Neighbours-Aware Proportional Fair Scheduler for Future Wireless Networks

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Abstract. In this paper, we present an uplink scenario where primary and secondary users coexist on the same set of radio resources. The primary users rely solely on a centralised scheduler within the base station for the assignment of resources, and the secondary users rely on an unslotted Carrier Sense Multiple Access (CSMA) protocol for channel access. We propose a novel centralised scheduling algorithm, Neighbours-Aware Proportional Fair (N-PF), which considers the uplink channel state conditions and the number of secondary users neighbouring each primary user in the aggregate scheduling metric. Through simulations we demonstrate that N-PF outperforms the chosen benchmark algorithm, Proportional Fair (PF), in terms of packet delivery rate while maintaining fairness.

Keywords: Proportional Fair · Neighbours-Aware · Primary users · Secondary users · Unslotted CSMA · Packet delivery rate · Fairness

1 Introduction

One of the practical challenges in the design of future wireless networks will be the presence of interference. Because the spectrum resource will remain limited, numerous primary users (hereafter denoted as scheduled nodes) and secondary users (hereafter denoted as uncoordinated nodes) will have to coexist on the same set of radio resources, resulting in enormous interference on communication links and consequently network performance degradation. Advanced medium access schemes can play a significant role towards achieving efficient utilization of radio resources and hence, current research activities on Medium Access Control (MAC) protocols are of paramount importance.

In this paper we present an uplink scenario where scheduled nodes and uncoordinated nodes coexist on the same pool of radio resources within a cell. Both groups of nodes transmit to a common base station (BS) but unlike scheduled nodes, the uncoordinated nodes do not have a global reference time and therefore, they are totally asynchronous with the base station and with each other. To access the channel, the uncoordinated nodes rely on an unslotted Carrier Sense Multiple Access with Collisions Avoidance (CSMA/CA) protocol, while

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the scheduled nodes rely on a centralised scheduling algorithm located within the base station for radio resources assignment. This scenario could be applicable in many different network instances of future generation wireless networks e.g., 5G and beyond. We propose and evaluate through simulation a novel centralised scheduling algorithm, which outperforms the baseline algorithm, i.e., proportional fair (PF), in terms of packet delivery rate, while maintaining fairness.

In wireless networks, MAC protocols are classified into two main groups: contention-based and contention-free MAC protocols. The contention-based MAC protocols are distributed in nature and suffer from packet collisions. Nodes whose packets collide, perform a random backoff before attempting to access the channel again for retransmission of the lost frames. Such protocols include ALOHA [1], slotted ALOHA [2] and CSMA/CA family of protocols [3]. On the other hand, the contention free MAC protocols are mainly coordinated in nature involving a centralised master entity which develops and allocates orthogonal or non-orthogonal radio resources according to some policies defined by the scheduling algorithms. Schedules assigned to users can either be in time, frequency, space, code or combination of more than one resource dimension. The conventional scheduling algorithms include: Round-Robin (RR), Earliest Deadline First (EDF) [4], Maximum Throughput (MT), and Proportional Fair (PF) [5]. Each scheduling algorithm aims at maximizing/minimizing some network performance metrics such as fairness measure, sum throughput, power consumption, latency, etc., subject to some constraints.

In this paper, we contribute to the performance of centralised uplink scheduling algorithms by proposing a novel algorithm, called Neighbour-Aware proportional Fair (N-PF), which takes into account both channel state conditions and the number of uncoordinated nodes neighbouring each of the scheduled nodes in the aggregate scheduling metric. To maximize packet delivery rate of the scheduled nodes, N-PF, prioritises users with large subsets of uncoordinated neighbours and good channel conditions. In fact, in the presence of capture effect, good uplink channel conditions for the scheduled nodes results in high packet capture probability (p_c), since p_c depends on the Signal to Interference Ratio (SIR). Similarly, a large subset of uncoordinated neighbours belonging to a given scheduled node results in high transmission success probability, because all the uncoordinated nodes in the subset can sense the scheduled transmissions in progress and refrain from accessing the channel.

