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Neighbors-Aware Proportional Fair scheduling for future wireless networks with mixed MAC protocols

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Abstract

In this paper, we consider a beyond-5G scenario, where two types of users, denoted as *scheduled* and *uncoordinated* nodes, coexist on the same set of radio resources for sending data to a base station. Scheduled nodes rely solely on a centralized scheduler within the base station for the assignment of resources, while uncoordinated nodes use an unslotted Carrier Sense Multiple Access (CSMA) protocol for channel access. We propose and evaluate through simulations: (a) a novel centralized resource scheduling algorithm, called Neighbors-Aware Proportional Fair (N-PF) and (b) a novel packet length adaptation algorithm, called Channel-Aware (CA) Packet Length Adaptation algorithm for the scheduled nodes. The N-PF algorithm considers the uplink channel state conditions and the number of uncoordinated nodes neighboring each scheduled node in the aggregate scheduling metric, in order to maximize packet transmission success probability. The CA algorithm provides an additional degree of freedom for improving the performance, thanks to the fact that scheduled nodes with lower number of hidden terminals, i.e., having higher packet capture probability, are assigned longer packet transmission opportunities. We consider two benchmark schemes: Proportional Fair (PF) algorithm, as a resource scheduling algorithm, and a discrete uniform distribution (DUD) scheme for packet lengths distribution. Simulation results show that the proposed schemes can result in significant gain in terms of network goodput, without compromising fairness, with respect to two benchmark solutions taken from the literature.

Keywords: Proportional Fair, Neighbors-Aware, Scheduling, Unslotted CSMA, Packet delivery rate, Fairness, Packet length adaptation

1 Background

In future wireless systems, such as 5G and beyond, the current dominating human-centric communication systems will be complemented by a tremendous increase in the number of smart devices, i.e., *things*, equipped with radio devices, possibly sensors, and uniquely addressable [1]. This will result in explosion of wireless traffic volume [2] and consequently exponential growth in demand of radio spectrum. However, the radio spectrum resource will remain limited, and thus, efficient radio resource utilization techniques, such as advanced medium access control (MAC) schemes, will be of paramount importance.

Based on the above motivation, we envision a novel scenario, where some users (hereafter denoted as *scheduled nodes*), synchronized and coordinated by a base station (BS), coexist on the same set of radio resources with some other users (hereafter denoted as *uncoordinated nodes*), asynchronous with the BS and among them. As shown in Fig. 1, scheduled nodes could be user equipment (i.e., cellular users), while uncoordinated nodes could be things of the Internet of Things (IoT) paradigm, i.e., cars, machines, buildings [3].

In wireless networks, MAC protocols are classified into two main groups: contention-based and contention-free. Contention-based protocols are distributed in nature and suffer from packet collisions. Nodes whose packets collide could perform a random backoff before attempting to access the channel again for retransmission of

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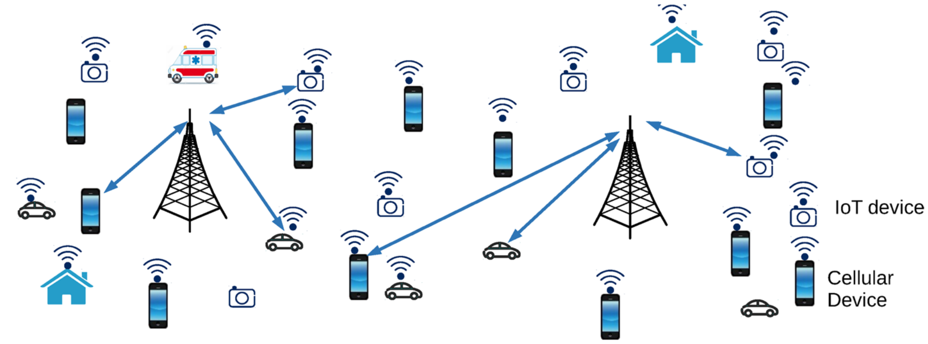

Fig. 1 Network scenario of future wireless networks

lost packets. Such protocols include ALOHA [4], slotted ALOHA [5], and Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) family of protocols [6]. On the other hand, contention-free protocols are mainly coordinated in nature involving a centralized master entity which allocates orthogonal or non-orthogonal resources to network users, using some policies defined by the scheduling algorithm. Radio resources 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) [7], Maximum Throughput (MT), and Proportional Fair (PF) [8]. Each scheduling algorithm aims at maximizing/minimizing some network performance metrics such as fairness, sum throughput, power consumption, latency, etc., subject to some constraints.

In this paper, we consider the uplink scenario illustrated in Fig. 2, where scheduled nodes and uncoordinated nodes transmit to a common base station using different MAC protocols. Uncoordinated nodes use an unslotted CSMA/CA protocol, while scheduled nodes rely on a centralized scheduling algorithm running at the BS. The main goal of our paper is to address the problem of centralized resource scheduling algorithm for scheduled nodes sharing the same channel with the uncoordinated nodes. In order to allow coexistence between scheduled and uncoordinated nodes, we impose scheduled nodes to occupy only a fraction of the slots assigned by the base station, leaving portions of a frame available for possible access by uncoordinated nodes (see Section 3.1 for details). With this coexistence mechanism, collisions between the scheduled and the uncoordinated nodes may occur when uncoordinated node(s) (i) fail(s) to “hear” scheduled transmission in progress due to the hidden terminal problem and start concurrent transmissions and (ii) transmit(s) long packets that overlap the portion of slot assigned to scheduled nodes. In order to reduce these collisions, we propose and evaluate through simulations a novel scheduling algorithm, called Neighbor-Aware Proportional Fair (N-PF), which takes into account both channel state conditions and the number of uncoordinated nodes neighboring each scheduled node in the aggregate scheduling metric. To maximize packet delivery rate of the scheduled nodes, N-PF prioritizes users with larger subsets of uncoordinated neighbors and good channel conditions. In fact, good uplink channel conditions result in higher packet capture probability, thanks to larger values of the signal-to-interference ratio. Similarly, a large subset of neighbors for 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.

