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Bandwidth Allocation in Cooperative Wireless Networks: Buffer Load Analysis and Fairness Evaluation

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Abstract

In modern cooperative wireless networks, the resource allocation is an issue of major significance. The cooperation of source and relay nodes in wireless networks towards improved performance and robustness requires the application of an efficient bandwidth sharing policy. Moreover, user requirements for multimedia content over wireless links necessitate the support of advanced Quality of Service (QoS) features. In this paper, a novel bandwidth allocation technique for cooperative wireless networks is proposed, which is able to satisfy the increased QoS requirements of network users taking into account both traffic priority and packet buffer load. The performance of the proposed scheme is examined by analyzing the impact of buffer load on bandwidth allocation. Moreover, fairness performance in resource sharing is also studied. The results obtained for the cooperative network scenario employed, are validated by simulations. Evidently, the improved performance achieved by the proposed technique indicates that it can be employed for efficient traffic differentiation. The flexible design architecture of the proposed technique indicates its capability to be integrated into Medium Access Control (MAC) protocols for cooperative wireless networks.

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Keywords

Buffer load analysis, MAC, fairness, QoS, cooperative wireless network

1. Introduction

The support of various integrated services via mobile computing devices over wireless networks necessitates high speed connectivity and robust error protection. Those requirements, along with the scarcity of the available spectrum and the network resources imply the need to develop new wireless techniques which optimize the efficient use of the available spectrum. Cooperative communication protocols are based on the cooperation among the involved nodes so as to achieve significant improvement in terms of the overall system capacity meeting at the same time the Quality of Service (QoS) requirements [1].

Cooperative techniques improve the performance of the wireless network by exploiting the broadcast nature of the wireless channel and adopting spatial diversity scheme. In this case different wireless nodes may collaborate to increase the robustness of the wireless system by decreasing the bit error rate and outage probabilities [2, 3]. In contrast to single-node transmissions, cooperative communication models may utilize multiple relay nodes transmitting simultaneously to the receiver. In such a system each node transmits each own data and collaborates with other nodes in forwarding their data [3]. Furthermore, in a cooperative relay communication system a source collaborates with a relay for data transmission. To this end, each node may receive multiple times the same information signal which is transmitted by the source and/or various relay nodes. In this instance, the reception of the information signal is enhanced due to the spatial diversity employed, which is effective in combating against multipath fading and inter-symbol interference problem [1, 4].

In a cooperative relay communication system the service data are buffered temporarily on the source node or in the relay nodes before they are transmitted to the next one. Data packets arriving from sources in the relay buffers are queued. Thus, the overall system throughput increases while aggravating queuing delay at the relay nodes gives rise to higher end-to-end transmission time [5]. Network parameters such as throughput, delay and jitter are affected by the incoming and service packet rate of the cooperative node. Moreover, data packets of different traffic types require to be are treated by the network according to their specific QoS characteristics.

Although the essentials of cooperative communications are originally applied on the physical layer; the notion of cooperation is applicable also on higher protocol layers for wireless networks. In this paper, a new technique for bandwidth sharing and buffer load balancing within the relay nodes of a cooperative wireless network is introduced considering packet priorities, fairness and buffer load. Furthermore, an analytical approach is presented to study the impact of buffer load level in a relay node on bandwidth sharing. It is demonstrated that queue load rate in the buffers significantly affects the prioritization of traffic loads regarding their probabilities of gaining medium access while they are temporarily buffered in the relays. Additionally, fairness aspect in the proposed scheme is studied employing an appropriate index which is based on the resource allocation applied within the network. The performance of the proposed technique is examined under multiple efficiency metrics through appropriate simulation results, which indicate its robustness and efficacy in QoS aware resource allocation.

The proposed technique can be adopted by any other mechanism associated with cooperative environments which differentiates packet traffic and deals with the overloaded queues in the buffers of the relay nodes. Generally, high loaded queues may give rise to excessive delays in packet delivery and also potential overflows. Considering that the proposed scheme is more general than the existing ones, one of its key points is its applicability to any Medium Access Control (MAC) protocol for cooperative relay communications.

The rest of the paper is organized as follows. Section 2 presents the related work in the field of cooperative communication focusing mainly on the MAC protocols proposed in literature and especially on the QoS aware techniques employed to allocate network resources. The proposed QoS scheme for cooperative wireless networks is defined in detail in Section 3. Moreover, some efficiency metrics with respect to bandwidth allocation and fairness provision are thoroughly examined. In Section 4, the simulation model is presented, which validates the analytical approach. The analytical results regarding packet buffers sending rates, loading rates and experienced fairness, when the proposed QoS scheme is adopted in the relay nodes of a cooperative wireless network, are presented in Section 5. Finally, in Section 6 the paper is concluded and future potentials are provided.

2. Related Work

Cooperative communications are very promising techniques which enhance the performance and the efficiency of wireless communication networks. The concept of cooperation was introduced in [6] where the capacity of a three node network was studied. In the presented model, spatial diversity gain was exploited, using different channels to transmit data in the relay nodes [6, 7]. In general, there are four main cooperative signaling methods proposed in the literature: detect and forward, amplify and forward, coded cooperation and compress and forward [1 - 3]. The operation of the traditional relays is based on the first technique, where the relay node receives the transmitted signals and it retransmits them to the receiver [7]. In the second technique, the relay nodes amplify the received signal and then forward them directly to the destination [8, 9]. When channel coding is integrated to cooperation and the regenerated message is encoded to provide additional error protection to the original message, then the cooperative technique employed is referred to as coded cooperation [10 - 12]. The fourth method exploits the statistical dependencies between the data received at the relay and the destination node by retransmitting a quantized version of the received message at the relay [1]. The technique of compress and forward is one of the most popular ones along with store and forward technique [1, 13].

