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Fuzzy Logic Based Opportunistic Scheduler Design to Improve Fairness in Cellular Wireless Networks

Hakkı Soy, Özgür Özdemir

***Abstract*— In the design of wireless scheduling policies, the fairness criterion plays an important role in upgrading the performance of the network. This paper concentrates on how the opportunistic scheduler can improve both throughput and fairness in cellular wireless networks. In order to improve the fairness while providing high throughput, we propose an adaptive scheduling algorithm by using fuzzy logic. Proposed scheduler operates on TDMA fashion and calculates the priority index of each node according to instantaneous channel quality and time-slot allocation among nodes. We analyse the fairness and throughput performances of proposed algorithm under both single and multiple antenna node scenarios via statistical simulations. The obtained results show that proposed algorithm can improve the fairness but at the expense of slight throughput loss compared to pure opportunistic scheduling algorithms.**

***Index Terms*—fairness, fuzzy logic, opportunistic scheduling, wireless network.**

I. Introduction

Wireless networks consist of spatially distributed autonomous nodes that communicate by exchanging packets via radio frequency (RF) signals. The key characteristic of the wireless channel is the fading due to the multipath propagation of the transmitted signal, which creates replicas of the transmitted signal that arrive at the receiver with different delays [1]. Due to the fading effect, the channel conditions of nodes have time-varying behavior at a certain time, which is called multiuser diversity [2]. Time and location dependent signal quality variations cause time-varying channel capacity. The utilization of multiuser diversity in wireless networks can increase the information theoretic capacity by allowing opportunistic usage of the channel [3].

Opportunistic scheduling exploits the multiuser diversity to maximize network throughput by granting higher priority to nodes with better channel quality [4, 5]. Recently, opportunistic approaches have drawn much research attention due to its throughput advantage [6]. In little scattering and/or slow fading environments, the multiuser diversity gain is obtained by opportunistic beamforming method by using multiple antennas at the base station (BS) [7]. But, always giving priority to the powerful nodes causes unfairness in access to the shared channel. Therefore, the achievable gain of opportunistic scheduler is generally restrained with fairness considerations. Since the fairness criterion plays an important role in throughput performance, there are several fair opportunistic scheduling schemes that have been proposed to reflect different trade-off scenarios [8, 9].

Hakkı Soy, Electrical and Electronics Engineering, Engineering and Architecture Faculty, Necmettin Erbakan University, Konya, Turkey, +90 532-5759111

Özgür Özdemir, Electrical Engineering, Qatar University, Doha, Qatar

Nowadays, wireless communication systems that employ multiple antennas at the transmitting end as well as the receiving end have attracted considerable attention due to the throughput advantage over traditional counterparts. The multiple-input multiple-output (MIMO) technology has the potential to be part of wireless networks such as wireless local area networks (WLANs) and mobile telecommunication networks beyond third-generation (3G) [10]. The one primary reason to use multiple-antenna nodes is to improve the link's quality and transmission reliability by minimizing the channel fluctuations due to fading effect with spatial diversity [11]. In receive diversity, the statistically independent copies of transmitted signal received from multiple antennas are conveniently weighted and combined. So, the effective SNR (ESNR) of the combined branches is obtained through diversity combining techniques [12].

In this study, unlike existing opportunistic scheduling algorithms, we introduce a fuzzy logic based scheduling algorithm that will be maintaining fairness among nodes by considering the number of channel access besides the instantaneous channel quality. Fuzzy logic can offer a simple presentation and a good framework to arrive at right decision in the design of scheduling algorithm. In proposed algorithm, the BS collects the instantaneous channel state information (CSI) from nodes, interprets channel assignment information (CAI) and prioritizes channel access accordingly. To evaluate the appropriateness of fuzzy approach, the performance of proposed scheduling algorithm is investigated against existing algorithms in terms of throughput and fairness. Our aim is to balance the trade-off between throughput and fairness for downlink transmission.

The rest of the paper is organized as follows: Section II presents system model and formulates channel quality, fairness, throughput measurement process. Section III describes the proposed scheduling algorithm. Section IV presents simulation results for both proposed and existing algorithms. Finally, Section V draws some conclusions.