Furthermore, we propose a novel Channel-Aware (CA) Packet Length Adaptation algorithm for the scheduled nodes, which serves as an additional degree of freedom for improving network performance. The CA algorithm is based on the following observation: there exists a circular area centered at the BS and having radius equal to the half of the sensing range (see the gray area in Fig. 2), where the uncoordinated nodes can sense any scheduled transmission from the area and refrain from accessing the channel. This area is denoted hereafter as Hidden Neighbor Free (HNF), and nodes within it are assigned an opportunity to transmit longer packets, because they can experience lower interference. Therefore, CA algorithm logically partitions the scheduled nodes into two sets: those which suffer from the hidden terminal problem (i.e., nodes outside the HNF region), using a discrete uniform distribution (DUD) scheme for packets lengths and nodes not having hidden terminals (i.e., nodes in the HNF region) allowed to transmit longer packets.

This paper is an extension of our previous work reported in [9]. As main differences w.r.t. [9], we underline the following: (1) we propose here a novel packet length adaptation algorithm, i.e., CA algorithm not included in [9]; (2) we made some modifications to the resource

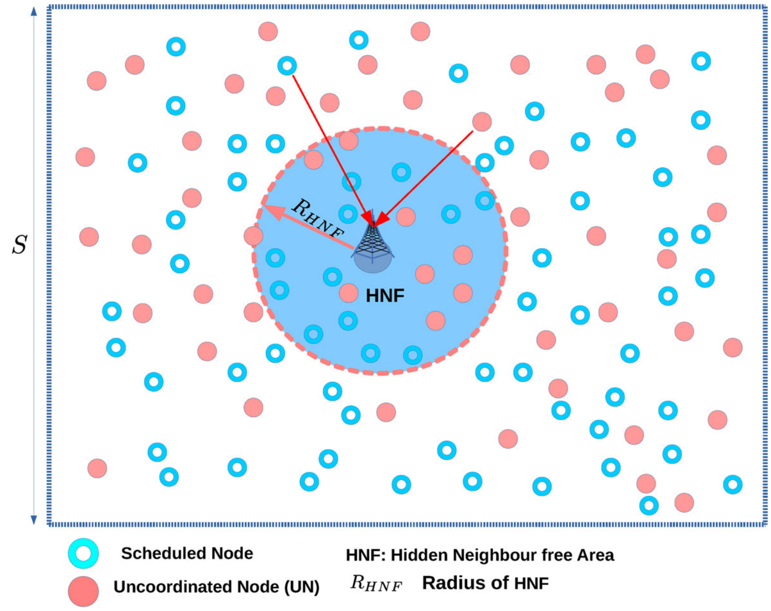

Fig. 2 Reference scenario

scheduling algorithm, N-PF; and (3) we consider here more different performance metrics, evaluating in details N-PF with different packet length adaptation schemes, and different system parameters.

In summary, the contribution of the paper includes the following:

- We study a new problem where scheduled nodes coexist on the same pool of radio resources with uncoordinated nodes.
- We propose a novel centralized resource scheduling algorithm, called N-PF, which takes into account the relative channel quality metric, and the relative neighborhood metric accounting for the presence of uncoordinated nodes in the cell.
- We propose a novel packet length adaptation algorithm, called CA algorithm.

Performance of N-PF and CA are evaluated via simulations and compared with benchmark solutions, based on Proportional Fair and discrete uniform distribution scheme for packets lengths. The impact of CSMA parameters (e.g., Clear Channel Assessment (CCA) threshold and backoff exponent (BE)) on the protocols, is also evaluated.

The rest of the paper is organized as follows: Section 2 discusses related literature, Section 3 describes the system model, Section 4 describes the benchmark and the proposed scheduling algorithms, Section 5 describes the packet length adaptation schemes, Section 6 reports numerical results and, finally, Section 7 provides the conclusion.

2 Related works

2.1 Coexistence of heterogeneous MAC schemes

In the past, a lot of research studies have been done on the coexistence of heterogeneous access schemes. However, this topic continues to attract increasing interests from the scientific and industrial communities because of its promising potential in IoT and beyond-5G networks. Authors in [10] classify the coexistence schemes into two main classes: mediated and autonomous coexistence. In mediated class, there is a network entity which serves as mediator between the coexisting networks to facilitate fair coexistence and mitigate collisions. The mediator also helps to ensure tight synchronization and coordination of the involved networks. This type of coexistence is applicable when two or more time-division multiplexing (TDM) systems share a common channel. On the other hand, autonomous coexistence does not need any coordination of the involved networks. In this class, we have TDM vs. CSMA and CSMA vs. CSMA networks. In our paper, we are concerned with TDM vs. CSMA coexistence.

The 3rd Generation Partnership Project (3GPP) proposes two main mechanisms for ensuring fair coexistence of LTE with WiFi and other technologies in the unlicensed spectrum: Listen Before Talk (LBT) and Carrier Sensing and Adaptive Transmission (CSAT) [11]. LBT is a random access scheme based on carrier sensing and backoff rules similar to WiFi. On the other hand, CSAT is a TDM-based scheduled scheme which is used by LTE-U small cell when no clear channel is found after long-term carrier sensing. The scheme defines a time (duty) cycle where the BS transmits in a fraction of the cycle and remains silent in the remaining duration. Therefore, when CSAT is used, TDM-based nodes (LTE network) coexist with random access-based nodes (WiFi or other technologies) on the same channel. The scope of these works is different from our work because (1) CSAT addresses coexistence in downlink LTE-U small cell, while our work is focused on an uplink scenario which is more challenging due to effects of hidden terminal problem and especially when the network has to cope with high traffic demands and (2) our work focuses on the design of a scheduling algorithm for the scheduled nodes, while in 3GPP standards, details of scheduling algorithms are not provided because it is a vendor-specific problem [12]. Furthermore, the existing traditional scheduling algorithms for radio networks may not be appropriate to be applied directly in the scenario, since they were never designed with coexistence problem in mind.