The physical layer capabilities and aspects of the cooperative communications have been extensively studied in the literature during the few last years. One issue of utmost importance is to efficiently share and provide access to medium, so that increased network performance is achieved. Thus, MAC protocols are employed to allocate the available bandwidth efficiently over the network nodes. In what follows, some of the existing research on MAC protocols for cooperative communications is reviewed.

In [14, 15] the first MAC protocol for cooperative communications, called CoopMac was introduced, based on the well known IEEE 802.11 protocol. CoopMac is based on the opportunities where a dual-hop relaying link may support higher data rate than the direct one. In this protocol, high data rate nodes assist low data rate ones by forwarding a part of their traffic, leading to a substantial increase in the overall network throughput, the reduction in packet delay as well as the decrease of the total energy consumption of all nodes. This protocol is realized through a set of new features applied on the data and control plane of the 802.11 MAC layer, while maintaining compatibility with the existing MAC. In CoopMac, the source node can choose a relay based on its availability. The earliest approach for the implementation of CoopMac in real environment was described in [4], where the authors described two different approaches employed for the implementation of CoopMac.

In [16] the authors proposed a novel MAC protocol to further exploit the physical layer multirate capability. They introduced the relay-enabled Distributed Coordination Function (rDCF) protocol which is based on the availability of each relay node to assist the other network nodes in data forwarding. Another cooperative protocol was proposed in [17] where the relay node forwards a packet only if an acknowledgment message is received indicating a decode failure of the packets in the destination node. The Persistent Relay Carrier Sensing Multiple Access (PRCSMA) protocol was studied in [18] and it facilitates the implementation of a Cooperative Automatic Repeat Request (C-ARQ) scheme in wireless networks to enhance their performance and to extend their coverage. Its operation is based on the following rule; if the destination receives a data packet containing errors, it can request its retransmission through the relays nodes. The same problem has been studied in [19] for cooperative wireless networks, where the proposed MAC protocol retransmits the needed packets through the cooperative relay nodes that is able to overhear the transmitted signals from the source and decode the information bits correctly.

A new protocol based on IEEE 802.11e MAC was proposed in [3] called Cooperative MAC (CMAC) protocol, which exploits the spatial diversity of cooperative communications. Specifically, CMAC employs a retransmission technique in which multiple versions of partially correct frames are combined to reconstruct the complete one. When this technique is combined with Forward Error Correction (FEC) it leads to an enhanced version of CMAC, called FCMAC, in which only the part of the frame that contains errors needs to be retransmitted [3]. In [20] a MAC protocol solution for cooperative communications in disturbed networks is described, where frames such as Relay Ready to Send (RRTS) and Ready to Send/Clear to Send are exchanged among the source, destination and the relay.

All the MAC protocols described above achieve improved performance compared to the pure IEEE 802.11 protocol on which they are based, but they are insufficient in terms of efficient bandwidth sharing when they are applied in cooperative communication networks [21]. Thus, there is a need to develop new QoS-aware bandwidth allocation schemes, which will be adopted by a cooperative based MAC protocol and will overcome the design problems of each protocol already proposed in literature and expand the efficiency of cooperative networks beyond their current limitations [21].

3. The Proposed QoS Scheme

In this section, a new QoS scheme is introduced that can be used by MAC protocols for cooperative wireless networks. The system model considered in this work is a generic multi-hop cooperative wireless network, where source and relay nodes cooperate in order to relay data packets towards out of range destination nodes. It is assumed that each node is typically capable of arranging packets into multiple buffers based on their traffic priorities, while it is aware of its adjacent nodes. A suitable routing algorithm at the network layer determines the transmission paths. The analysis includes the study of the proposed resource allocation technique and the corresponding impact of the buffered traffic in source or relay nodes on bandwidth allocation. Moreover, an efficiency metric is presented which quantifies fairness in resource allocation within the cooperative wireless network.

3.1. The Resource Allocation Technique

The objective of the proposed technique for cooperative networks is to offer guaranteed QoS to the network users by differentiating the network traffic according to its priority. Moreover, sufficient resources are provided by the proposed protocol to nodes with high load, which may be caused by either excessive traffic generation or the need for increased packet relay, so as to limit excessive delays and packet drops. Consider that every node has a different packet buffer for each traffic priority level. This is a common approach which was used also in IEEE 802.11e standard [22]. The resources allocated to a specific packet buffer are proportional to its load and traffic priority. Thus, packet prioritization is ensured according to the specific QoS requirements of each traffic type supported and heavy loaded nodes are assigned with sufficient network resources. Note that this technique could also lead to power saving, since the number of necessary retransmissions of packets dropped due to buffer overflow can be reduced.

According to the aforementioned concept, network resources are allocated to individual packet buffers. Hence, the total bandwidth a node is allowed to use equals to the sum of the resources allocated to its buffers. In what follows we consider different packet buffers, each of which requires a bandwidth portion to transmit their load. Let N denote the number of buffers in a single node. A buffer i is characterized by the quantity $Q_i(t)$, which depends on the buffer priority and its load at time t. It holds

$$Q_i(t) = z^{p_i} L_i(t), \qquad (1)$$

where $i \in \{1,...,N\}$, $z \geq 1$ is a preset priority factor, $p_i \in \mathbb{Z}^*$ is the priority of ith buffer and $L_i(t)$ denotes the actual load of ith buffer at a given time t. The priority factor z is defined by the ratio of the bandwidth assigned to a buffer divided by the bandwidth assigned to an equally loaded buffer having the consecutive lower priority. To understand how the priority factor works, suppose that there are two buffers, $i \in \{A, B\}$, within a network segment and z equals to 2. Moreover, let buffer A is assigned with double priority over B and that both buffers are equally loaded. Thus, the buffer A is allowed to use twice the bandwidth of B. Let $normQ_i(t)$ denote the normalized portion of bandwidth allocated to ith buffer by the proposed resource allocation technique, defined by

$$normQ_i(t) = Q_i(t) \Big/ \sum_{k=1}^{N} Q_k(t). \qquad (2)$$

Each node can be eventually characterized by a quantity determined by summing the $Q_i(t)$ values of all buffers supported by the node. Resources are allocated to nodes based on this aggregated quantity, while the bandwidth portion allocated to ith buffer depends on the $Q_i(t)$ value.

