Cooperative Medium Access Control Based on Spectrum Leasing

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***Abstract*—Based on cooperative spectrum leasing, a distributed "win–win" (WW) cooperative framework is designed to encourage the licensed source node (SN) to lease some part of its spectral resources to the unlicensed relay node (RN) for the sake of simultaneously improving the SN's achievable rate and for reducing the energy consumption (EC). The potential candidate RNs carry out autonomous decisions concerning whether to contend for a cooperative transmission opportunity, which could dissipate some of their battery power, while conveying their traffic in light of their individual service requirements. Furthermore, a WW cooperative medium-access-control (MAC) protocol is designed to implement the proposed distributed WW cooperative framework. Simulation results demonstrate that our WW cooperative MAC protocol is capable of providing both substantial rate improvements and considerable energy savings for the cooperative spectrum leasing system.**

***Index Terms*—Author, please supply index terms/keywords for your paper. To download the IEEE Taxonomy go to http://www.ieee.org/documents/taxonomy_v101.pdf.**

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I. Introduction

COOPERATIVE communications techniques have recently attracted substantial research attention [1] as a benefit of their significant throughput improvements, energy savings, and coverage enhancements. However, these benefits may be eroded by the conventional higher layer protocols, which were designed for classic noncooperative systems. Hence, it is important to design appropriate medium-access-control (MAC) protocols to support cooperative physical layer techniques.

In contrast with the legacy wireless MAC protocols, cooperative MAC protocols aim to cooperatively schedule the medium access of all nodes while allowing the relay nodes (RNs) to buffer and forward the others' data frames using the broadcast nature of the wireless network, instead of ignoring these data frames. There are numerous contributions in the literature on designing cooperative MAC protocols, most of which aim to maximize the throughput [2]–[6], including the widely recognized CoopMAC of [7]. However, a potential impediment of the CoopMAC is that its energy efficiency was traded off against the throughput benefits claimed. Therefore, [8]–[12] aimed to minimize the energy consumption (EC) by developing energy-efficient cooperative MAC protocols. To jointly consider these conflicting design objectives, Luo *et al.* [13] and Zhou *et al.* [14] designed meritorious algorithms to improve the achievable throughput and to simultaneously enhance the energy efficiency achieved.

However, the aforementioned cooperative MAC protocols, such as CoopMAC, were developed based on the common assumption that the relays agree to altruistically forward the data of the source node (SN). This unconditional altruistic behavior is unrealistic to expect from mobile stations. In fact, a greedy RN behavior is likely to be the norm in spectrum leasing [15], where the licensed SN intends to lease some part of its spectral resources to the unlicensed RN in exchange for appropriate "remuneration." In this spectrum leasing system, the unlicensed RNs also have an incentive to support the SN to achieve its quality-of-service (QoS) target in exchange for a transmission opportunity. This cooperation allows both the SN and the RN to satisfy its individual requirement. Based on this cooperative spectrum leasing system, some early theoretical studies have been conducted in [16]–[21]. Bearing in mind the greedy behavior of the mobile RNs, meritorious game-theoretic frameworks were proposed in [16]–[19] to maximize the SN's *transmit rate* while simultaneously satisfying the requirements of the RNs. Based on game theory, Hafeez and Elmirghani [20] and Jayaweera *et al.* [21] aimed to minimize the *EC* of cooperative spectrum leasing systems by designing beneficial game-aided strategies. However, the joint optimization of the transmit rate and of the EC has not been considered in these existing works. Furthermore, the design of an appropriate cooperative MAC protocol for practically implementing the theoretical framework was not discussed in [16]–[21].

Against this backdrop, the contributions of this paper are as follows.

1) We first formulate a distributed "win–win" (WW) cooperative framework (DWWCF) to encourage the SN to lease part of its spectral resources to the unlicensed RN for the sake of improving the SN's *transmit rate* and for simultaneously reducing the SN's *EC* while ensuring that the unlicensed RNs are capable of securing a transmission opportunity for *their own traffic* and for satisfying their QoS. Furthermore, the proposed DWWCF selects the

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best RN for the sake of *minimizing the system's transmit power*.