Another approach widely studied in literature to address spectrum sharing and coexistence is the cognitive radio [13]. With cognitive radio network (CRN), nodes are classified into two categories: primary (licensed) users and secondary (cognitive) users. The secondary users opportunistically access under-utilized spectrum licensed to incumbent systems [14]. Authors in [10] study the problem of heterogeneous coexistence between TDM and CSMA networks in TV White Space (TVWS) spectrum and address hidden terminal problem with a beacon transmission mechanism. Centralized scheduling in cognitive radio networks is studied in [15, 16]. Our work is different because in our scenario, neither the scheduled nor the uncoordinated nodes rely on cognitive radio principles to enhance coexistence.

The IEEE 802.15.4 MAC provides an option for a TDMA mode which operates without carrier sensing. Authors in [17] study the problem of coexistence between ZigBee with TDMA MAC and WiFi. The work proposes a new paradigm which relies on busy tone signals to enhance the mutual observability between ZigBee and WiFi in order to improve on coexistence. The Time-Slotted Channel Hopping (TSCH) protocol proposed in IEEE802.15.4e standard is expected to coexist with random access schemes used by other technologies in the unlicensed bands [18]. TSCH-based devices can mitigate interference and fading through channel hopping technique. Traffic Aware Scheduling algorithm for reliable low-power multi-hop IEEE 802.15.4e networks is studied in [19]. The authors propose a new scheme based on graph theory method of matching and coloring. The probabilistic TDMA (PTDMA) [20] and Z-MAC [21] protocols are hybrid access schemes which combine features of both TDMA and CSMA. They are designed with the flexibility to switch between CSMA and TDMA based on the state of contention in the network. According to these schemes, each node in the network is assigned a time slot to transmit but it could capture the channel on any other slot after performing CSMA procedure. Similarly, authors in [22] propose a hybrid MAC protocol for heterogeneous Machine-to-Machine (M2M) networks which combine features of contention-based and TDMA schemes. A spectrum-aware cluster-based energy-efficient routing hybrid scheme is discussed in [23]. In this scheme, the TDMA and CSMA operate on different channels.

In summary, to the best knowledge of the authors, the N-PF is the first uplink centralised algorithm to address the problem of scheduling competing scheduled users accounting for the effects of the uncoordinated users in the aggregate scheduling metric.

2.2 Packet length adaptation

The literature on packet length adaptation schemes is extensive, especially in 802.11 WLANs [24, 25]. However, very few works exploit packet size adaptation in a heterogeneous coexistence of scheduled and uncoordinated users on the same channel to enhance the performance of one or both of the user groups involved. Furthermore, most of the existing works account only for channel errors which occur due to the time-varying SNR on links and neglect the effects of hidden terminals. In [26, 27], authors propose a loss-based packet length adaptation algorithm for IEEE.802.11 WLANs with hidden terminals operating in a time-varying wireless channel. The authors have shown that accounting for the effect of hidden terminals in the packet loss models can improve the throughput significantly. In [28], authors consider IEEE.802.11b WLAN under interference from IEEE 802.15.4 network. The authors demonstrate that packet length optimization can result in improved throughput in the presence of interference. Dynamic packet size optimization and channel selection for cognitive radio sensor networks is studied in [29]. Finally, [30] studies frame aggregation schemes in 802.11n WLAN with channel errors and proposes optimal frame size adaptation algorithm.

In our work, we propose a new packet length adaptation scheme, denoted as CA, for the scheduled nodes which takes advantage of the capture effect phenomenon to improve on goodput of the scheduled nodes. According to the operation of the algorithm, scheduled nodes within the HNF region are assigned the maximum possible packet size, while those outside the HNF region are assigned packet lengths according to discrete uniform distribution of packet sizes with a goal of maximizing goodput by minimizing collision losses. Therefore, with this scheme, in each slot, the fraction of time for exclusive transmission by uncoordinated nodes is affected and, in fact, it varies depending on which scheduled node is transmitting.

3 The system model

3.1 Reference scenario and radio resources

We consider an uplink scenario in a single square cell of side S, consisting of K scheduled nodes, M uncoordinated nodes, and a single BS placed in the center of the cell. All nodes are randomly and uniformly distributed within the cell as shown in Fig. 2.

Radio resources are in the form of time division multiple access (TDMA) slots (hereafter referred as slots). In particular, time is divided into frames, composed of T slots, each subdivided into t equally sized sub-slots (see Fig. 3). When a scheduled node is assigned a TDMA slot to transmit, its transmissions begin at the boundary of that slot and occupy the channel only for a fraction of the slot, leaving the remaining fraction for possible uncoordinated node transmissions. Therefore, with this paradigm, a scheduled node can only access the channel in the first part of the slot, while an uncoordinated node is not restricted and accesses the channel depending on the CSMA/CA protocol.

3.2 Traffic model

All nodes generate packets according to a Poisson arrival process with arrival rate λ [bytes/frame]. Regarding the packet length, uncoordinated nodes transmit equal length packets of L bytes, while scheduled nodes are allowed to transmit packet sizes determined according to the packet length adaptation schemes described in Section 5.

3.3 Channel and packet capture models

Let P_{T} and P_{R} denote the transmit and received powers, respectively, then P_{R} is given by:

$$P_{\mathrm{R}}[\,\mathrm{dBm}] = P_{\mathrm{T}}(\mathrm{dBm}) - P_{\mathrm{L}}(\mathrm{dB}) \qquad (1)$$

where P_{L} is the path-loss between the transmitter and the receiver. If we let i be a network node connected to the base station, then i is affected by the path-loss, $P_{\mathrm{L_i}}$, according to the following model

$$P_{\mathrm{L_i}}(d)(\mathrm{dB}) = k_0(\mathrm{dB}) + k_1 \log_{10} d(i,\mathrm{BS}) - \gamma_i(\mathrm{dB}) \qquad (2)$$

where k_0 is the path-loss at 1 m given by $20\log_{10}\frac{4\pi}{\lambda}$, where λ is the wavelength and $k_1 = 10{\cdot}\eta$, being η the propagation path-loss exponent dependent on the environment, and $d(i,\mathrm{BS})$ is the distance between user i and the base station. In linear scale, γ_i is an exponentially distributed component with unit mean, accounting for Rayleigh fading effect on the link.