3.2. Packet Transmission Rates Estimation and Buffer Load Analysis

In what follows the analysis of bandwidth allocation among different packet buffers is presented. Specifically, the impact of the Packet Generation Rate (PGR) on bandwidth sharing policy is studied. Note that PGR includes both the packets that are initially generated in the node and those which arrive from other nodes in order to be retransmitted by the relay node. According to the resource allocation technique presented above, the resources allocated to each buffer are proportional to its actual load and traffic priority. Thus, PGR is not directly indicative of the resources allocated to a buffer. Specifically, the priority and traffic rate of many flows that are generated in a node for relaying is a priori known (like in most multimedia streams).

However, even in this case, the channel access probability of the respective packet buffers cannot be directly deduced. As a result, we are unable to estimate the expected level of satisfaction regarding the scheduled communication, in order to predetermine whether the required service level will be provided. Therefore, it is very difficult to conclude whether it is necessary to adjust accordingly the parameters regarding traffic priority and resource allocation.

Assume the case where two priority buffers (N=2) are employed and each one receives packets from its corresponding traffic flow. Let $f_i(t)$, $i=\{1,2\}$, be the function which denotes the number of bits that have been sent by buffer i till time t. Evidently, the Packet Transmission Rate (PTR) is equal to $f_i'(t)$, that is the first derivative of $f_i(t)$. The objective of the analysis is to determine the ratio of the two buffer PTRs, which is denoted by c. Note that the following analysis holds when the buffers aggregated load rate is higher than the total network bandwidth capacity b. In any other case, the allocated bandwidth to each buffer is adequate so that the PTR equals the PGR. Considering the PTR ratio, it holds

$$\frac{f_1'(t)}{f_2'(t)} = c \xrightarrow{f_1'(t)+f_2'(t)=b} f_1'(t) = c(b - f_1'(t)) \longrightarrow f_1'(t) = \frac{cb}{1+c} \xrightarrow{(1),(2)} \frac{z^{p_1} L_1(t)}{z^{p_1} L_1(t) + z^{p_2} L_2(t)} b = \frac{cb}{1+c} \longrightarrow$$

$$z^{p_1} L_1(t) = c z^{p_2} L_2(t) \,. \tag{3}$$

Without loss of generality, let assume that the PGR of each buffer remains constant in time. In general, the mean PGR, a_i, of the time interval under consideration can be used. For example, consider the case where PGR follows the Poisson distribution. Thus, the PGR is equal to the expected mean value λ. Suppose that the total number of bits which have entered the ith buffer to be transmitted from the beginning of the observation interval (t=0) until time t is given by $G_i(t)$. Evidently, the first derivative of $G_i(t)$ approximates a_i. Given that a_i is constant, its integral over time, i.e. $G_i(t)$, is a linear function of t. Since each buffer eventually acquires a specific portion of the available bandwidth, then $f_i'(t)$ is also constant in time, hence, $f_i(t)$ is a linear function of t. Therefore, c can be determined as follows

$$(3) \xrightarrow{G_i(t)-f_i(t)=L_i(t)} z^{p_1-p_2}(G_1(t) - f_1(t)) = c(G_2(t) - f_2(t)) \xrightarrow{G_i'(t)=a_i}$$

$$z^{p_1-p_2}(a_1 t - f_1'(t)t) = c(a_2 t - f_2'(t)t) \xrightarrow{p_1-p_2=r} z^r\left(a_1 - \frac{cb}{1+c}\right) = c\left[a_2 - \left(b - \frac{cb}{1+c}\right)\right] \longrightarrow$$

$$a_2 c^2 + (a_2 - b - a_1 z^r + b z^r)c - a_1 z^r = 0 \,. \tag{4}$$

Solving the quadratic equation for c results in the following formula

$$c = \frac{-(a_2 - b - a_1 z^r + b z^r) + \sqrt{(a_2 - b - a_1 z^r + b z^r)^2 + 4 a_1 a_2 z^r}}{2a_2}. \quad (5)$$

Note that as expected, two solutions are obtained by solving (4). However, since the sending rate is a non- negative number, only the positive value of c is considered.

Let us now examine a general case, where multiple packet buffers are employed by each node. All node buffers are categorized according to their priority level into two virtual buffers, where each one corresponds to a different priority level. Evidently, the PGR of each virtual buffer is equal to the sum of the PGRs of the corresponding node buffers. Thus, the problem is simplified to the two buffer problem, where each buffer PTR can be calculated by equation (5). Then, the PTR of each individual buffer is proportional to the transmission rate of the respective virtual buffer.

Suppose that there are l_1 and l_2 buffers of priority p_1 and p_2, respectively. Then, (1) can be rewritten as follows

$$Q_{ik}(t) = z^{p_i} L_{ik}(t), \quad (6)$$

where $k \in \{1,...,l_i\}$, where $l_i = l_1$ or $l_i = l_2$ if k refers to the first or second virtual buffer, respectively, $i \in \{1,2\}$, $Q_{ik}(t)$ is a quantity indicative of the priority level and the load of kth buffer, p_i denotes the traffic flow priority level and $L_{ik}(t)$ is the actual buffer load. Let $L_i(t)$ denote the actual load of ith virtual buffer at a given time t, defined as below

$$L_i(t) = \sum_{k=1}^{l_i} L_{ik}(t). \quad (7)$$

Evidently, $L_i(t)$ is equal to the aggregated load of all buffers belonging to ith priority level, $i \in \{1,2\}$. Moreover, the PGR a_i of each virtual buffer is equal to the aggregate sum of the PGRs a_{ik} of its individual buffers, given by

$$a_i = \sum_{k=1}^{l_i} a_{ik}. \quad (8)$$

Notice that if the priority level and the PGR of the abstract unified buffers are known, we can use (5) to calculate their sending rates.

