, "Cross-Layer Multiservice Scheduling for Mobile WiMAX Systems", In *IEEE Wireless Communications and Networking Conf. (WCNC) Proceedings*, Las Vegas, NV, pp. 1531-1535, April, 2008.

[12] I. G. Frimis, and S. A. Kotsopoulos, "QoS-Based Proportional Fair Allocation Algorithm for OFDMA Wireless Cellular Systems", *IEEE Communications Letters*, vol. 15, no. 10, pp. 1091-1093, Oct. 2011.

[13] T.-D. Nguyen and Y. Han, "A Proportional Fairness Algorithm with QoS Provision in Downlink OFDMA Systems", *IEEE Communications Letters*, vol. 10, no. 11, pp. 760-762, Nov. 2006.

[14] M. Putzke, C. Wietfeld, "Self-organizing OFDMA systems by random frequency hopping", In proceedings of the 4th IFIP Wireless Days, Niagara Falls, Ontario, Oct. 2011

[15] Z. Kostić, I. Marić, X. Wang, "Fundamentals of dynamic frequency hopping in cellular systems", *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 11, pp. 2254-2266, 2001.

[16] Z. Kostić, N.. Sollenberger, "Performance and implementation of dynamic frequency hopping in limited-bandwidth cellular systems", *IEEE Transactions on Wireless Communications*, vol. 1, no. 1, pp. 28-36, 2002.

[17] IEEE Standard for Local and Metropolitan Area Networks, Part 16: Air interface for broadband wireless access systems, Std. 802.16 -revision of IEEE Std. 802.16-2004, 2009.

[18] G. Ren, H. Zhang, Y. Chang, "SNR estimation algorithm based on the preamble for OFDM systems in frequency selective channels", *IEEE Transactions on Communications*, vol. 57, no. 8, pp. 2230-2234. 2009.

[19] H. Zhang, G. Bi, L. Zhang, "Adaptive subcarrier allocation and bit loading for voice/data transmission in multiuser OFDM systems", *Wireless Communications and Mobile Computing*, vol. 9, no. 7, pp. 894-908, 2009.

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