The main contributions of this paper can be summarised as: (a) we study a new problem where scheduled nodes coexist on the same pool of radio resources with uncoordinated nodes; (b) we propose and evaluate through simulation a novel scheduling algorithm for the scenario, N-PF, which takes into account the relative channel quality metric, and the relative neighbourhood metric accounting for the presence of uncoordinated nodes in the cell; (c) we evaluate through simulation the impact of CSMA parameters (e.g., Clear Channel Assessment (CCA) threshold, NB_{max}, and backoff exponent (BE)) on the benchmark and the proposed algorithms.

The rest of the paper is organised as follows: Sect. 2 discusses related literature, Sect. 3 describes the system model, Sect. 4 describes the benchmark and the proposed scheduling algorithms, Sect. 5 describes simulator setup and the numerical results and finally Sect. 6 provides conclusions.

2 Related Literature

In the past, most MAC protocols for wireless networks have been designed to work in an environment where all users on the same set of radio resources rely exclusively on a centralised scheduling algorithms for resource assignments or contention based MAC protocols for channel access. However, a few studies in literature have been carried out on hybrid MAC protocols which combine features of ordinary TDMA and contention MAC based schemes. The Probabilistic TDMA (PTDMA) in [6], is an hybrid MAC protocol for a single-hop wireless LAN. PTDMA adapts the behaviour of the MAC between TDMA and CSMA according to the level of contention in the network. In [7], DrxMAC, an hybrid MAC protocol for low power and resource constrained devices is discussed. DrxMAC is a slotted TDMA protocol with in-slot carrier sensing, and more than one device can be assigned the same slot. In [8], the authors proposed an hybrid MAC protocol for heterogeneous Machine to Machine (M2M) networks which combine features of contention based and TDMA schemes. [9] Proposes a spectrum-aware cluster-based energy-efficient routing scheme with an hybrid MAC which combine CSMA and TDMA schemes, but the two schemes operate on non conflicting set of radio resources. In IEEE 802.15.4 standard [10], the MAC protocol for beacon-enabled mode uses slotted CSMA/CA as the default channel access scheme, but the coordinator optionally assigns granted time slots to some nodes based on need.

In our work we consider an hybrid scenario, where the scheduled nodes rely on a centralised scheduling scheme for resources assignments, while the uncoordinated nodes rely on an unslotted CSMA/CA protocol for the channel access. Both groups of users coexist on the same set of radio resources. To the best of our knowledge, N-PF is the first dynamic centralised scheduling algorithm to account for the uncoordinated neighbours of the scheduled nodes as a part of aggregate scheduling metric in an hybrid scenario.

3 The System Model

We consider an uplink scenario in a single square cell of side 1 km, consisting of K scheduled nodes $\{j = 1, ..., K\}$, M uncoordinated nodes $\{i = 1, ..., M\}$, a single base station (BS) placed at the center of the cell, and a single frequency TDMA channel. Scheduled nodes are synchronized with the BS and they rely on a scheduler located within the BS for radio resources assignment, while uncoordinated nodes are asynchronous with the BS and they rely on a CSMA/CA MAC protocol for channel access. All nodes are randomly and uniformly distributed within the cell as shown in Fig. 1. Moreover, the scheduled and uncoordinated nodes transmit towards the BS on the same set of radio resources. Radio resources are in form of TDMA slots (hereafter referred as slots). A single frame is divided