Notation. The boldface is used for vectors. For a given vector **v**, v_i denotes the ith element of the vector and $\mathbf{v}^H$ denotes the Hermitian transpose of the vector. $\|\cdot\|$ represents the Euclidean norm of the enclosed vector and $E[\cdot]$ denotes expectation operator. □□ (μ, σ^2) represents the circularly symmetric complex Gaussian random variable with mean μ and variance σ^2.

II. System Model

The system of interest is a single cell of the cellular wireless network that consists of multiple nodes. The BS coordinates all data transmissions within its coverage range. Connection from the BS to the nodes takes place on the downlink channel, while the opposite occurs on the uplink channel. Only the BS has access to the downlink channel, while uplink channel is shared among nodes.

A. Wireless Network with Single Antenna Nodes

The downlink system model of the considered network setup is shown in Figure 1. The BS is equipped with M antennas serving K nodes whereas each node is equipped with single antenna. The channel between the kth SN and the BS is denoted by $M \times 1$ vector $\mathbf{h}_k = [h_{k,1}\ h_{k,2}\ \dots\ h_{k,M}]^{\mathrm{T}}$ and the elements of $\mathbf{h}_k$ are independent and identically distributed (i.i.d.) adopting circularly symmetric, complex, Gaussian distribution whose mean is zero and variance which is $\bar{\gamma}$, $h_{k,m} \sim$ □□ $(0, \bar{\gamma})$. It is assumed that the channel is frequency flat, block-Rayleigh fading and the channel vector $\mathbf{h}_k$ is considered to be constant over a fixed number of time slots called one frame and changes between different frames independently.

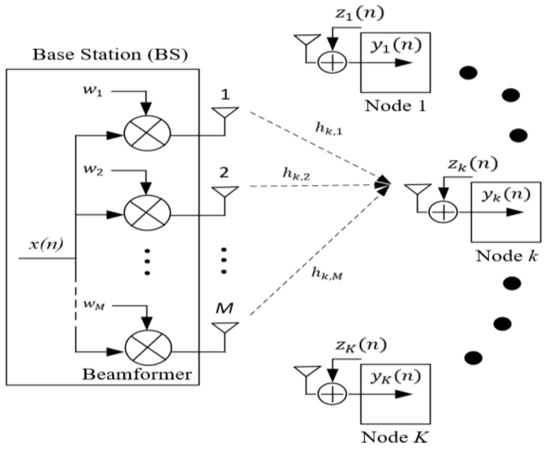

Figure 1. The system model with single antenna nodes.

The BS forms the beam by choosing the $M \times 1$ random beamforming vector $\mathbf{w}$ whose distribution is identical to the distribution of $\mathbf{h}_k$ but normalized to keep the transmit power fixed, $\mathbf{w} \sim \mathbf{h}/\|\mathbf{h}\|$. The pilot signal $x(n)$ with power $\mathrm{E}[x^2(n)] = \varepsilon_x$ is transmitted from the BS to the nodes. The received signal $y_k(n)$ at the kth node may be written as

$$y_k(n) = \left(\mathbf{w}^{\mathrm{H}}\mathbf{h}_k\right)x(n) + z_k(n) \tag{1}$$

where $z_k(n)$ is the circularly symmetric, complex, additive white Gaussian noise (AWGN) with distribution □□ $(0, \sigma^2)$. Note that, by randomly changing the beamforming vector $\mathbf{w}$ at each time slot, the observed composite channel process of the kth node $(\mathbf{w}^{\mathrm{H}}\mathbf{h}_k)$ changes from time slot to time slot due to the time-varying beamforming vector.

In order to simplify the analysis, we assume that the channel statistics of all the nodes are the same and the ratio of the transmit energy to the noise variance (ε_x/σ^2) is 1. So, without loss of generality, the path loss together with all the other powers is lumped into the channel process. With these assumptions, the SNR of the kth node can be written as

$$\gamma_k = \mathbf{w}^{\mathrm{H}}\mathbf{h}_k\mathbf{h}_k^{\mathrm{H}}\mathbf{w} \tag{2}$$

In proposed method, we use normalized SNR (N-SNR) as alternative channel quality metric due to its suitability to the fuzzy inference systems. N-SNR is defined as the ratio of the received SNR to the maximum SNR. The N-SNR of the kth node can be computed as

$$\eta_k = \frac{\mathbf{w}^{\mathrm{H}}\mathbf{h}_k\mathbf{h}_k^{\mathrm{H}}\mathbf{w}}{\mathbf{h}_k^{\mathrm{H}}\mathbf{h}_k}. \tag{3}$$

Note that the N-SNR value is in [0,1] interval.