2) Second, a WW cooperative MAC protocol is developed to *practically implement* our DWWCF in a cooperative spectrum leasing system (CSLS) by designing the required *signaling procedures* to implement the negotiation between the SN and the greedy RN. Similarly, the *frame structure* of both the data and control messages is also conceived to convey all the required information. Hence, the proposed WW cooperative MAC protocol is a throughput- and energy-oriented protocol rather than a single-objective cooperative MAC protocol, such as CoopMAC [7], which is a throughput-oriented protocol. Furthermore, the proposed WW cooperative MAC protocol is designed for more realistic scenario having rewarded RNs rather than altruistic RNs, which was considered in most existing cooperative MAC protocol, such as the CoopMAC [7]. To simplify the signaling procedures at the MAC layer, the proposed WW cooperative MAC protocol relies on a *distributed RN selection scheme*, rather than either centralized or table-based RN selection scheme, which was exploited by many cooperative MAC protocols, such as CoopMAC [7], allowing the SN to select the best RN relying on the global information in the SN's CoopTable.

3) Additionally, in contrast with the RN's time/frequency slot reservation strategy of [17], superposition coding (SPC) is invoked at the RN for jointly encoding both the SN's and RN's data based on a cooperative spectrum leasing system. Fortunately, the resultant interference can be eliminated at the destination node (DN) using successive interference cancelation (SIC) to separate the SN's and RN's data while beneficially amalgamating both the direct and relayed components using frame combining.

The remainder of this paper is organized as follows. The network's architecture and our DWWCF are introduced in Section II. Section III describes the proposed WW cooperative MAC protocol, whereas in Section IV, the attainable performance of our scheme is quantified. Finally, we conclude in Section V.

II. System Model and Distributed Win-Win Cooperative Framework

A. System Model

Before embarking on outlining our DWWCF, we introduce our network topology and outline our assumptions.

As shown in Fig. 1, we consider a cooperative network having a single SN $\mathcal{S}$ and a total of N RNs in the set $\mathcal{R} = \{\mathcal{R}_1, \ldots, \mathcal{R}_N\}$, as well as a common DN $\mathcal{D}$, where $\mathcal{D}$ may be a base station (BS) or an ad hoc cluster head. Both $\mathcal{S}$ and $\mathcal{D}$ are granted access to the licensed spectrum, whereas the N RNs are not licensees. To simplify our investigations, we made the following assumptions. All the channels involved are assumed to undergo quasi-static Rayleigh fading; hence, the complex-valued fading envelope remains constant during a transmission

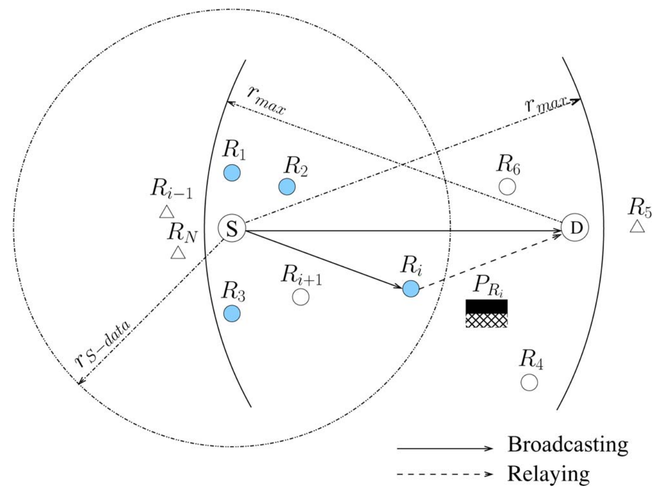


Fig. 1. Cooperative topology consists of one SN $\mathcal{S}$, one DN $\mathcal{D}$, and a total of N RNs $\mathcal{R} = \{\mathcal{R}_1, \ldots, \mathcal{R}_N\}$.

burst,[1] whereas it is faded independently between the consecutive transmission bursts. Within a given transmission burst, the duplex bidirectional channels between a pair of actively communicating nodes are assumed to be identical, whereas the channels of any of the remaining links are independent. We assume perfect channel estimation for all nodes concerning their own channels,[2] but no knowledge of the remaining links is assumed. Additionally, the nodes' own position information is perfectly known at each node. We consider the effects of free-space path loss that is modeled by $\rho = \lambda^2/16\pi^2 d^\eta$, where λ represents the wavelength, d is the transmitter-to-receiver distance and η denotes the path-loss exponent, which is 2. All nodes are assumed to be limited by the same maximum transmit power $P_{\max}$.