Suppose that $\mathbf{P}_i$ is the priority level of the ith virtual buffer and $Q_i(t)$ is a quantity indicative of its priority level and load. Based on (1), $Q_i(t)$ is given by

$$Q_i(t) = z^{p_i} L_i(t) = z^{p_i} \sum_{k=1}^{l_i} L_{ik}(t) = \sum_{k=1}^{l_i} z^{p_i} L_{ik}(t) = \sum_{k=1}^{l_i} Q_{ik}(t)\,, \tag{9}$$

where $i \in \{1,2\}$. According to the proposed resource allocation technique the PTR $f'_{ik}(t)$ of kth individual buffer can be determined as a portion of the corresponding virtual buffer PTR $f'_i(t)$, obtained by

$$f'_{ik}(t) = \frac{Q_{ik}(t)}{Q_i(t)} f'_i(t) = \frac{L_{ik}(t)}{L_i(t)} f'_i(t) = \frac{G_{ik}(t) - f_{ik}(t)}{G_i(t) - f_i(t)} f'_i(t) = \frac{(a_{ik} - f'_{ik}(t))t}{(a_i - f'_i(t))t} f'_i(t) \longrightarrow$$

$$f'_{ik}(t) = \frac{a_{ik}}{a_i} f'_i(t)\,, \tag{10}$$

where $G_i(t)$ and $G_{ik}(t)$ denote the aggregated load of ith virtual buffer and kth individual buffer, respectively, till time t.

In the case where multiple virtual packet buffers are employed and each one corresponds to a certain traffic priority level, the analysis becomes more complex. Specifically, the same approach as presented above can be applied for two virtual packet buffers at a time to obtain a system of equations for the PTRs of each virtual buffer. Then, the PTR of each virtual buffer can be calculated via solving the system of equations. In this case, the following notations are employed

- V is the number of virtual buffers, where $V \le N$,
- $f_r'(t)$ is the PTR of the rth virtual packet buffer, $r \in \{i, j\}$, $i, j \in \{1,...,V\}$, which is equal to the bandwidth assigned to it,
- b_{ij} denotes the aggregated bandwidth assigned to i and j buffers, i≠j,
- $c[b_{ij}]$ is the ratio of ith to jth PTRs, i.e. $c[b_{ij}] = f'_i(t) / f'_j(t)$, determined by (5) as a function of b_{ij}.

To illustrate the operation of the proposed bandwidth allocation scheme we examine the case where three priority levels are supported. Thus, three virtual packet buffers are used. By applying the proposed technique the following system of equations are obtained

$$f'_1(t) = \frac{c[b_{12}]b_{12}}{1 + c[b_{12}]}\,, \tag{11}$$

$$f_2'(t) = \frac{c[b_{23}]b_{23}}{1 + c[b_{23}]}, \tag{12}$$

$$b_{12} = f_1'(t) + f_2'(t), \tag{13}$$

$$b_{23} = f_2'(t) + f_3'(t), \tag{14}$$

$$f_1'(t) = b - f_2'(t) - f_3'(t), \tag{15}$$

where b is the total available bandwidth. The solution of this system of five equations provides the $f_1'(t)$, $f_2'(t)$, $f_3'(t)$, as well as the b_{12}, b_{23}.

In the analysis presented above it has been assumed that node buffers have infinite capacity. Thus, to perform a more realistic scenario analysis, buffers of finite capacity are employed. This limitation actually results into two cases. In the first case, a buffer is assigned less bandwidth than its request in order to serve its PGR; therefore, it finally reaches its maximum capacity. In the second case, the bandwidth allocated to the buffer is adequate to serve its PGR, thus its load remains constant. The steps followed to determine which one of the two cases holds and calculate the PTRs are given in the algorithm described below.

Algorithm description for finite capacity buffers

---

i) The portion of the bandwidth that ith buffer of capacity C_i is allowed to use is given by

$$W_i = \frac{z^{p_i} C_i}{\sum_{k=1}^{N} C_k} b. \tag{16}$$

ii) If $W_i \geq a_i$, the PTR of ith buffer is equal to a_i. Moreover, b is reduced by a_i; thus

$$b \leftarrow b - a_i. \tag{17}$$

Then, the algorithm goes to step i to determine the PTR of the rest buffers, otherwise the algorithm ends.

iii) If $W_i < a_i$ the algorithm returns to step i and examines the next buffer, until all buffers are characterized by sending rate equal to a_i or no one of the remaining buffers satisfies the inequality of step ii.

iv) If there is at least one buffer that cannot be allocated enough bandwidth to satisfy its PGR requirement, then all buffers become full. In this case, the PTR for each buffer is proportional to the normalized W_i values.

3.3. Fairness Analysis

In literature, various metrics are employed to measure the efficiency of resource allocation schemes. Fairness constitutes one of the most significant efficiency metrics, since it is indicative of the way resources are allocated within a broadcast network, such as a cooperative wireless network. Conventionally, the objective is to evenly distribute network resources to ensure fairness among node buffers. However, in modern networks, where multiple traffic flows are supported corresponding to different priority levels, fairness concept has been altered. The objective is to allocate more resources to those node buffers which have higher demands compared to the rest ones. To this end, the proposed resource allocation technique takes into account traffic priority level and the actual buffer load. Nevertheless, a side effect of traffic load prioritization is that overloaded buffers often monopolize network resources, which is an undesirable case. The proposed resource allocation technique addresses the problem of unconstrained access of high priority or overloaded buffers to network resources, while at the same time ensures increased bandwidth allocation. Thus, every packet buffer of a node has non-zero probability to serve its corresponding load.