B. Wireless Network with Multiple Antenna Nodes

The BS is equipped with M antennas serving K nodes which has L antennas provided that $L \leq M$. The channel between the kth node and the BS is denoted by $L \times \mathrm{M}$ matrix $\mathbf{H}_k = [h_{k,1}\ \dots\ h_{k,L}]^{\mathrm{H}}$ and each row of $\mathbf{H}_k$ is given by $M \times 1$ channel gain vector $\mathbf{h}_{k,l}$ from all antennas of the BS to the lth antenna of the kth node. Each entry of the channel gain vector $h_{k,l,m}$ is the channel gain from the mth antenna of the BS to the lth antenna of the kth node for $m = 1, \dots, M$, $l = 1, \dots, L$ and $k = 1, \dots, K$. The channel gain coefficients are modeled to be independent and identically distributed (i.i.d.) adopting circularly symmetric complex Gaussian distribution, $h_{k,l,m} \sim$ □□ $(0, \bar{\gamma})$.

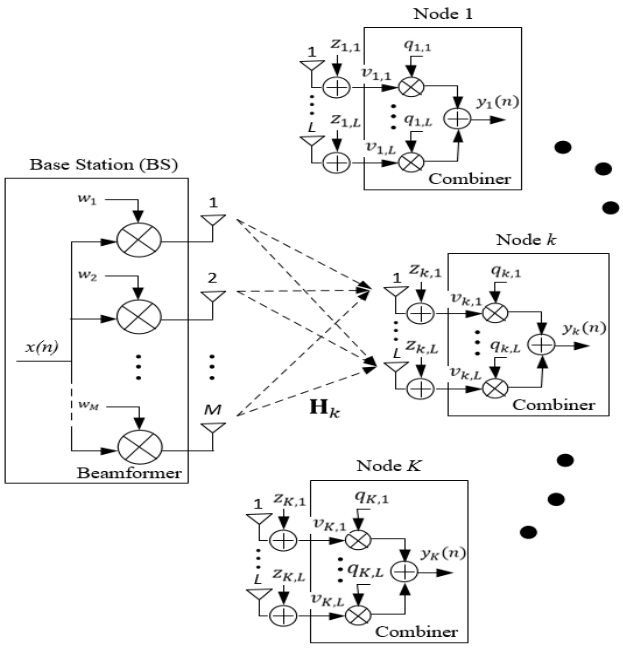

Figure 2. The system model with multiple antenna nodes.

The BS forms the single beam by choosing the $M \times 1$ beamforming vector $\mathbf{w} = [w_1\ \dots\ w_M]^{\mathrm{T}}$. The distribution of $\mathbf{w}$ is the same as $\mathbf{h}_{k,l}$ but it is normalized to 1 to keep the power fixed $\mathbf{w} \sim \mathbf{h}/\|\mathbf{h}\|$ so that $\mathbf{w}^{\mathrm{H}}\mathbf{w} = 1$. The pilot signal $x(n)$ with power ε_x is transmitted from BS to nodes. The received signal $\mathbf{v}_k = [\mathrm{v}_{k,1}\ \dots\ \mathrm{v}_{k,L}]^{\mathrm{T}}$ at the kth node is written as

$$\mathbf{v}_k(n) = \left(\mathbf{H}_k\mathbf{w}\right)x(n) + \mathbf{z}_k(n) \tag{4}$$

where $\mathbf{z}_k(n) = [z_{k,1}(n)\ \dots\ z_{k,L}(n)]^{\mathrm{T}}$ represents additive white Gaussian noise (AWGN) term which is modeled as i.i.d. □□ $(0, \sigma^2)$. The observed channel states of the nodes $(\mathbf{H}_k\mathbf{w})$ change continuously as a result of the beamforming vector changed by the BS as in single antenna node case. It is assumed that each node can obtain its own channel $\mathbf{H}_k$ perfectly from training signals. The received signal at the lth antenna of the kth node can be expressed as

$$v_{k,l}(n) = \left(\mathbf{h}_{k,l}^{H}\mathbf{w}\right)x(n) + z_{k,l}(n). \tag{5}$$