B. Distributed WW Cooperative Framework

1) SN's Behavior: Rather than relying on monetary remuneration, $\mathcal{S}$ in our DWWCF intends to lease part of its spectrum to the RNs in exchange for cooperatively supporting the source's transmission. Based on the RN's assistance, $\mathcal{S}$ is capable of successfully conveying its data at a *reduced* transmit power of $P_{\mathcal{S}-\mathrm{data}}$ and an *increased* transmit rate of $\alpha C^{\max}_{\mathcal{S},\mathcal{D}} (\alpha \geq 1)$, which is the SN's target transmit rate. In greater detail, α is the ratio of the desired and affordable throughput termed as the SN's "factor of greediness," whereas $C^{\max}_{\mathcal{S},\mathcal{D}}$ is the maximum achievable rate of the source-to-destination (SD) link, which can be formulated as $C^{\max}_{\mathcal{S},\mathcal{D}} = \log_2(1 + (\rho_{\mathcal{S},\mathcal{D}} |h_{\mathcal{S},\mathcal{D}}|^2 P_{\max}/P_N))$, where P_N is the power of the additive white Gaussian noise, whereas $|h_{\mathcal{S},\mathcal{D}}|$ denotes the magnitude of the flat Rayleigh channel between $\mathcal{S}$ and $\mathcal{D}$. Furthermore, $\rho_{\mathcal{S},\mathcal{D}}$ is the free-space path-loss gain between $\mathcal{S}$ and $\mathcal{D}$. If $\mathcal{S}$ cannot acquire any cooperative transmission assistance, it directly transmits its data to $\mathcal{D}$ at a higher transmit power

[1] We define a transmission burst as a single transmission attempt, excluding any subsequent retransmission attempts.

[2] The effect of realistic imperfect channel estimation is evaluated in Section IV-F.

$P_{\mathcal{S}}^{nc}$ and lower transmit rate $R_{\mathcal{S}}^{nc}$. Hence, $\mathcal{S}$ has two Objective Functions (OF) in our DWWCF, which may be formulated as

$$\mathrm{OF}_{\mathcal{S}1} = \max\left\{\xi_{\mathcal{S}} \cdot R_{\mathcal{S}}^{req} + (1-\xi_{\mathcal{S}}) \cdot R_{\mathcal{S}}^{nc}\right\} \quad (1)$$
$$\mathrm{OF}_{\mathcal{S}2} = \min\left\{\xi_{\mathcal{S}} \cdot P_{\mathcal{S}-\mathrm{data}} + (1-\xi_{\mathcal{S}}) \cdot P_{\mathcal{S}}^{nc}\right\} \quad (2)$$

subject to $R_{\mathcal{S}}^{req} = \alpha C_{\mathcal{S},\mathcal{D}}^{\max} > R_{\mathcal{S}}^{nc}$ and $\alpha \geq 1$, as well as $P_{\mathcal{S}-\mathrm{data}} < P_{\mathcal{S}}^{nc}$, where $\xi_{\mathcal{S}}$ denotes the cooperative probability of SN.

2) RN's Behavior: According to our DWWCF, the RN has an incentive to forward data for $\mathcal{S}$ for the sake of accessing the SN's spectrum to convey its own traffic. The selfish RN $\mathcal{R}_i$ reserves a certain fraction of $\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$ $(0 < \beta < 1)$ of the Relay-to-Destination (RD) channel's capacity for conveying its own traffic, where β is the RN's "factor of greediness" and $C_{\mathcal{R}_i,\mathcal{D}}^{\max}$ is given by: $C_{\mathcal{R}_i,\mathcal{D}}^{\max} = \log_2(1 + (\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\max}/P_N))$, while $|h_{\mathcal{R}_i,\mathcal{D}}|$ denotes the magnitude of the flat Rayleigh channel between $\mathcal{R}_i$ as well as $\mathcal{D}$, and $\rho_{\mathcal{R}_i,\mathcal{D}}$ is the free-space path-loss gain between $\mathcal{R}_i$ and $\mathcal{D}$. Based on our DWWCF, each RN $\mathcal{R}_i$ carries out autonomous decisions concerning its own cooperative strategy by optimizing its own OF, which may be formulated as

$$\mathrm{OF}_{\mathrm{RN}1} = \max\left\{\xi_{\mathcal{R}_i} \cdot \beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}\right\} \quad (3)$$

subject to $0 < \beta < 1$, where $\xi_{\mathcal{R}_i}$ denotes the probability that RN $\mathcal{R}_i$ is granted the transmission opportunity.