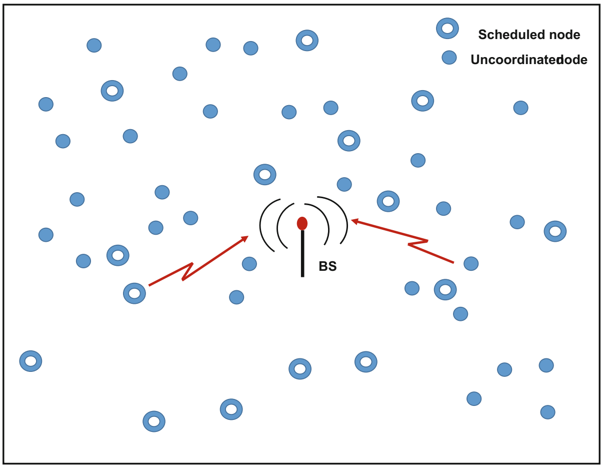

Fig. 1. The system model.

into T slots $\{s = 0, ..., T-1\}$ of unit length, each of which is subdivided into t equal-sized sub-slots $\{ss = 0, ..., t-1\}$.

All devices generate packets of equal length (L sub-slots) according to a Poisson arrival process with arrival rate λ. For the scheduled nodes, when a new packet arrives it is buffered until the base station grants the user a slot to transmit the packet, while in the case of uncoordinated nodes, when a new packet arrives it is buffered until the device successfully contends for a transmission opportunity and finishes transmission of the packet or unsuccessfully contents for a transmission opportunity and drops the packet. Each of the scheduled nodes can only be assigned at maximum a single unique slot in a given frame to transmit a single packet. When assigned to a given slot index s, the node starts transmission at the beginning of that slot. On the other hand uncoordinated nodes can start transmission at any instant along the time-line when the channel access attempt is successful. Depending on the number of packets in the buffer, uncoordinated nodes can attempt transmission of more than one packet, but for each packet the normal CSMA procedure has to be performed.

Let i be a network user connected to the base station, i is affected by path-loss according to the model given as

$$P_{Li}(d)(dB) = k_0(dB) + k_1 \log_{10} d(i, BS)(dB) - \gamma_i(dB) \quad (1)$$

where k_0 and k_1 are constants depending on the propagation environment and the channel frequency, $d(i, BS)$ is the distance between user i and the base station. In linear scale, γ_i is an exponentially distributed component accounting for Rayleigh fading effect on the link. A packet is considered to have been correctly received if for the entire packet transmission time both the Signal to Noise Ratio (SNR) and the SIR are above the respective system thresholds as given by

$$SNR > \xi \; and \; SIR > \alpha \quad (2)$$

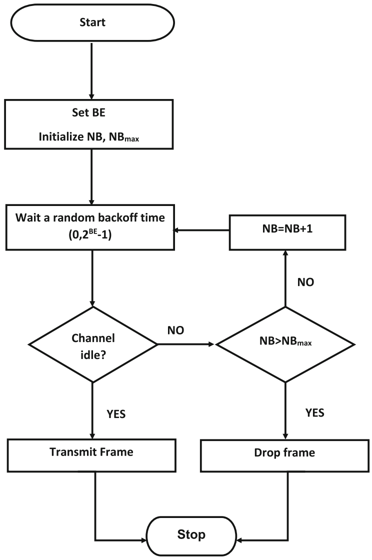

Fig. 2. The CSMA/CA protocol.

For simplicity, uncoordinated node i is considered to be a neighbour of the scheduled node j only if i can hear transmissions of j. Let $\mathcal{U}_{j_n} = \{1, 2, ..., n\}$ denote the subset of all uncoordinated nodes neighbouring j. The properties of $\mathcal{U}_{j_n}$ i.e. cardinality of the subset and its elements change according to the time coherence of the channel because of Rayleigh fading effect on links. Therefore $\mathcal{U}_{j_n}$ has a minimum and a maximum cardinality of 0 and M respectively.

The CSMA protocol implemented in our model is represented by Fig. 2. In the protocol BE is set to a fixed value. Clear Channel Assessment (CCA) is performed using Energy Detection (ED) technique. As shown in the figure the channel access attempt fails when the channel is sensed to be busy in all backoff stages up to the maximum stage (NB_{max}).