Generally, it is difficult to quantify fairness, since the sense of network fairness is quite subjective. Jain's Fairness Index (JFI) constitutes the best known metric to measure fairness in resource allocation scheme [23]. Specifically, JFI considers the average throughput of each network node to determine a value within the closed interval $\left[0,1\right]$. In this work, JFI is employed to measure fairness among different packet buffers. Based on the presented bandwidth allocation analysis, the analytical expression of JFI regarding the buffers of two priority levels is determined as a function of ratio c as follows

$$\mathrm{JFI}=\frac{\left(\sum_{i=1}^{2} f_i'(t)\right)^2}{2\sum_{i=1}^{2}\left(f_i'(t)\right)^2}\xrightarrow[\frac{f_1'(t)}{f_2'(t)}=c]{f_1'(t)+f_2'(t)=b}\mathrm{JFI}=\frac{b^2}{2\times\left[\left(\frac{cb}{1+c}\right)^2+\left(b-\frac{cb}{1+c}\right)^2\right]}\longrightarrow\mathrm{JFI}=\frac{b^2}{\frac{2b^2\left(1+c^2\right)}{\left(1+c\right)^2}}\longrightarrow$$

$$\mathrm{JFI}=\frac{\left(1+c\right)^2}{2\left(1+c^2\right)}. \tag{18}$$

Note that if we are interested to determine the fairness among the network nodes, then JFI is given by

$$\mathrm{JFI} = \frac{\left(\sum_{j=1}^{M} \sum_{i=1}^{N} f_i'(t) \right)^2}{M \sum_{j=1}^{M} \left(\sum_{i=1}^{N} f_i'(t) \right)^2}, \tag{19}$$

where M is the total number of nodes involved in our cooperative network and N is the number of packet buffers for each node.

4. Simulation Model

The proposed resource allocation technique is verified employing a simulator developed in C#. The simulator repeats consecutive bandwidth allocation cycles for the presented technique. The programming loop that implements the bandwidth assigning cycle is given below for two priority levels.

Simulation cycle loop

```
do
{
 L1 += a1;
 L2 += a2;
 Q1 = Math.Pow( z, p1 ) * L1;
 Q2 = Math.Pow( z, p2 ) * L2;
 normQ1 = Q1 / ( Q1 + Q2 );
 normQ2 = Q2 / ( Q1 + Q2 );
 S1 = normQ1 * b;
 S2 = normQ2 * b;
 if ( S1 > L1 )
  {
   S1 = L1;
   S2 = b - S1;
   if ( S2 > L2 )
    S2 = L2;
  }
 else if ( S2 > L2 )
  {
   S2 = L2;
   S1 = b - S2;
   if ( S1 > L1 )
    S1 = L1;
  }
 L1 -= S1;
 L2 -= S2;
} while <TERMINATION CONDITION>
```

The actual PTR of ith buffer, $i = \{1, 2\}$, is denoted by S_i. Moreover, the total number of bits that can be sent by all buffers during an operation is denoted by b. The number of bits entering in the first or the second buffer during an operation cycle is represented by a_1 and a_2, respectively. The termination condition of the cycle loop is set to a preset maximum number of cycles or a convergence condition, i.e. a maximum allowed divergence of the sending rates ratio S_1/S_2 between two consecutive cycles.

The accuracy of the analysis is validated through the simulation results, which demonstrate that the PTRs ratio converges to c, as defined in (5). Fig. 1 depicts the convergence of ratio S_1/S_2 to c for variable number of operation cycles. Moreover, several curves are obtained using different values of PGRs ratio a_1/a_2 and priority levels ratio z^{p_1}/z^{p_2}. The values of the rest network parameters employed in the simulations are the following: b=1000, a_2=1000, z=2 and p_2 =4. Y-axis in Fig. 1 represents the difference between the PTRs ratio obtained by the simulations and the corresponding values obtained by the analysis, i.e. S_1/S_2 – c. Fig. 1 illustrates that the PTRs ratio obtained by the simulation has a slight divergence from c when the simulation is employed for low number of cycles. However, this difference converges to 0 as the number of simulation cycles increases. Note that the convergence is achieved for low number of cycles, since the difference between the simulation results and the values obtained by the analysis is almost 0 for less than 10 cycles in every case examined.

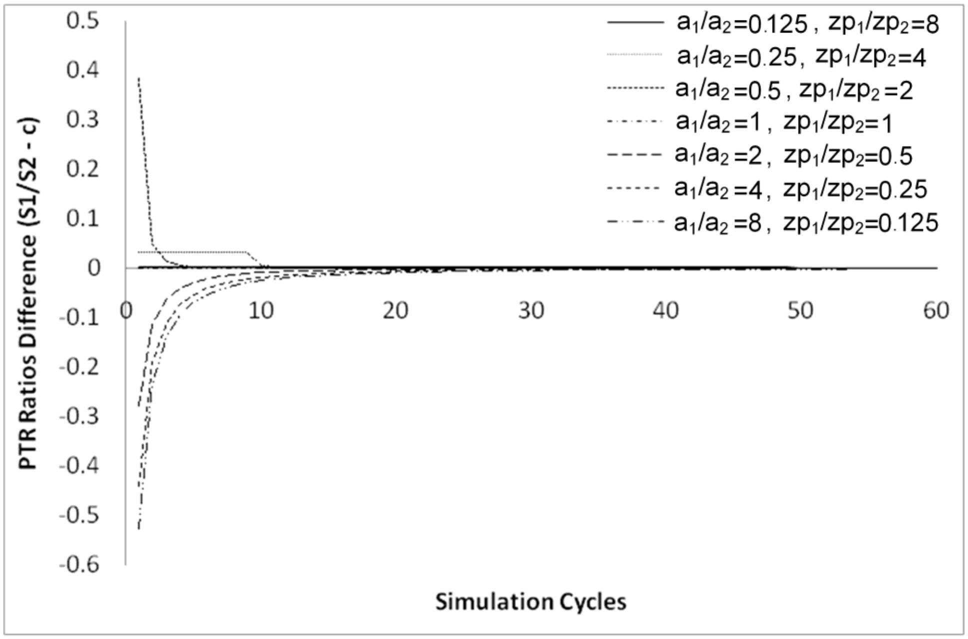

Fig. 1. Convergence speed between the PTRs ratio provided by the simulation program to the one determined by the analysis.