When the RNs provide cooperative transmission assistance, extra energy is dissipated when relaying data for $\mathcal{S}$. Hence, another OF is designed in our DWWCF to select the best RN, which may be formulated as

$$\mathrm{OF}_{\mathrm{RN}2} = \min \sum_{i=1}^{N} \left\{\xi_{\mathcal{R}_i} \cdot P_{\mathcal{R}_i}\right\} \quad (4)$$

subject to $\sum_{i=1}^{N} \xi_{\mathcal{R}_i} \leq 1$, and $P_{\mathcal{R}_i} \leq P_{\max}$, where $P_{\mathcal{R}_i}$ is the RN's transmit power required for successfully forwarding the SN's data and for simultaneously conveying its own data. Based on the above OFs, it is quite a challenge to mathematically solve these optimization problems in our DWWCF. Hence, we designed a WW cooperative MAC protocol to implement our DWWCF.

III. Win-Win Cooperative Medium Access Control Protocol Description

Based on the request-to-send/clear-to-send (RTS/CTS) signaling of the legacy IEEE 802.11 protocol, a WW cooperative MAC protocol is developed to implement our DWWCF, which is formulated in Section II-B. The proposed signaling procedure is detailed in Fig. 2, which includes three phases, as detailed in the following.

A. Phase I: Initialization

Before $\mathcal{S}$ transmits any data frame, it issues an RTS message to $\mathcal{D}$ at the maximum transmission power $P_{\max}$ to reserve the shared channel, as shown in Fig. 2. When $\mathcal{D}$ correctly receives the RTS message, it replies with a CTS message, employing the same transmission power $P_{\max}$. The instantaneous transmission ranges of the sources are shown in Fig. 1. To elaborate a little further, we include the transmitter's position information into the RTS and CTS signaling frame; thus, any RNs in the set $\mathcal{R}$, which can overhear both the RTS and CTS messages, will be aware of the imminently forthcoming transmission and of the position information on $\mathcal{S}$ and $\mathcal{D}$. Based on the knowledge of their own position and on the position of the SN and the DN, these RNs are capable of calculating the distances from both the SN and the DN to themselves. These RNs, which are denoted by filled or hollow circles in Fig. 1, form a potential cooperative RN set $\mathcal{R}_c \subset \mathcal{R}$.

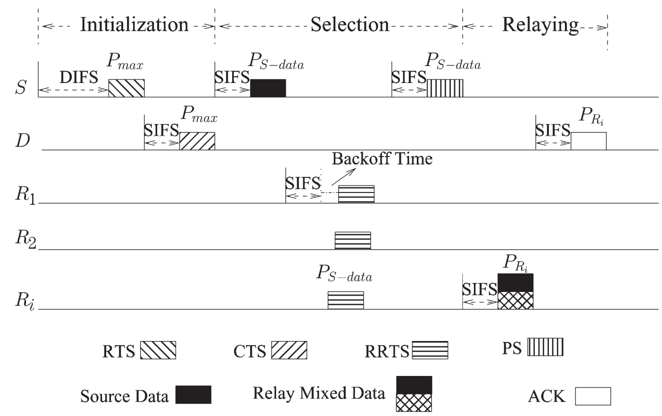


Fig. 2. Overall signaling procedure. RTS: Request-to-send. CTS: Clear-to-send. RRTS: Relay-request-to-send. PS: Please-send. ACK: Acknowledgement. DIFS: Distributed interframe space. SIFS: Short interframe space.

B. Phase II: Relay Selection

Following the initialization phase, the RN selection procedure is constituted by a data transmission and two beacon message exchanges, as detailed in the following.