So, the SNR of the kth node on the lth antenna is given by

$$\gamma_{k,l} = \mathrm{E}\left[\left|\mathbf{h}_{k,l}^{\mathrm{H}}\mathbf{w}\right|^2\right] = \mathbf{w}^{\mathrm{H}}\mathbf{h}_{k,l}\mathbf{h}_{k,l}^{\mathrm{H}}\mathbf{w}. \tag{6}$$

The signals received from all antennas of each node are linearly combined to improve the ESNR. The nodes combine the received signals $\mathbf{v}_k(n)$ by multiplying the $L \times 1$ weighting vector $\mathbf{q}_k = [q_{k,1} \dots q_{k,L}]^{\mathrm{T}}$. The received signal at the kth node after linear combining can be expressed as

$$y_k(n) = \mathbf{q}_k^{\mathrm{H}}\mathbf{v}_k(n) = \sum_{l=1}^{L} q_{k,l}^{*} v_{k,l}(n). \tag{7}$$

In selection combining (SC), the kth node selects the l^*th antenna with the highest SNR where l^* is determined as

$$l^* = \arg\max_{1\le l\le L}(\gamma_{k,l}) \tag{8}$$

and the entries of the weighting vector $\mathbf{q}_k$ is given by

$$q_{k,l} = \begin{cases} 1 & l = l^* \\ 0 & \text{otherwise.} \end{cases} \tag{9}$$

Finally, the received signal at the kth node is then written as

$$y_k(n) = q_{k,l^*}^{*} v_{k,l^*}(n) = \left(\mathbf{h}_{k,l^*}^{H}\mathbf{w}\right)x(n) + z_{k,l^*}(n) \tag{10}$$

and the ESNR of the kth node can be found as

$$\gamma_k = \mathrm{E}\left[\left|\mathbf{h}_{k,l^*}^{\mathrm{H}}\mathbf{w}\right|^2\right] = \gamma_{k,l^*} = \max_{1\le l\le L}\left\{\gamma_{k,l}\right\}. \tag{11}$$

In order to make it suitable to fuzzy inference, ESNR measurement is normalized in proposed method. The normalized ESNR (N-ESNR) is calculated as the ratio of the received ESNR to the maximum ESNR. The N-ESNR of the kth node is computed as

$$\eta_k = \frac{\mathbf{w}^{\mathrm{H}}\mathbf{h}_{k,l^*}\mathbf{h}_{k,l^*}^{\mathrm{H}}\mathbf{w}}{\mathbf{h}_{k,l^*}^{\mathrm{H}}\mathbf{h}_{k,l^*}}. \tag{12}$$

The N-ESNR value is also in [0,1] interval.

C. Scheduling Algorithms

The channel allocation task is controlled by a centralized scheduler runs at the BS according to MAC protocol. The nodes send a request to BS for channel access. A MAC protocol determines how multiple nodes access to the wireless channel by pre-defined scheduling algorithm. In order to provide a collision-free schedule, it is assumed that only a single node can use the channel at a certain time-slot. Most of the existing MAC protocols use the time division multiple access (TDMA) mechanism where time is divided into equal-sized slots. If K represents the number of nodes in the network, the simple TDMA based algorithm which uses round robin (RR) scheduling provides the highest fairness among the nodes when the time-slots are allocated in rounds of K time-slots [13].

The TDMA scheme with opportunistic scheduling approach takes advantage of favorable channel conditions in assigning time-slots to the nodes and gives higher throughput than non-opportunistic RR algorithm. Several algorithms may be found in the literature for scheduling nodes in an opportunistic way. In maximum SNR scheduling algorithm, the BS assigns the current time-slot to the node with the highest SNR. In practice, the average SNRs of the nodes are different due to differences in distances to the BS. Therefore, giving priority to the nodes with the highest SNR causes unfairness in the network. On the other hand, maximum N-SNR scheduling algorithm achieves fairness among all nodes at the expense of throughput loss [14].