4 Benchmark and Proposed Algorithms

4.1 Proportional Fair Scheduling Algorithm

Wireless networks are characterized by time varying channel conditions, which are independent for different users. The proportional fair algorithm is designed to take advantage of multiuser diversity, while maintaining comparable long term throughput for all users. Let $R_j(s)$ denote the instantaneous data rate that user j can achieve at time instant s, and $T_j(s)$ be the average throughput for user j up to time slot s. The proportional fair scheduler selects the user, denoted as j^* with the best relative channel quality according to the metric $R_j(s)/T_j(s)$ for transmission. The average throughput $T_j(s)$ for all the users is updated as

$$T_j(s+1) = \begin{cases} (1-\beta)T_j(s) + \beta R_j(s), & j = j^* \\ (1-\beta)T_j(s), & j \neq j^* \end{cases} \tag{3}$$

where $0 \leq \beta \leq 1$ and $1/\beta$ is the time constant of the exponential moving average. By changing β the scheduler can trade off between the throughput of the system and temporal fairness among the users. In this paper, R_j is computed according to the normalised Shannon capacity formula as $\log_2(1 + SNR)$.

4.2 The Proposed Scheduling Algorithm

Extending the PF algorithm to account for the number of uncoordinated nodes neighbouring each of the scheduled nodes in a scenario where uncoordinated nodes coexists with scheduled nodes on the same set of radio resources, can lead to significant improvement in the performance of the algorithm. At time instant s, our proposed algorithm, N-PF, selects the user, denoted as j^*, with the best aggregate scheduling metric given as

$$\frac{R_j(s)}{T_j(s)} * \left(\frac{1}{\Omega_j}\right)^{\rho} \tag{4}$$

where $\rho \geq 0$ is an optimization constant used by the scheduler to emphasize or de-emphasize relative neighbourhood metric Ω_j during scheduling. For $\rho = 0$, the algorithm turns to be the PF algorithm. For higher values of ρ, the metric Ω_j becomes predominant. For a given scheduled node j, the metric Ω_j is given by

$$\Omega_j = \begin{cases} 1 - \left(\frac{n_j(s)}{M}\right), & M > 0 \,\&\, n_j(s) \neq M \\ b, & M > 0 \,\&\, n_j(s) = M \\ 1, & M = 0 \end{cases} \tag{5}$$

where $n_j(s)$ is the number of uncoordinated neighbours of scheduled node j at time instant s, M is the total number of uncoordinated nodes deployed within the cell and b is an arbitrarily small positive constant.

5 Simulator Setup and Numerical Results

5.1 Simulator Setup

A C++ simulator is used to evaluate the performance of N-PF algorithm. The simulator implements the system model as described in Sect. 3. A single TDMA frame is divided into 10 slots, and each slot is subdivided into 200 sub-slots. The scheduling algorithm runs at the beginning of each new frame. We assume that the BS and all users have omnidirectional antennas. Default parameters considered in our simulations are summarised in Table 1.

A single simulation consists of 1000 frames. Results are averaged over 10 different scenarios, characterised by different nodes' positions the area.

Table 1. Default simulation parameters

Parameter	*Value*	Parameter	*Value*
Transmit power	$30dBm$	SNR threshold (ξ)	5 dB
β	0.1	SIR threshold (α)	3 dB
k_o	$41.7dB$	BS height	20 m
k_1	3.0	NB_{max}	10
λ	1 $packet/frame$	CCA threshold	$-85dBm$
M	40 nodes	CCA duration	8 sub-slots
K	30 nodes	Contention Window (CW)	31 sub-slots
Packet length	50 sub-slots		

5.2 Performance Metrics

1. **Jain Index (JI)** [11], given as

$$Jain\ Index = \left(\sum_{j=1}^{K} x_j\right)^2 / \left(K \sum_{j=1}^{K} x_j^2\right) \quad (6)$$

   where x_j is the average number of radio resource units allocated to user j within an interval of 1000 frames.
2. **Packet Delivery Rate (PDR)** is given by

$$PDR = \frac{n^o\ of\ successful\ packets}{n^o\ of\ transmitted\ packets} * 100 \quad (7)$$