1) Step I—Invitation for Cooperation: If $\mathcal{S}$ does not receive a CTS message from $\mathcal{D}$, it would retransmit the RTS message as specified in the legacy IEEE 802.11 protocol [22]. In contrast, if $\mathcal{S}$ receives a CTS message from $\mathcal{D}$, it broadcasts its data frame after a short interframe space (SIFS) interval at *reduced* power of $P_{\mathcal{S}-\mathrm{data}}$ and *its target transmit rate* of $\alpha C_{\mathcal{S},\mathcal{D}}^{\max}$ $(\alpha \geq 1)$, as shown in Fig. 2. As a result, both $\mathcal{D}$ and the RNs in the set $\mathcal{R}_c$ will hear this broadcast. When α is higher than unity, the SN's data cannot be successfully transmitted to $\mathcal{D}$ in its entirety. However, $\mathcal{D}$ will store this data frame and exploits the classic Chase combining scheme [23] to combine it with the duplicated data frame independently transmitted by the potential candidate relays, for the sake of achieving rate improvements. Therefore, the SN's aggregated rate achieved by using Chase combining may be expressed as [24]

$$\alpha C_{\mathcal{S},\mathcal{D}}^{\max} = \log_2\left(1 + \gamma_{\mathcal{S},\mathcal{D}}^{(1)} + \gamma_{\mathcal{R}_i}^{\mathcal{S}}\right) \quad (5)$$

subject to $\alpha \geq 1$, where $\gamma_{\mathcal{S},\mathcal{D}}^{(1)}$ denotes the receiver's signal-to-interference-plus-noise ratio (SINR) related to the direct transmission during the broadcast phase. Furthermore, $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ represents the receive SINR of the SN's data frame, which is transmitted during the relaying phase to be introduced. Based

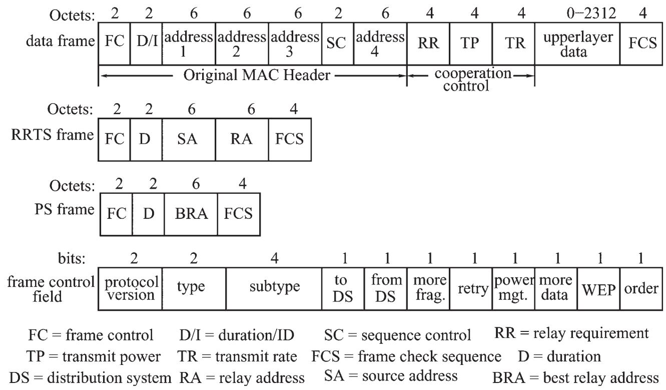


Fig. 3. Formats of the data frames, the RRTS message, and the PS message.

on the estimated channel state information (CSI) of the SD link, $\mathcal{S}$ first calculates the receive SINR of $\gamma^{(1)}_{\mathcal{S},\mathcal{D}}$ achieved by the direct transmission during the broadcast phase. Then, based on $\gamma^{(1)}_{\mathcal{S},\mathcal{D}}$ and (5), $\mathcal{S}$ calculates the receive SINR of $\gamma^{\mathcal{S}}_{\mathcal{R}_i}$, which must be guaranteed by the best RN and includes the value of $\gamma^{\mathcal{S}}_{\mathcal{R}_i}$ into the relay requirement (RR) field of its data frame for implicitly informing the RNs of the SN's transmit requirement $\alpha C^{\max}_{\mathcal{S},\mathcal{D}}$. The RNs in the vicinity, which correctly receive the SN's data frame, are capable of inferring the value of $\gamma^{\mathcal{S}}_{\mathcal{R}_i}$ by reading the RR field of the appropriately designed cooperative MAC data frame, as shown in Fig. 3.[3]

2) Step II—Contend for Cooperation: For clarity, we break the discussion of this step into several subtopics, namely, the cooperative decision, the backoff algorithm, and contention message derivation.