To increase the short-term fairness, the opportunistic RR (ORR) scheduling algorithm is introduced in [15]. ORR algorithm is different from the simple RR scheduling, the best node among all nodes is chosen for the first time-slot in a round. At the next time-slot, this node taken out of the competition and the best out of the remaining nodes is selected for channel assignment. This procedure is repeated until the last round, where the latter node is scheduled. ORR algorithm ensures the constraint that the K nodes should get exactly one time-slot each within the same round as well as RR scheduling.

The ORR algorithm can be combined with maximum N-SNR scheduling to achieve higher throughput than ORR, by scheduling the node with highest N-SNR. This algorithm is denoted as the normalized ORR (N-ORR) [15]. In case of the wireless network with multiple antenna nodes, the existing algorithms can be applied by using ESNR and N-ESNR channel quality metrics instead of SNR and N-SNR.

D. Fairness & Throughput Analysis

The fairness is defined by how equally the channel assignments are allocated to nodes. The Jain's fairness index (JFI) is frequently used to measure fairness of different scheduling algorithms in wireless networks. By considering the time-slot allocation (instead of the throughput allocation) JFI is defined as follows:

$$I_{JFI} = \frac{\left|\sum_{k=1}^{K} x_k\right|^2}{K\sum_{k=1}^{K} x_k^2} \tag{13}$$

where x_k is the number of allocated time-slots to node k in a round [16].

The throughput is a function of the average SNR of nodes that access to the channel. The throughput of applied scheduling algorithm is boosted by increasing the nodes' channel quality as shown by Shannon's theorem [17].

III. Proposed Fuzzy Scheduling Algorithm

Fuzzy logic implements human experiences and preferences via membership functions and fuzzy rules. It can be used as a general methodology to incorporate knowledge into decision makers, such as schedulers in wireless networks. Proposed fuzzy logic based algorithm exploits the nodes' channel assignment in making the scheduling decision and tries to improve the fairness over the network while simultaneously employing opportunistic strategy to increase the total throughput by selecting nodes with high channel quality as much as possible.

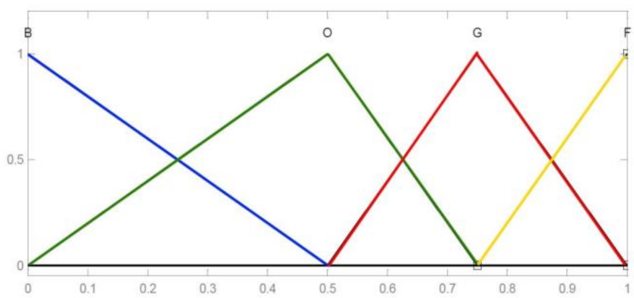

Figure 3. Input membership functions for CSI.

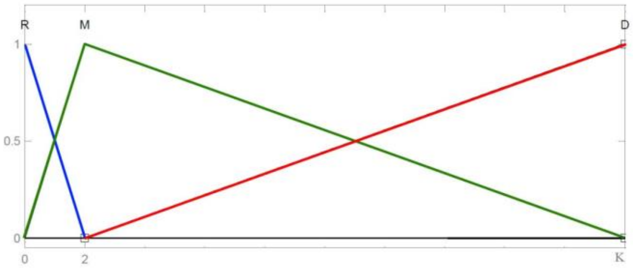

Figure 4. Input membership functions for CAI.

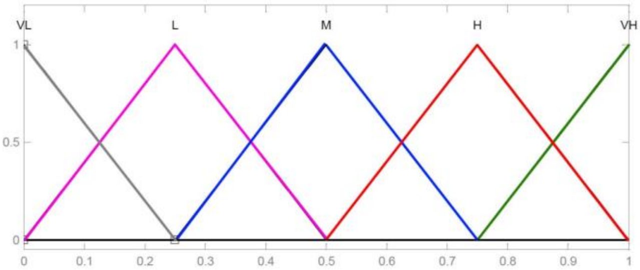

Figure 5. Output membership functions for PI.

The proposed fuzzy scheduler has two input variables and one output variable. The input variables are CSI and CAI. The output variable is priority index (PI). The PI of each node is calculated according to input variables. CSI is measured as N-SNR and N-ESNR metrics for single antenna and multiple antenna node configurations, respectively. CAI is measured by number of channel access in the same round for every node. There are four linguistic terms that are used for CSI: Bad (B), Ordinary (O), Good (G) and Favorable (F) and three linguistic terms that are used for CAI: Rare (R), Middle (M) and Dense (D). Membership functions of input variables are shown in Figure 3 and Figure 4, respectively. As shown in Figure 5, there are five linguistic variables are used for the PI: Very Low (VL), Low (L), Medium (M), High (H) and Very High (VH).