5. Results and Discussion

In this section, the analytical results are presented for a cooperative network that employs the proposed resource allocation technique. The considered scenario involves two source nodes, SC_i, $i=\{1,2\}$, that generate traffic of priority p_i. The destination of these two traffic streams is node D, which is out of the source nodes range. Thus, each node SC_i cooperates with R_i for packet relaying. Each node R_i receives packets from SC_i with rate a_i. The packets are buffered in the relay nodes and then they are forwarded to D with PTR S_i. Note that the infinite buffer case is considered for the results obtained, which is a typical assumption in analysis of similar queuing systems [24]. The described network topology is illustrated in Fig. 2, where circles depict which nodes are in range for direct communication. In the scenario examined, both relay nodes, R_1 and R_2, request bandwidth to forward different priority packets to the common destination node D. Furthermore, the case of traffic flows with equal priorities is also examined.

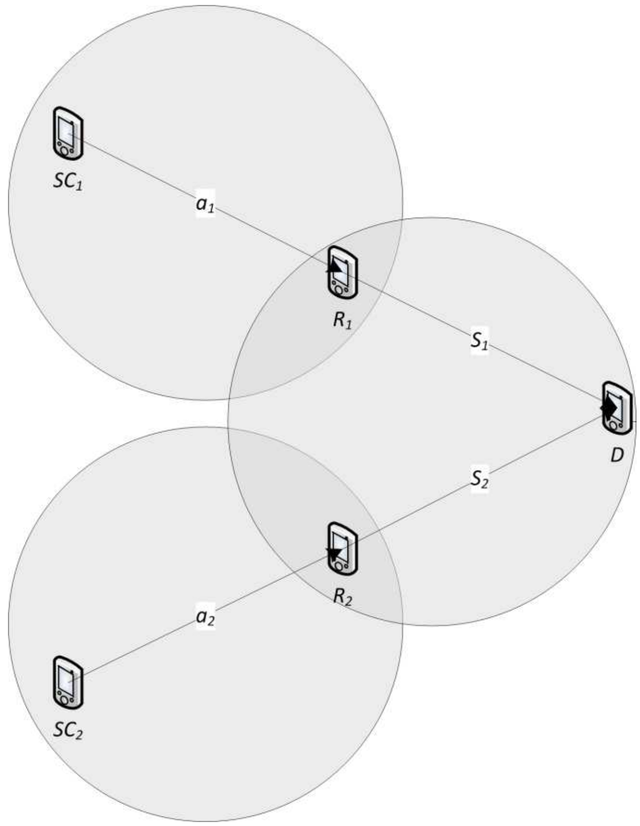

Fig. 2. Topology of the examined cooperative network scenario.

In Fig. 3, the log-log plot depicts the impact of the PGRs ratio on the PTRs ratio for various priority levels. The values for the network parameters employed are the same with the ones used in Section 4. As it is demonstrated in Fig. 3, the PTRs ratio is proportional to the PGRs ratio only when the buffer traffic of both relay nodes have the same priority ($z^{p_1}/z^{p_2} = 1$). Moreover, the PTRs ratio increases with the increase of ratio a_1/a_2 or/and the increase of ratio z^{p_1}/z^{p_2}. Specifically, the rate of increase becomes lower as z^{p_1}/z^{p_2} gets closer to unity and/or as the ratio a_1/a_2 decreases. The impact of both ratios, z^{p_1}/z^{p_2} and a_1/a_2, on the PTRs ratio is illustrated by a log-log-log 3D graph in Fig. 4.

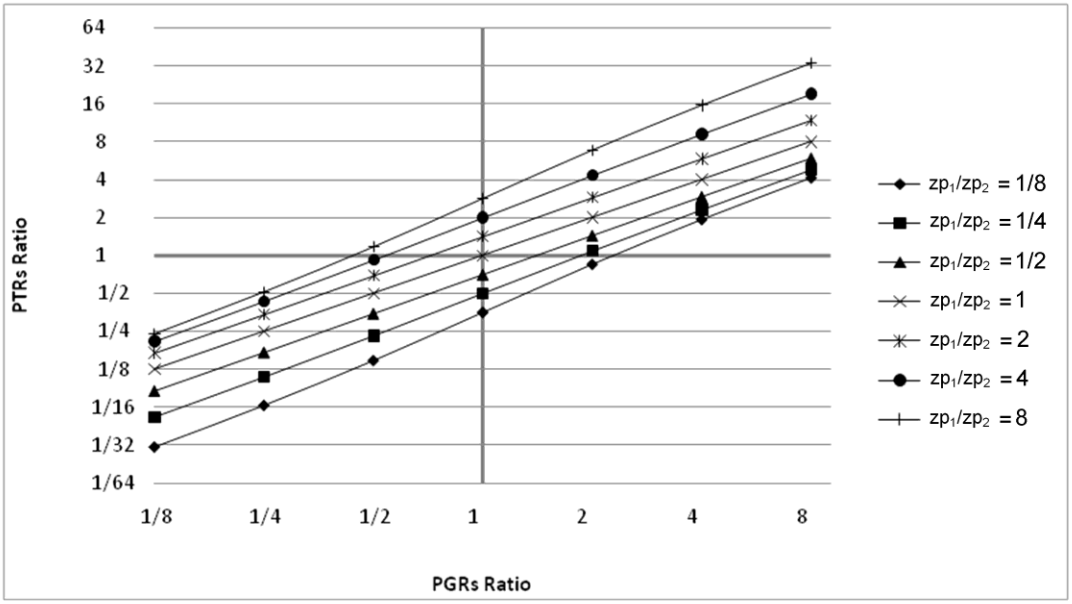

Fig. 3. PTRs ratio versus PGRs ratio for varying priorities ratio.