Cooperation decision: If a particular RN $\mathcal{R}_i \in \mathcal{R}_c$ erroneously receives the data frame from $\mathcal{S}$, $\mathcal{R}_i$ would drop this data frame and would keep on sensing the channel, as shown in Table I. On the other hand, if cooperative RN $\mathcal{R}_i \in \mathcal{R}_c$ correctly receives a data frame from $\mathcal{S}$, it calculates the transmit power $P^{\mathcal{S}}_{\mathcal{R}_i}$ necessitated to satisfy the SN-rate requirement and the transmit power $P^{\mathcal{R}}_{\mathcal{R}_i}$ required to guarantee a throughput of $\beta C^{\max}_{\mathcal{R}_i,\mathcal{D}}$. If the sum of transmit power $P_{\mathcal{R}_i} = P^{\mathcal{S}}_{\mathcal{R}_i} + P^{\mathcal{R}}_{\mathcal{R}_i}$ is higher than $P_{\max}$, $\mathcal{R}_i$ has to give up contending for the cooperative opportunity and drop this SN's data frame, as shown in Table I. On the other hand, if $P_{\mathcal{R}_i}$ does not exceed $P_{\max}$, $\mathcal{R}_i$ would send a relay-request-to-send (RRTS) message to $\mathcal{S}$ after waiting for a SIFS interval and its backoff time, which is calculated based on the proposed backoff algorithm for the sake of contending for a transmission opportunity, as shown in Table I. The RRTS message in Fig. 2 informs $\mathcal{S}$ about the RN's correct reception and its intention to cooperate. Hence, the specific RNs, which decide to contend for the transmission opportunity form a smaller contending set of $\mathcal{R}_{cc} \in \mathcal{R}_c$. These RNs are represented by the filled circles in Fig. 1. It is noted that the value of $P_{\mathcal{R}_i}$ is not included in the RRTS message in Fig. 3 since the proposed backoff algorithm can identify the different values of $P_{\mathcal{R}_i}$ promised by the contending RNs.

[3]Apart from the cooperative control fields of the data frame, as shown in Fig. 3, the remaining fields are the same as those of the data frame specified in the IEEE 802.11 standards [22].

TABLE I
PROCEDURE OF THE RN SUBMISSION COOPERATIVE DECISION

```
if erroneously receive data frame Data_i from S
    drop data frame Data_i
else
    read the RN requirement γ^S_{R_i}
    calculate the values of P^S_{R_i}, P^R_{R_i} and P_{R_i}
    if P_{R_i} ≤ P_max
        calculate its backoff time T_{R_i,bo}
        backoff for T_{R_i,bo} interval
        if T_{R_i,bo} timeout
            send RRTS to S
             wait for PS message
         else
             keep backoff
      else
          drop data frame Data_i
```

Backoff algorithm: To minimize the total transmit power of the RNs, which is formulated by (4), we design a backoff algorithm to select the best RN. As shown in Fig. 2, before issuing the RRTS message, the RN $\mathcal{R}_i \in \mathcal{R}_{cc}$ has to wait for a SIFS interval and for subsequent backoff duration of $T_{\mathcal{R}_i,\mathrm{bo}}$, which is defined as $T_{\mathcal{R}_i,\mathrm{bo}} = \varphi_{\mathcal{R}_i} T_w$, where $T_w = \mathrm{CWmin} \cdot \mathrm{SlotTime}$ is the contention window (CW) length,[4] with CWmin being the minimum CW duration specified in the IEEE802.11 standards [22]. The coefficient $\varphi_{\mathcal{R}_i}$ is defined as $\varphi_{\mathcal{R}_i} = P_{\mathcal{R}_i^{\min}}/P_{\max}$. Hence, the specific candidate RN, which promises the lowest transmit power, may first transmit its RRTS message as a benefit of its shortest backoff time. In each RN selection phase, $\mathcal{S}$ has to wait for a fixed period of $(T_w + \mathrm{SlotTime})$ to collect the responses of the potential candidate RNs. If $\mathcal{S}$ correctly receives the RRTS message before its fixed waiting duration times out, it selects the transmitter of that specific RRTS, which was the first one to be correctly received as the best RN, without considering the RRTS messages arriving later and without comparing the specific transmit power promised by the individual candidate RNs. Hence, the best RN is selected in a distributed manner both without a centralized controller and without any information exchange between the candidate RNs. Since the value of $P_{\mathcal{R}_i^{\min}}$ promised by the candidate RN $\mathcal{R}_i$ is always lower than $P_{\max}$, the backoff time allocated to $\mathcal{R}_i$ will not exceed the SN's fixed waiting duration of $(T_w + \mathrm{SlotTime})$. Hence, all the candidate RNs may issue their RRTS messages before $\mathcal{S}$ stops waiting for the responses.