The scheduling decisions are determined by using a set of rules in fuzzy scheduler. Fuzzy rules are written based on the empirical knowledge obtained from domain expert's knowledge and stored in rule base as a two-dimensional matrix. The Mamdani type fuzzy inference model is used for decision-making stage. Table 1 shows the fuzzy conditional rules for proposed scheduler to improve fairness when compared with pure opportunistic scheduling algorithms. We also try to adjust the trade-off between the throughput and fairness by only changing rule base in scheduler. Then, we create 3 different versions of rule base to provide the different quality of service (QoS) requirements in wireless networks.

PI		CSI			
		B	O	G	F
CAI	R	M	H	VH	VH
	M	VL	L	M	H
	D	VL	VL	L	M

Table 1. Rule Base 1 for the fairness-oriented scheduling.

PI		CSI			
		B	O	G	F
CAI	R	M	H	VH	VH
	M	L	M	H	VH
	D	VL	L	M	H

Table 2. Rule Base 2 for the balanced scheduling.

PI		CSI			
		B	O	G	F
CAI	R	L	M	H	VH
	M	VL	L	M	H
	D	VL	VL	M	H

Table 3. Rule Base 3 for the throughput-oriented scheduling.

The fuzzy scheduler calculates the PI value of each node according to current network conditions. The input variables have 12 combinations and the corresponding output is shown from the tabulation. The weighted-mean method is adopted to convert the fuzzy output into crisp value of PI [18]. The scheduler selects the node with the largest value of PI among all nodes in the network. According to the used rules, the nodes with strong channel quality and rare channel access are more fortunate to have opportunity for channel assignment.

IV. Simulation Results

The fairness and throughput performances of the proposed scheduling algorithm are evaluated with statistical (Monte Carlo) simulation under Rayleigh fading channel. In order to validate obtained results, the proposed algorithm is compared with several algorithms, which are introduced in Section II(C). The obtained results are shown for both single and multiple antenna cases, 4 × 1 and 4 × 2 antenna configurations. In comparison, the number of iterations is chosen as 1000 to achieve an acceptable convergence and the number of time slots in an iteration is taken as the number of nodes in the network. We assume that the $\overline{\gamma} = 1$ to eliminate the effect of average SNR on the simulation results. It is also assumed that all of the transmit-receive antenna pairs are independent and there is no correlation among them.

Initially, we start our performance evaluation with a simple scenario where the nodes have single antenna. Figure 6 plots the fairness performance of proposed algorithms by JFI. It means that the higher value of JFI implies higher fairness in channel assignment. Note that, the RR based algorithms (RR, ORR and N-ORR) have the best fairness index. Proposed algorithm has better fairness than the pure opportunistic algorithms (maximum SNR/N-SNR) and its performance close to the RR based algorithms. It is clearly shown that the maximum SNR scheduling algorithm has the worst fairness performance among all evaluated algorithms.

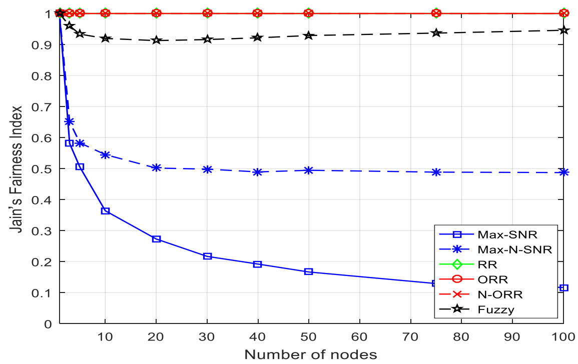

Figure 6. Fairness performance of wireless network with single antenna nodes for $M = 4$.

The throughput performance of proposed algorithm against others is shown by Figure 7. The maximum SNR algorithm has the more powerful throughput than the others. However, proposed algorithm has also better throughput performance than the RR based algorithms. Contrary to the fairness comparison, the simple RR scheduling has the worst throughput performance among all evaluated algorithms.