We assume that a packet is correctly received if the conditions given below are satisfied:
1) No physical layer (PHY) issues are present. For a given packet of interest, we first compute the packet error probability, p_{e}, due to PHY layer, assuming that no forward error correction is applied, which is given by

$$p_{\mathrm{e}} = 1 - (1 - \mathrm{BER})^{l} \qquad (3)$$

where l is the number of bits transmitted (i.e., $l = L * 8$) and *BER* is the bit error rate, which depends on the modulation scheme used. In our model, we adopt a Quadrature Phase Shift Keying (QPSK) modulation, and hence,

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}(\sqrt{\mathrm{SNR}}) \qquad (4)$$

where erfc is the complementary error function and SNR is the signal-to-noise ratio in linear units, given by

$$\mathrm{SNR} = P_{\mathrm{R}}(W)/P_{\mathrm{n}}(W) \qquad (5)$$

where P_{n} is the noise power. The PHY layer issues happens with probability p_{e}.

2) If no PHY layer issues are present, then we check if SIR $\geq \alpha$ for the entire duration of packet transmission, where α is the protection ratio (also denoted as capture threshold) and SIR is the signal-to-interference ratio metric.

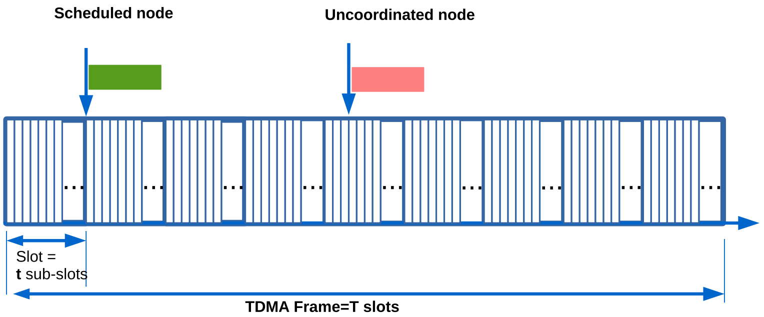

Fig. 3 Frame structure and packet transmission initial times

Finally, we assume that an uncoordinated node i is a neighbor of a scheduled node j if i can "hear" transmissions of j, that is, $P_{\mathrm{R}} \geq \mathrm{CCA}_{\mathrm{thr}}$, where $\mathrm{CCA}_{\mathrm{thr}}$ is the Clear Channel Assessment (CCA) threshold. Let $\mathcal{N}_{j_n} = \{1, 2, ..., n_j\}$ denote the subset of all uncoordinated nodes neighboring j. The properties of $\mathcal{N}_{j_n}$, i.e., cardinality of the subset and its elements change according to the coherence time of the channel because of Rayleigh fading effect on links. Therefore, $\mathcal{N}_{j_n}$ has a minimum and a maximum cardinality of 0 and M, respectively.

3.4 The CSMA/CA protocol

It is out of scope of this paper to propose a new CSMA/CA protocol; therefore, we consider the protocol, whose flowchart is reported in Fig. 4. Before transmission, the contending nodes sense the channel to ascertain whether it is busy or idle: the channel is ascertained to be busy if the level of sensed power in the channel is above a certain CCA threshold, $\mathrm{CCA}_{\mathrm{thr}}$. At the beginning of the backoff process for a given node, the node selects randomly and uniformly a backoff delay time from the contention window as

$$\mathcal{U} \sim [\,0, 2^{\mathrm{BE}} - 1] \tag{6}$$

where $\mathcal{U}$ denotes uniform distribution and BE is the backoff exponent set to a fixed value (see Table 1). As in the case of many CSMA/CA protocols, we impose a maximum number of backoff stages, $\mathrm{NB}_{\max}$, after which the channel access attempt is considered to have failed. Finally, retransmissions of lost packets are not considered.

4 Scheduling algorithms

We first describe the benchmark protocol considered in this paper, that is Proportional Fair, and then we report our proposed solution.

4.1 Benchmark algorithm: Proportional Fair

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 multi-user 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:

$$T_j(s+1) = \begin{cases} (1-\beta)T_j(s) + \beta R_j(s), & j = j^* \\ (1-\beta)T_j(s), & j \neq j^* \end{cases} \tag{7}$$

where $0 \leq \beta \leq 1$ and $1/\beta$ is the averaging time window [31]. 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

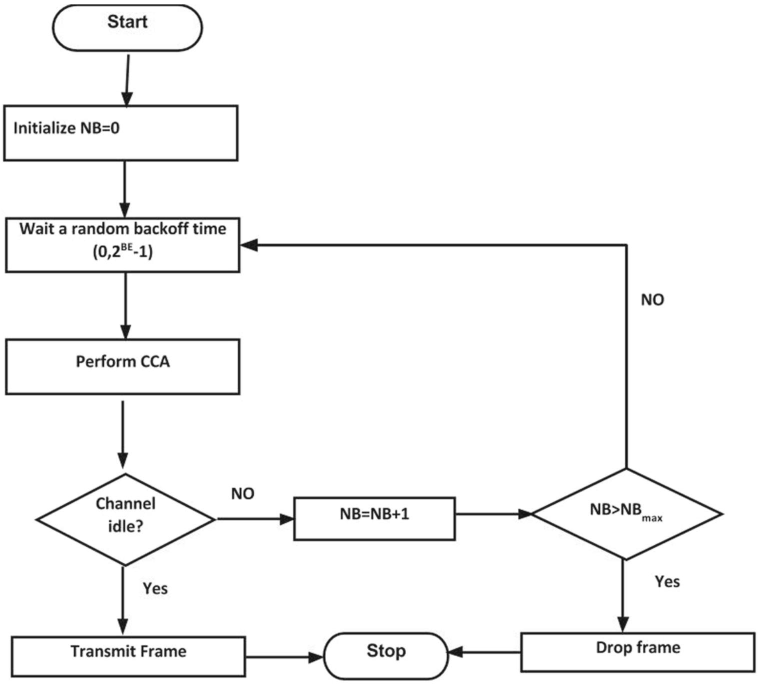

Fig. 4 The CSMA/CA protocol

Table 1 Default simulation parameters

Parameter	Value
β	0.1
M	50 nodes
K	100 nodes
Packet length	50 sub-slots
$L_{\max}$	200 sub-slots
$L_{\min}$	10 sub-slots
S	1000 m
Fade margin (γ_f)	5 dB
Bit rate	1 Mbps
SIR threshold (α)	3 dB
BS height	20 m
$NB_{\max}$	10
CCA threshold ($\mathrm{CCA_{thr}}$)	−85 dBm
CCA duration	8 sub-slots
Contention window (CW)	31 sub-slots
1 sub-slot	$80\mu s$
BE	5
b	$0.1/M$
Channel coherence time	10 slots

according to the normalized Shannon capacity formula as $\log_2(1 + \mathrm{SNR})$.