3. **Blocking Rate (BR)**: if we let U_A be the number of unsuccessful channel access attempts and T_A be the total number of channel access attempts, BR is then given by

$$BR = \frac{U_A}{T_A} * 100 \quad (8)$$

5.3 Results

Where not indicated, default parameters in Table 1 should be assumed. Figure 3 shows packet delivery rate (PDR) metric for the scheduled nodes versus ρ with different number of uncoordinated nodes deployed. From the figure, PDR increases with increasing ρ and decreases with increasing number of uncoordinated nodes (M). The former trend is due to the fact that, for higher values of ρ the scheduler selects the scheduled nodes with best Ω_j metric which results in minimizing collision loss probability. The latter trend is attributed to the fact that, packet collision losses increase with increasing M.

Figure 4 shows how the JI varies with the neighbour metric coefficient (ρ). According to the figure, the JI slightly increases with increasing ρ for values

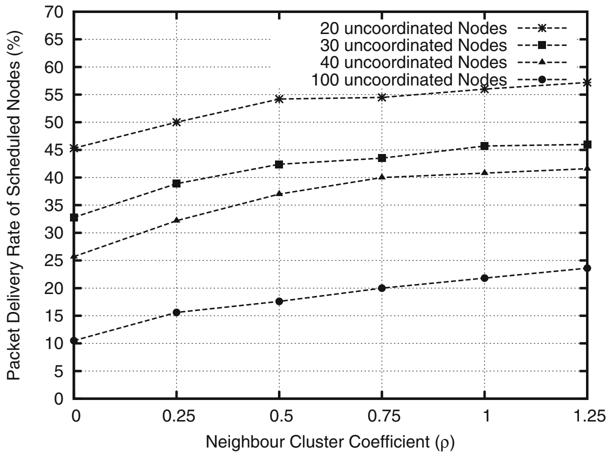

Fig. 3. Packet delivery rate of the scheduled nodes with $K = 30$ and different values of uncoordinated nodes (M).

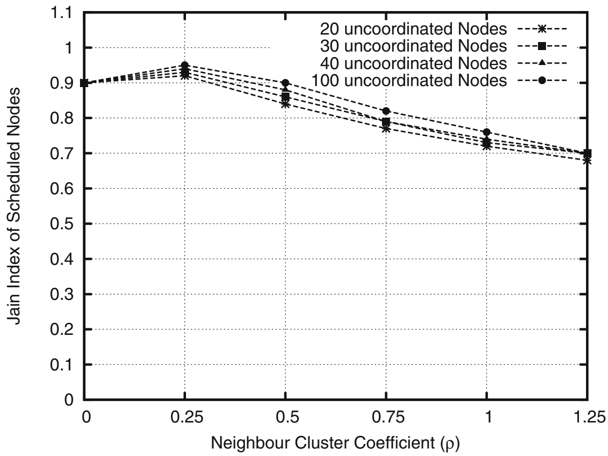

Fig. 4. Jain index of the scheduled nodes with K=30 and different values of M.

of ρ between 0 and 0.25. This effect can be attributed to the additional randomness introduced in the scheduling algorithm by Ω_j metric. Above $\rho = 0.5$, the JI decreases with increasing ρ because the Ω_j component becomes predominant. The decreasing performance in fairness is compensated by an improved performance in PDR as shown in Fig. 3.