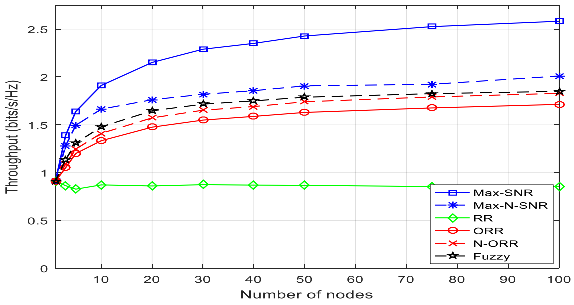

Figure 7. Throughput performance of wireless network with single antenna nodes for $M = 4$.

After that, we extend our analysis to allow multiple antenna nodes in wireless network. As seen from Figure 8, the proposed algorithm has an important fairness advantage over the opportunistic maximum ESNR/N-ESNR algorithms. All of the compared algorithms have similar characteristics with the single antenna node case in Figure 6.

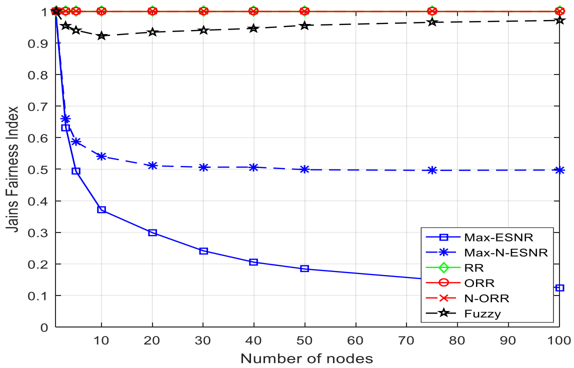

Figure 8. Fairness performance of wireless network with multiple antenna nodes for $M = 4$ and $L = 2$.

Figure 9 shows the throughput performance in wireless networks with multiple antenna nodes. We can see that the throughput performance of proposed algorithm is better than that of single antenna case. The obtained results are listed in Table 4. But, the throughput gain is limited in proposed algorithm comparing with the others. As seen from the plot, the ORR and N-ORR algorithms outperform the proposed algorithm when the number of nodes is greater than 30 and 50, respectively.

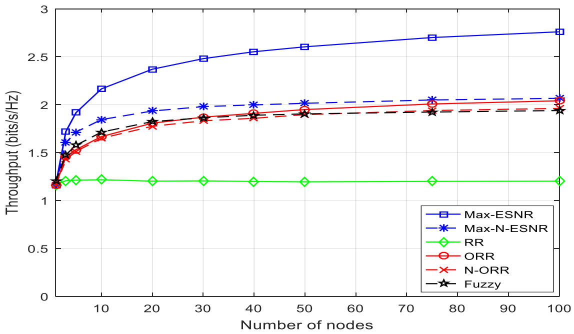

Figure 9. Throughput performance of wireless network with multiple antenna nodes for $M = 4$ and $L = 2$.

	Number of nodes					
	1	10	30	50	75	100
L=1	0,910	1,479	1,716	1,788	1,826	1,850
L=2	1,200	1,713	1,863	1,903	1,922	1,938

Table 4. Throughput performance of proposed algorithm for single and multiple antenna node configurations.

Finally, we analyze the trade-off between throughput and fairness by using different rule bases for proposed algorithm. According to Figure 10, the Rule Base 1 provides fairest channel distribution among nodes, while the Rule Base 3 has worst of it. In contrast, the Rule Base 3 offers best throughput performance as shown in Figure 11. The Rule Base 2 balances the throughput and fairness requirements.

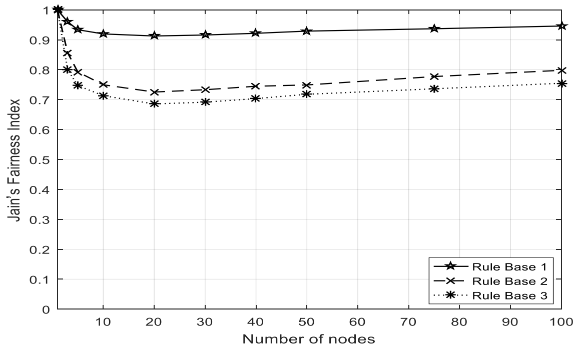

Figure 10. Fairness performance of wireless network with single antenna nodes for $M = 4$.