4.2 Proposed algorithm: Neighbors-Aware Proportional Fair

We modify the PF algorithm encapsulating into the scheduling metric the number of uncoordinated nodes neighboring each scheduled node. At time instant s, our proposed algorithm N-PF selects the user, denoted as j^*, with the largest aggregate scheduling metric given as:

$$\frac{R_j(s)}{T_j(s)} * \left(\frac{1}{\Omega_j(s)}\right)^{\rho} \tag{8}$$

where $\rho \geq 0$ is an optimization constant used by the scheduler to emphasize or de-emphasize relative neighborhood metric Ω_j during scheduling. For $\rho = 0$, the algorithm turns to be the PF algorithm. For higher values of ρ, the term $1/\Omega_j(s)$ becomes predominant. For a given scheduled node j and with perfect knowledge of the number of its uncoordinated neighbors ($n_j(s)$) at time instant s, $\Omega_j(s)$ is given by:

$$\Omega_j(s) = \begin{cases} 1 - \left(\frac{n_j(s)}{M}\right), & M > 0 \;\&\; n_j(s) \neq M \\ b, & M > 0 \;\&\; n_j(s) = M \\ 1, & M = 0 \end{cases} \tag{9}$$

where M is the total number of uncoordinated nodes deployed in the cell and b is an arbitrarily small positive constant.

5 Packet length distribution schemes

We first describe the benchmark packet length distribution considered in this paper, and then we report our proposed solution.

5.1 Benchmark scheme: discrete uniform distribution

The benchmark packet length selection algorithm is based on a discrete uniform distribution of packet lengths. In this scheme, a scheduled node selects a packet length, L, to transmit according to

$$L \sim \mathcal{U}\big[L_{\min}, L_{\max}\big] \tag{10}$$

where $L_{\min}$ and $L_{\max}$ are the minimum and maximum possible packet sizes in bytes supported, respectively. The difference between two consecutive packet sizes in the ordered set is a fixed constant ΔL which is set to $L_{\min}$ in the rest of this paper.

5.2 Proposed scheme: Channel-Aware Packet Length Adaptation

In collision-prone CSMA-based wireless networks with hidden terminals, packet length adaptation schemes can play an important role in mitigating the effects of collisions. Losses of long packets due to collisions can result in significant waste of network radio spectrum and energy [32]. The probability of packet collisions and hence losses due to the presence of hidden terminals increases with packet size. This can be attributed to the fact that when the packet length increases, the set of hidden terminals for a given node has to remain silent for a longer time in order to avoid collisions. Similarly, as the number of hidden terminals increases, the chance of collision and losses increases due to the increased average number of transmissions from the set of hidden terminals. In such a condition, small packets transmission are favorable, but if not carefully optimized based on the wireless channel conditions, it can result in low network throughput and channel under utilization.

The CA algorithm is a packet length adaptation algorithm for the scheduled nodes which aims at achieving high throughput by assigning long packet transmission opportunities to those scheduled nodes within the HNF area (see Fig. 2). The HFN area is a circle, centered at the BS, and whose radius, R_{HNF}, is given by:

$$R_{\mathrm{HNF}} = \frac{\tilde{R}_{\mathrm{s}}}{2} \tag{11}$$

where $\tilde{R}_\mathrm{s}$ is the approximated carrier sensing range in meters, computed by adding a fading margin, γ_f:

$$\tilde{R}_\mathrm{s} = 10^{\frac{P_\mathrm{T}-(\mathrm{CCA}_\mathrm{thr}+\gamma_\mathrm{f})-k_0}{k_1}} \quad [m] \tag{12}$$

where k_0 and k_1 assume the same meaning as in Eq. (2).

A scheduled node j belongs to the HNF area if the SNR measured at the base station (SNR_j) is greater than a given threshold (ξ), i.e.,

$$\mathrm{SNR}_j \geq \xi \tag{13}$$

where ξ is the SNR threshold in dB given by:

$$\xi = P_\mathrm{T} - (k_0 + k_1 \log_{10} R_\mathrm{HNF}) - P_\mathrm{n} \tag{14}$$

and P_n is the noise power in dBm. Therefore, if the link quality of a given node j is high such that $\mathrm{SNR}_j \geq \xi$, the node is considered to belong to the HNF area regardless of its physical location in the cell. Within the HNF area, almost all uncoordinated nodes in the region can sense any ongoing scheduled transmission within the region and refrain from accessing the channel. Moreover, the packet capture success probability of the scheduled nodes in the region is very high even in the presence of concurrent uncoordinated transmission(s) from outside the HNF area. The CA algorithm runs within the BS to determine appropriate packet lengths for the scheduled nodes: nodes in the HNF area are assigned maximum allowable packet length, L_max, while those outside the HNF area are assigned packet lengths randomly and uniformly distributed between L_min and L_max, according to the DUD algorithm.