Figure 5 shows the blocking rate (BR) metric versus ρ for the uncoordinated nodes. BR increases with increasing ρ and M. As shown in the figure, BR slightly increases with increasing ρ because the scheduler selects users with the best Ω_j metric and as a consequence more uncoordinated nodes are blocked

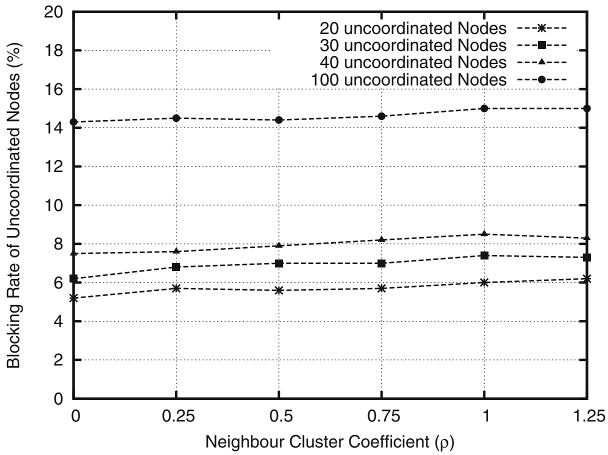

Fig. 5. Packet blocking rate of the uncoordinated nodes with $K = 30$ and different values of M.

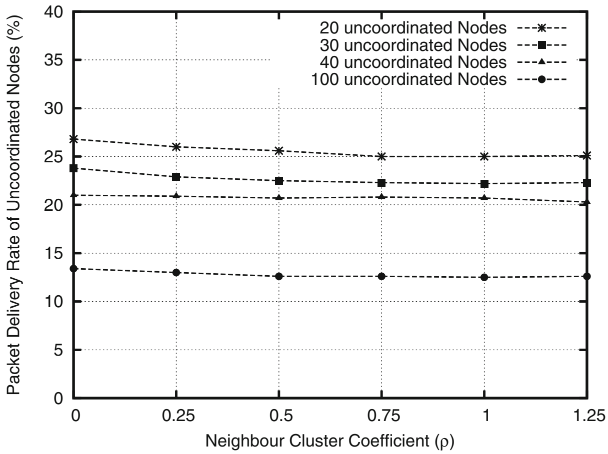

Fig. 6. Packet delivery rate of the uncoordinated nodes with $K = 30$ and different values of M.

from accessing the channel when scheduled nodes are transmitting. On the other hand, BR increases with increasing M because of increasing contention which result in many uncoordinated nodes reaching NB_{max} and consequently dropping packets. Likewise, according to Fig. 6 the PDR of the uncoordinated nodes slightly decrease with increasing ρ because of increasing packet collision loss probability.

Figure 7 shows the impact of packet length on packet delivery rate. The PDR of scheduled nodes increases with decreasing packet length. This is because the probability of packet collisions decreases with decreasing packet transmission time.

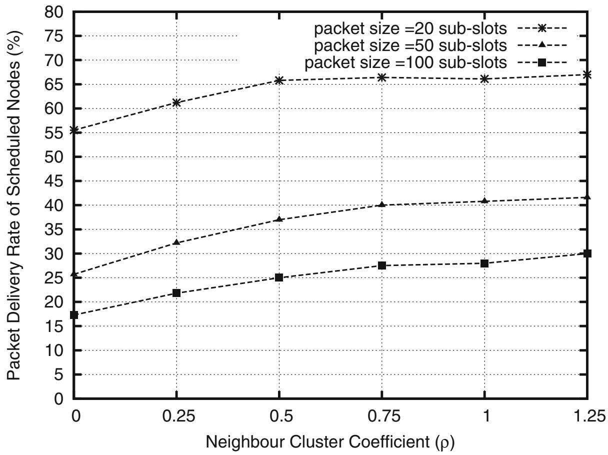

Fig. 7. Packet delivery rate of the scheduled nodes with $K = 30$ and $M = 40$ and different packet sizes.