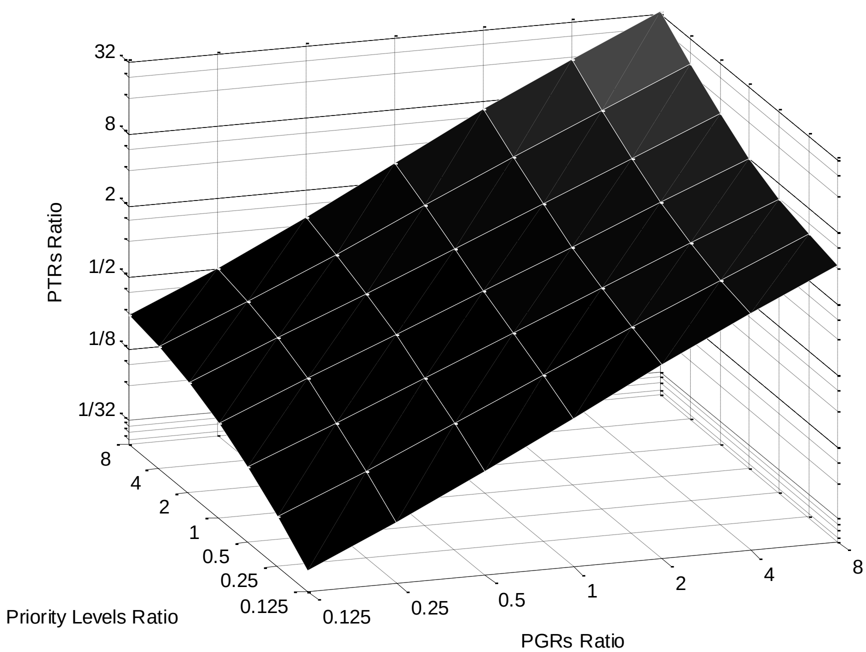

Fig. 4. The combined effect of PGRs and priority level ratios on the PTRs ratio.

According to equation (2) it can be deduced that the network bandwidth is shared proportionally to the buffer load. However, this does not necessarily hold for PGR. This is illustrated in Fig. 5 where the divergence between the ratio of the PTRs determined by the proposed technique and the ratio of the corresponding PTRs calculated proportionally to buffer load is depicted versus the priority levels ratio for different PGR ratios. Evidently, from Fig. 5 it can be observed that this difference becomes even larger as the priority levels ratio deviates from unity, while it decreases when the two priority levels are equal. Moreover, greater PGRs ratio corresponds to greater differences between the two PTRs ratios.

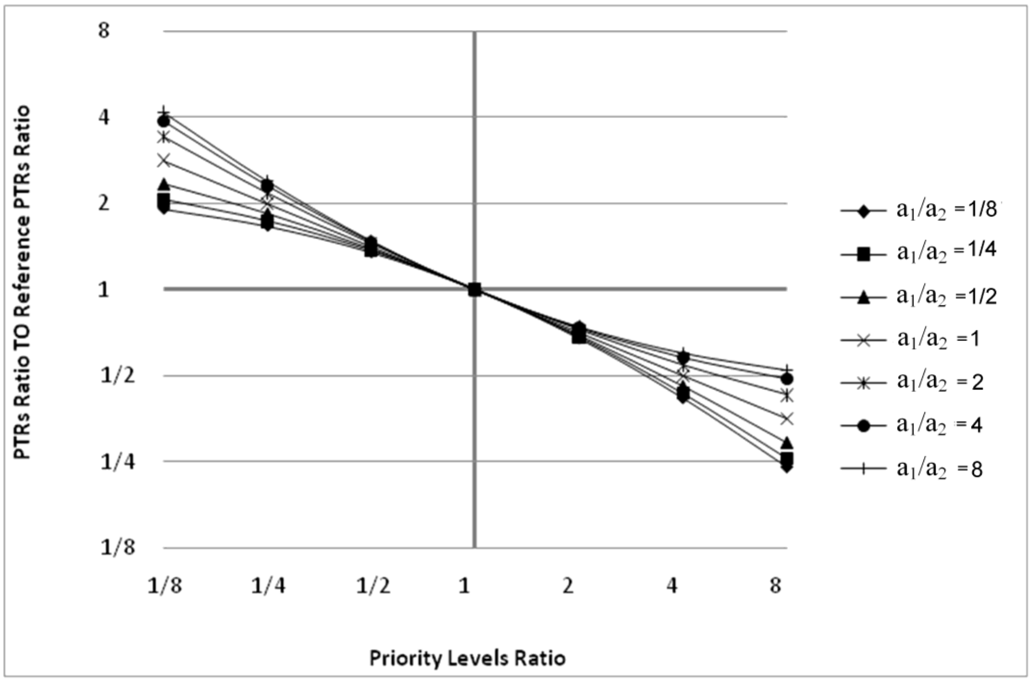

Fig. 5. The divergence between the ratio of the PTRs determined by the proposed technique and the ratio of the corresponding PTRs calculated proportionally to buffer load versus the priority levels ratio for different PGR ratios.

Next, the performance of the proposed resource allocation technique is evaluated according to JFI. In Fig 6, JFI is plotted versus the priority factor for different sets of priority levels. The load rates ratio is set to 1. Evidently, as the priority factor increases, the higher priority traffic is favored at a greater degree compared to the lower priority traffic, as it is expected by equation (1). Thus, JFI decreases with the increase of the priority factor. Moreover, JFI increases as the difference between the two priority levels increases. Note that absolute fairness is achieved when JFI is equal to 1, which denotes that both traffic flows are assigned equal priority. Hence, for $p_1 = p_2$ JFI remains constant to 1. However, this means that traffic is not differentiated, which is usually not the case in a QoS aware scheme.