6 Results and discussion

6.1 Simulator and parameters

A C++ simulator implementing the algorithms and the system model described above has been used. We simulate a square cell of length 1 km, a single BS placed at the center of the cell, and variable number of scheduled and uncoordinated nodes which are randomly and uniformly distributed in the cell. We assume that all nodes have omnidirectional antennas. We consider a single frequency channel partitioned into time frames with each frame consisting of 10 equal slots. Each slot is further subdivided into 200 equal sub-slots of 80-μs duration. Within each sub-slot, only 10 B of traffic can be transmitted. The path-loss is computed as given by the path-loss model in Eq. (2) with k_0 and k_1 set to 40.7 dB and 30, respectively. For both types of nodes, the traffic arrival rate is set to 500 B per frame. Uncoordinated nodes always transmit packets of fixed length set to 50 sub-slots (i.e., 500 B), while scheduled nodes transmit either fixed-length or variable-length packets depending on whether the packet adaptation algorithm is used or not. The resource scheduling algorithm runs at the beginning of each new frame. Each scheduled node requesting for resources is assigned a maximum of one slot per frame. The parameters of the CSMA/CA protocol and other default parameters used in this simulation are summarized in Table 1. A single simulation consists of 1000 frames. Results are averaged over 10 different simulation scenarios, characterized by different nodes' positions in the area.

6.2 Performance metrics

1. Jain Index (JI), given as

$$\text{Jain Index} = \left(\sum_{j=1}^{K} x_j\right)^2 \Big/ \left(K \sum_{j=1}^{K} x_j^2\right) \tag{15}$$

   where x_j is the average number of radio resource units, i.e., slots, allocated to user j within an interval of 1000 frames.
2. Packet delivery rate (PDR) is given by:

$$\mathrm{PDR} = \frac{\text{no of successful packets}}{\text{no of transmitted packets}} * 100 \tag{16}$$

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, where a channel access attempt is unsuccessful if a node fails to capture the channel after reaching maximum allowable retries, then BR is then given by:

$$\mathrm{BR} = \frac{U_A}{T_A} * 100 \tag{17}$$

   BR estimates the level of inhibition in the access to the channel suffered by CSMA-based nodes.
4. Network goodput (NG) is given by:

$$\mathrm{NG} = \frac{\text{correctly received bits in } N \text{ frames}}{\text{time duration for } N \text{ frames}}$$

   where at the numerator, we have the sum of the number of bits correctly received at the BS when transmitted by the K scheduled nodes (NG for scheduled nodes) or by the M uncoordinated nodes (NG for uncoordinated nodes).
5. Channel Utilization Index (CUI) is given by:

$$\mathrm{CUI} = \frac{\text{Aggregate Goodput}}{\text{Bit Rate}}$$

   where aggregate goodput is the total network goodput (i.e., sum of the network goodput of scheduled nodes and uncoordinated nodes).

6.3 Results with fixed-length packets

In this subsection, we compare results obtained for the N-PF algorithm and the benchmark algorithm, Proportional Fair, obtained by setting $\rho = 0$ in the N-PF algorithm. Packet length adaptation scheme is not applied; therefore, both the scheduled and the uncoordinated nodes transmit packets of fixed length.

Figure 5 shows the packet delivery rate for the scheduled nodes versus ρ for different number of uncoordinated nodes. From the figure, it is evident that N-PF algorithm achieves up to 35% gain compared with PF algorithm in all cases. Furthermore, the PDR increases with ρ and decreases when increasing the number of uncoordinated nodes, M. The former trend is due to the fact that, for higher values of ρ, the scheduler selects the nodes with the largest value of $1/\Omega_j$ (i.e., having the largest number of neighbors, n_j), which results in minimizing collision loss probability. The latter trend is attributed to the fact that packet collisions rise when increasing M.

Figure 6 shows the impact of packet length on packet delivery rate. The PDR of scheduled nodes increases by decreasing packet length because of lower collisions probability.

Figures 7 and 8 show the impact of CSMA parameters (BE and CCA threshold) on the scheduler. As can be seen, the performance of N-PF compared to the PF algorithm improves with decreasing $\mathrm{CCA_{thr}}$. For example, in the case of $\mathrm{CCA_{thr}}$ equal to −90 dBm, the gap between N-PF and PF algorithms in terms of PDR can be up to 50%. Furthermore, as a general trend for all the cases, packet delivery rate of the scheduled nodes increases when decreasing $\mathrm{CCA_{thr}}$ and increasing BE because (a) decreasing $\mathrm{CCA_{thr}}$ results in lower average number of hidden neighbors per scheduled node and (b) increasing BE spreads the channel access time for the uncoordinated nodes in a larger time window, hence reduces losses.

6.4 Results with CA and DUD schemes

In this subsection, we provide results obtained when applying CA and DUD packet length adaptation schemes together with the N-PF resource allocation algorithm.

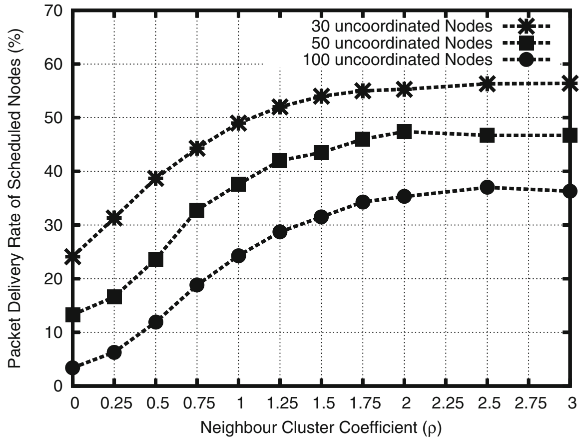

Fig. 5 Packet delivery rate of the scheduled nodes with $K = 100, \mathrm{CCA_{thr}} = -85$ dBm, and $L = 50$ sub-slots and different values M

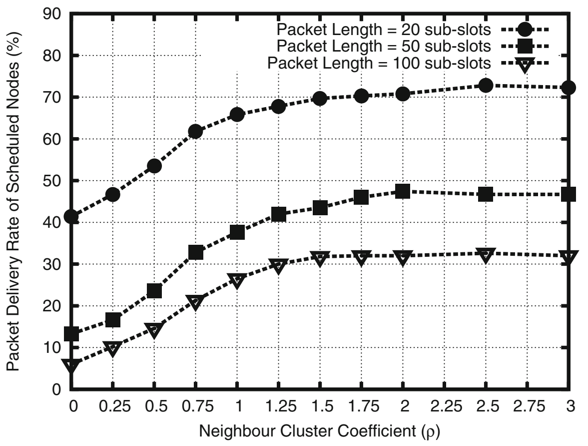

Fig. 6 Packet delivery rate of the scheduled nodes with $K = 100, M = 50, CCA_{\mathrm{thr}}$ =-85 dBm, and different packet sizes