As shown by Figure 12 and Figure 13, when the multiple antennas are equipped on the nodes, the proposed algorithm gives the similar characteristics with the single antenna node case for different rule bases.

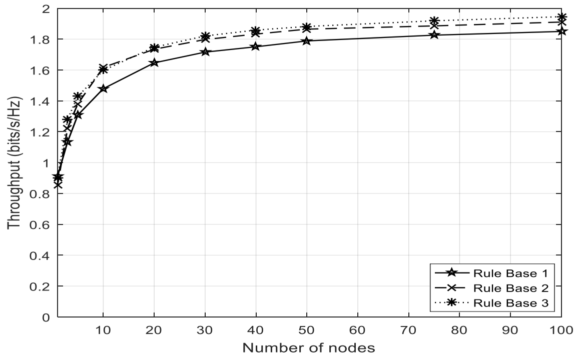

Figure 11. Throughput performance of wireless network with single antenna nodes for $M = 4$.

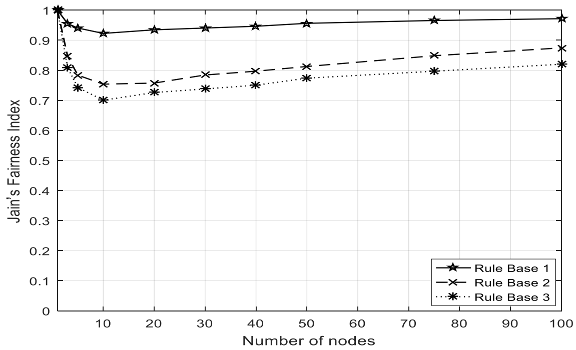

Figure 12. Fairness performance of wireless network with multiple antenna nodes for $M = 4$ and $L = 2$.

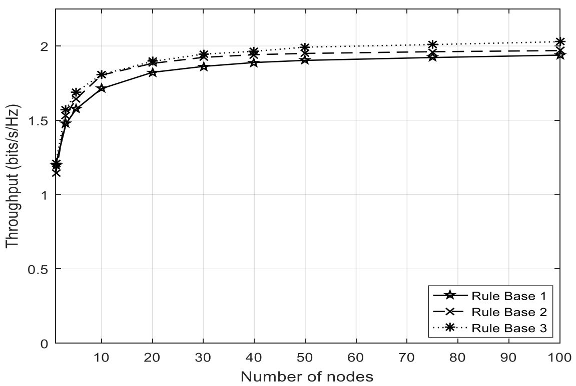

Figure 13. Throughput performance of wireless network with multiple antenna nodes for M = 4 and L = 2.

V. Conclusion

In this study, we have explored the fairness-throughput trade-off in wireless networks. In doing so, we have proposed a novel fuzzy logic based opportunistic scheduling algorithm to improve the fairness performance in cellular wireless networks. Proposed algorithm was analyzed in terms of fairness and throughput performances. It was also compared to other well-known scheduling algorithms. We have also extended our analysis to investigate the performance of proposed algorithm in a system model with multiple antenna nodes. According to obtained results, we can say that our proposed fuzzy scheduling algorithm has throughput advantage over RR based algorithms and also has fairness advantage over maximum SNR/NSNR algorithms. Proposed method also allows to adjust the trade-off between the fairness and throughput by only changing rule base in scheduler.

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Hakkı Soy received the B.S. degree in Electronics Engineering from Uludağ University, Turkey in 1999, M.S. degree in Electronic and Computer Systems Education from Selçuk University, Turkey in 2006 and the Ph.D. degree in Electrical and Electronics Engineering from Selçuk University, Turkey, in 2013. His research focuses on opportunistic scheduling in wireless networks, cross-layer design techniques, distributed opportunistic access schemes, multiple antenna systems, and sensor networks.

Özgür Özdemir received the B.S. degree in Electrical and Electronics Engineering from Boğaziçi University, Turkey in 1999 and the M.S. and the Ph.D. degrees in Electrical Engineering from The University of Texas at Dallas, Dallas, TX, in 2002 and 2007, respectively. His research interests include CDMA2000, 1xEVDO, opportunistic approaches in wireless systems, experimental multiple antenna systems, signal processing, and multiuser detection.