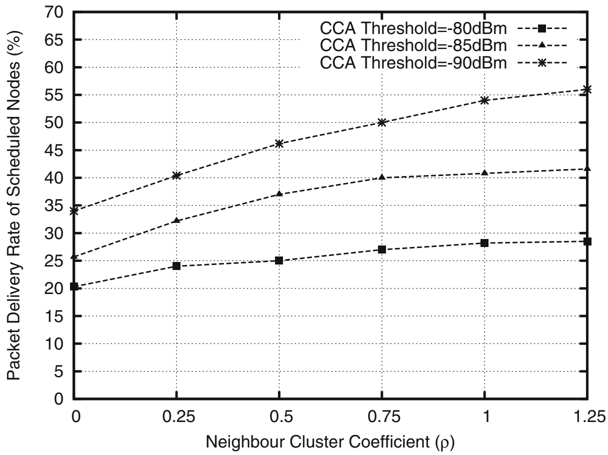

Fig. 8. Packet delivery rate of the scheduled nodes with $K = 30$, $M = 40$ and different values of CCA thresholds.

Figures 8, 9 and 10 show the impact of CSMA parameters on the scheduler i.e. BE, CCA threshold and NB_{max}. Packet delivery rate of the scheduled nodes increases with decreasing CCA threshold and increasing BE because these parameters have an impact of reducing packet collisions. On the other hand, the delivery rate slightly increases with decreasing NB_{max} because decreasing NB_{max} results in an increased blocking rate of uncoordinated nodes and hence decreased collisions.

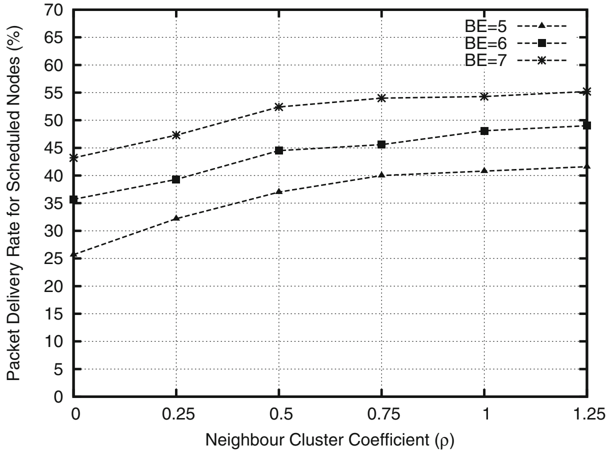

Fig. 9. Packet delivery rate of the scheduled nodes with $K = 30$ and $M = 40$ and different values of **BE**.

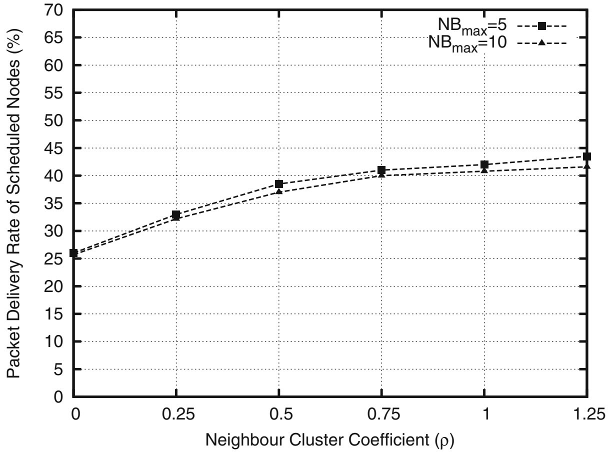

Fig. 10. Packet delivery rate of the scheduled nodes with $K = 30$ and $M = 40$ and different values of NB_{max}.

6 Conclusion

This paper presents a novel centralised scheduling algorithm for a scenario where scheduled nodes and uncoordinated nodes coexist on the same pool of radio resources. The proposed algorithm takes into account relative channel quality metric and relative neighbourhood metric in order to maximize packet delivery rate while maintaining fairness. Performance evaluations through simulations have demonstrated that, with respect to the benchmark algorithm, the proposed algorithm: (i) improves performance of scheduled nodes in terms of packet delivery rate rate; (ii) for small values of ρ, it improves the performance of scheduled nodes in terms of Jain index of fairness; (iii) maintains comparable network performance in terms of blocking rate.

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