Figure 9 shows the network goodput for scheduled and uncoordinated nodes when varying ρ, for different values of $\mathrm{CCA_{thr}}$. This metric increases with ρ for scheduled nodes, demonstrating that the term $1/\Omega_j(s)$ in Eq. (8) strongly impacts the goodput. On the other hand, when increasing ρ, larger priority is given to scheduled nodes having more neighbors, resulting in having more uncoordinated nodes refrained from accessing the channel. Therefore, NG for uncoordinated nodes decreases with ρ. This is demonstrated also in Fig. 10, where the blocking rate for uncoordinated nodes is shown as a function of ρ: as expected, BR increases with ρ.

With reference to the comparison between CA and DUD packet length algorithms, in Fig. 9, we can see that CA always improves the goodput for scheduled nodes because of the effect of transmitting longer packets. On

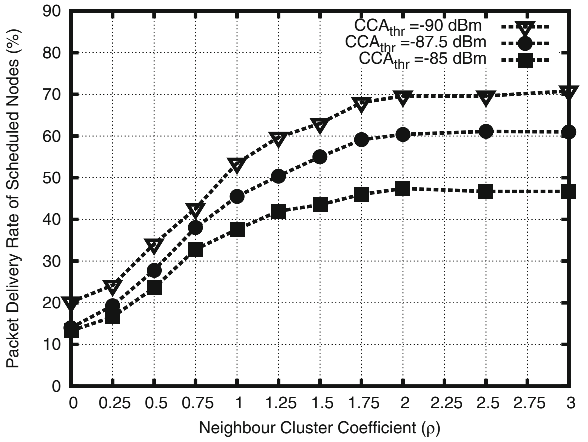

Fig. 7 Packet delivery rate of the scheduled nodes with $K = 100, M = 50$, and different values of $\mathrm{CCA_{thr}}$

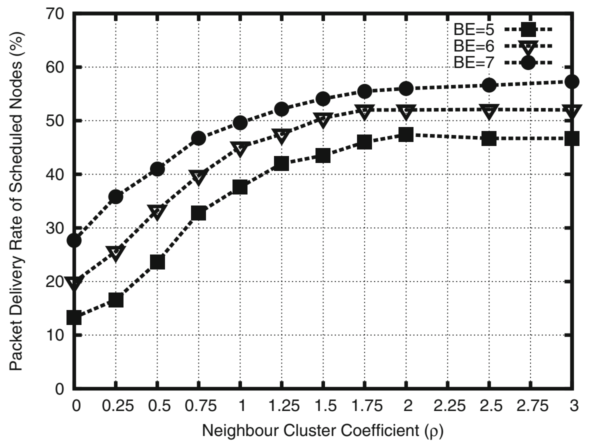

Fig. 8 Packet delivery rate of the scheduled nodes with $K = 100, M = 50$, and $\mathrm{CCA_{thr}} = -85$ dBm and different values of BE

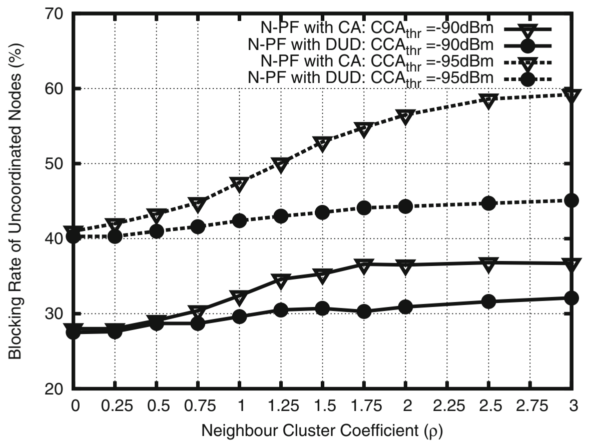

Fig. 10 Blocking rate of uncoordinated nodes with CA and DUD algorithms, for $K = 100, M = 100$, and different values of $\mathrm{CCA_{thr}}$

the other hand, CA worsens performance for uncoordinated nodes, since it gives more priority in the access to the channel (i.e., longer packets) to scheduled nodes. As shown in Fig. 10, in fact, the blocking rate for uncoordinated nodes increases when using CA.

Similar results/behaviors can be seen also in Fig. 11 showing the effects of using N-PF and CA on the packet delivery rate: PDR for scheduled nodes increases with ρ, while it decreases for uncoordinated nodes. In the figure, we can also see that, as expected, the packet delivery rate of both scheduled and uncoordinated nodes decreases with increasing the number of uncoordinated nodes, due to larger collision rate.

Figure 9 also shows the notable improvement of the goodput that can be reached when using N-PF w.r.t. to the case of PF ($\rho = 0$), when CA is used; this improvement is much larger than the worsening obtained for uncoordinated nodes. This is demonstrated also in Fig. 12, where the overall channel utilization index as a function of ρ is shown. As can be seen, both the use of N-PF and CA improve the channel utilization.

Regarding the impact of the $\mathrm{CCA_{thr}}$, in Fig. 12, it is shown that the channel utilization increase by decreasing the CCA threshold, since scheduled nodes may "hear" more uncoordinated nodes. This results again in increasing the blocking rate for uncoordinated node, shown in Fig. 10.