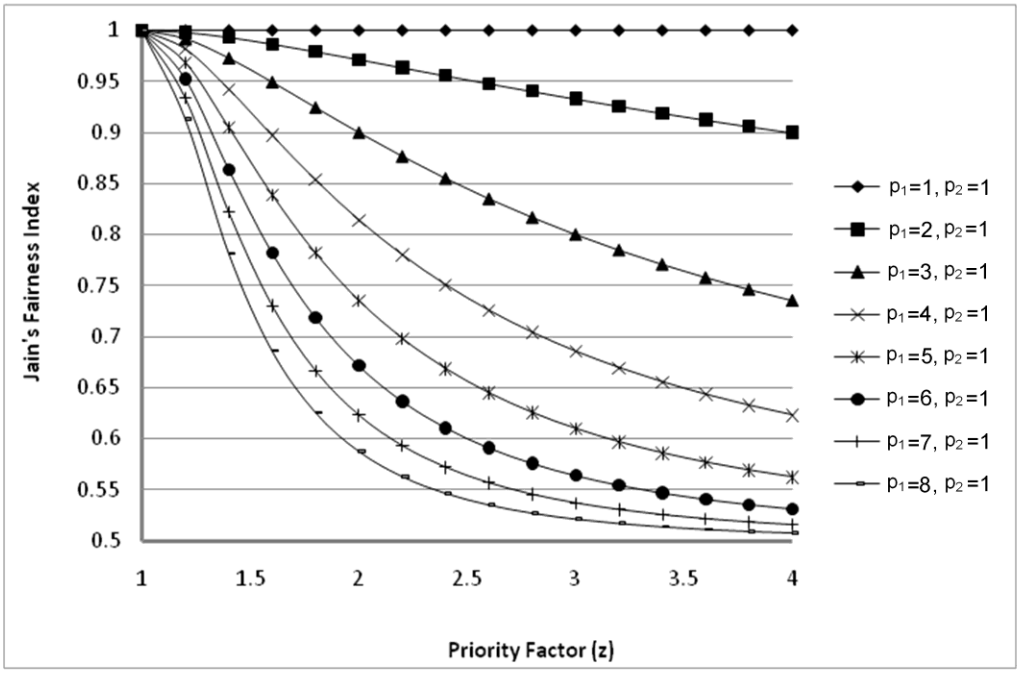

Fig. 6. The impact of the priority factor on JFI.

In Fig. 7, JFI is plotted versus the priority levels ratio for various values of the PGRs ratio. Evidently, JFI increases when the PGRs ratio and the priority levels ratios take values closer to unity. However, when a low PGRs ratio is combined with a high priority levels ratio, or vice versa, then JFI increases, since one ratio retracts the effect of the other one. As it is observed, Fig. 7 is symmetrical to the y-axis, since appropriate values for the set of the examined ratios correspond to the same JFI value.

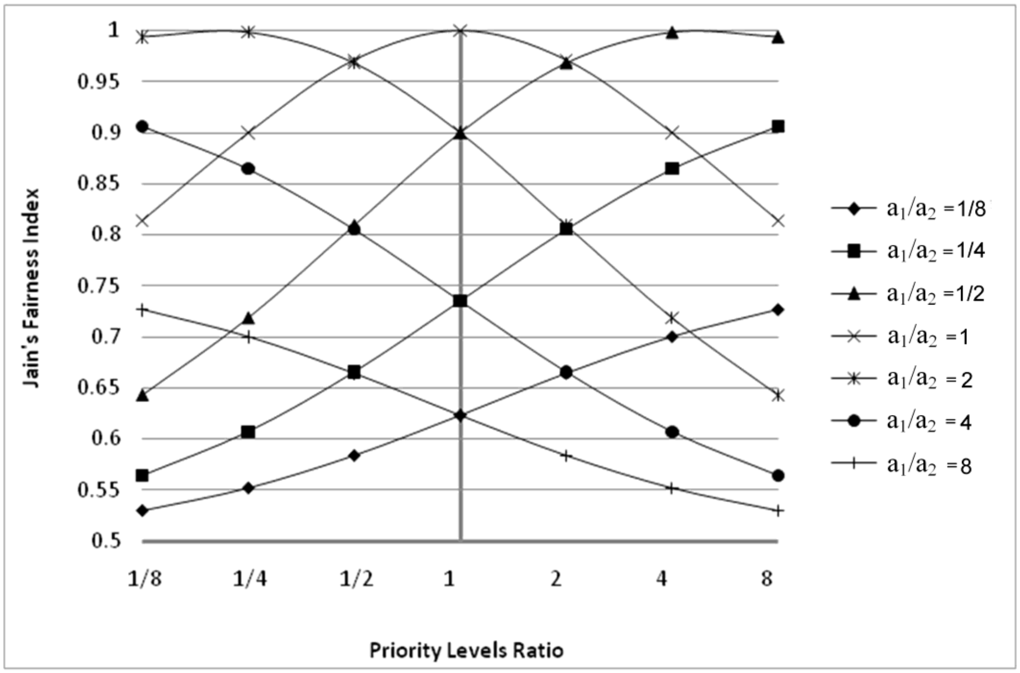

Fig. 7. The effect of the priority levels ratio on JFI for different PGRs ratios.

6. Conclusion

In this work, a QoS aware resource allocation technique for cooperative wireless networks is proposed. The parameters considered by the presented analysis are the traffic priority, the packet buffer load and the PGRs. The analytical results for the buffers PTRs and network fairness have been validated via simulation. In order to study the network behavior when the introduced model is adopted, a certain cooperative scenario has been considered. The results obtained reveal the way that the traffic priority level and the PGR affect the buffer PTR and fairness performance. The results indicate that the proposed technique can efficiently differentiate traffic in a cooperative wireless network. Furthermore, this technique may be adopted by future MAC protocols which take into account the traffic QoS requirements, such as its priority level, and the PGRs to allocate the resources within a cooperative wireless network.

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