We conclude by showing in Fig. 13 the Jain index for N-PF with CA and DUD algorithms as a function of ρ, for different values of the CCA threshold. In all cases there exists an optimum value of ρ maximizing the Jain Index. In fact, when ρ is low, the scheduling metric is mainly affected by the first term of Eq. (8), while the term $1/\Omega_j$ only introduces an additional randomness into the scheduling algorithm, resulting in increasing fairness when ρ increases. When ρ becomes large, the impact

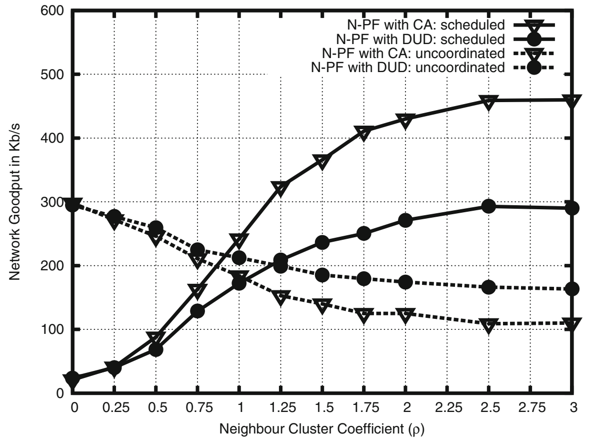

Fig. 9 Network goodput with CA and DUD algorithms, for $K = 100, M = 100$, and $\mathrm{CCA_{thr}} = -90$ dBm

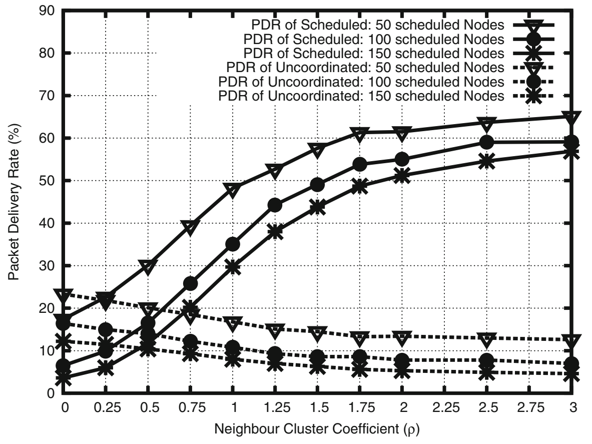

Fig. 11 Packet delivery rate in the case of N-PF with CA algorithm, for $K = 100, \mathrm{CCA_{thr}} = -90$ dBm, and different values of M

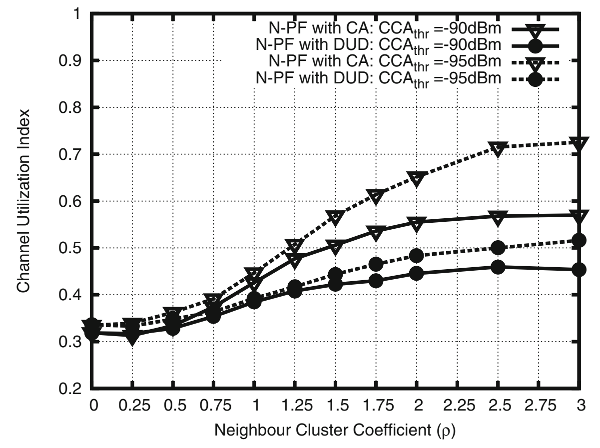

Fig. 12 Channel utilization index with CA and DUD algorithms, for $K = 100, M = 100$, and different values of CCA_{thr}

of the second term in Eq. (8) is predominant and a further increasing of ρ results in lower Jain Index, since the N-PF algorithm tends to unfairly treat nodes. N-PF, in fact, gives more priority to scheduled nodes with a larger set of neighbors. Moreover, the optimal value of Jain Index shifts to the right with decreasing CCA_{thr}: when decreasing the CCA threshold, the sensing area of nodes increases, reducing border effects and resulting in larger fairness. Moreover, we can note that when ρ is lower than the optimum value, CA is slightly better than DUD, due to the randomness introduced by the CA algorithm on the N-PF algorithm. While for large values of ρ, the trend reverses and N-PF with DUD outperforms CA because CA introduces additional disparity in resource allocation.

Finally, note that by properly setting the value of ρ, N-PF allows the improvement also of fairness w.r.t. the PF algorithm.

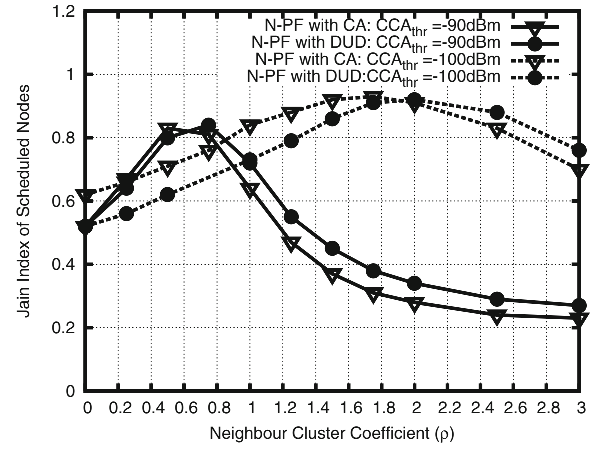

Fig. 13 Jain Index of the scheduled nodes with CA and DUD algorithms, for $K = 100, M = 100$, and different values of CCA_{thr}

7 Conclusions

This paper presents a novel centralized scheduling algorithm for resource assignment for a scenario where scheduled nodes coexist on the same pool of radio resources with uncoordinated nodes. Through simulations, we have demonstrated that the N-PF algorithm outperforms the benchmark algorithm, that is proportional fair, in terms of network goodput, packet delivery rate, and channel utilization, without compromising fairness. Moreover, we have proposed a Channel-Aware Packet Length Adaptation algorithm, which allows to further improve the network goodput when compared to the discrete uniform distribution packet length selection scheme. Finally, we have shown the effect of different CSMA parameters, as the backoff exponent and the CCA threshold. Results show that the performance improvement of N-PF algorithm in terms of Jain Index and channel utilization, compared to PF algorithm, increases with decreasing CCA_{thr}. In conclusion, by properly setting ρ, N-PF with CA can achieve, with respect to PF with DUD, a gain of 800% in terms of network goodput for scheduled nodes, 133% in terms of channel utilization, and 50% in terms of Jain Index.

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Authors' contributions

All authors contributed to the work. All authors read and approved the final manuscript.

Competing interests

The authors declare that they have no competing interests.

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