Contention message derivation: According to our backoff algorithm, the specific RN promising the lowest power may be granted the transmission opportunity to minimize the total transmit power of RNs. Hence, the greedy RN has to minimize its transmit power by *only* satisfying its rate requirement of $\beta C^{\max}_{\mathcal{R}_i,\mathcal{D}}$ to wait for a shorter backoff time,

[4]In the IEEE 802.11 standard, a SlotTime consists of the time required to physically sense the medium and to declare the channel as "clear," as well as the MAC processing delay, the propagation delay, and the "receiver/transmitter turn-around time," which is the time required for the physical layer to change from receiving to transmitting at the start of the first bit [22].

which is calculated based on the proposed backoff algorithm. Therefore, we have

$$P_{\mathcal{R}_i^{\min}}\left(P_{\mathcal{R}_i}^{\mathcal{S}}, P_{\mathcal{R}_i^{\min}}^{\mathcal{R}} \middle| \alpha, \beta\right) = P_{\mathcal{R}_i}^{\mathcal{S}} + P_{\mathcal{R}_i^{\min}}^{\mathcal{R}} \qquad (6)$$

subject to the condition of $C_{\mathcal{R}_i}^{\mathcal{R}} = \beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$ and $\alpha > 1$, as well as $0 < \beta < 1$.

Let us now consider how to find $P_{\mathcal{R}_i}^{\mathcal{S}}$ and $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$ of (6). In our design, the RN employs SPC for jointly encoding both the SN's and its own data. $\mathcal{D}$ then extracts the SN's data from the relayed composite signal with the aid of SIC. Finally, the extracted relayed component and the direct component are combined. Assuming that $\mathcal{D}$ treats the RN's data frame as interference, the receive SINR $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ of the SN's data frame relayed by the RN is given by $\gamma_{\mathcal{R}_i}^{\mathcal{S}} = (\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\mathcal{R}_i}^{\mathcal{S}})/(P_N + \rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\mathcal{R}_i}^{\mathcal{R}})$. After successfully retrieving the SN's data frame, $\mathcal{D}$ becomes capable of decoding the RN's data frame by removing the SN's interference with the aid of a SIC scheme [25]. Hence, the achievable rate of the RN may be formulated as $C_{\mathcal{R}_i}^{\mathcal{R}} = \log_2(1 + (\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\mathcal{R}_i}^{\mathcal{R}}/P_N))$. According to the relaying strategy employed, the RN calculates the minimum power required for the rate $C_{\mathcal{R}_i}^{\mathcal{R}}$ to reach $\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$. Thus, the value of $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$ is explicitly given as $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}} = ((2^{\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}} - 1)P_N)/(\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2)$, which is subjected to $0 < \beta < 1$. Likewise, based on the metrics of $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ and $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$, the RN is capable of calculating the transmit power $P_{\mathcal{R}_i}^{\mathcal{S}}$ required for successfully delivering the SN's data at a throughput of $\alpha C_{\mathcal{S},\mathcal{D}}^{\max}$, which is given by $P_{\mathcal{R}_i}^{\mathcal{S}} = \gamma_{\mathcal{R}_i}^{\mathcal{S}}((P_N/\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2) + P_{\mathcal{R}_i^{\min}}^{\mathcal{R}})$, where $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ has been given in Step I. Based on the given derivation, $\mathcal{R}_i$ calculates the value of $P_{\mathcal{R}_i}^{\min}$ as the sum of $P_{\mathcal{R}_i}^{\mathcal{S}}$ and $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$.

3) Step III—Accept for Cooperation: After waiting for the fixed duration of $(T_w + \mathrm{SlotTime})$ specified by the proposed backoff algorithm and for a subsequent SIFS interval, $\mathcal{S}$ replies to the best RN $\mathcal{R}_{\hat{i}}$ associated with the first RRTS message that was correctly received by sending a please-send (PS) message if $\mathcal{S}$ correctly received the RRTS message during its fixed waiting period of $(T_w + \mathrm{SlotTime})$, as shown in Fig. 2 and Table II. The format of the PS frame is characterized in Fig. 3. Since the SN sends its data frame and PS message at the same transmission power of $P_{\mathcal{S}-\mathrm{data}}$, all the RNs, which have correctly received the data frame from the SN will overhear the PS message. This guarantees that only the best RN forwards its data frame to $\mathcal{D}$ during the data-forwarding phase.

C. Phase III: Cooperative Transmission

In this phase, the best RN $\mathcal{R}_{\hat{i}}$ forwards the superimposed SR data to $\mathcal{D}$ if $\mathcal{S}$ successfully selects the best RN. Otherwise, $\mathcal{S}$ retransmits its data frame to $\mathcal{D}$, as shown in Fig. 2 and Table II.

1) Data Forwarding and Relay Retransmission: If RN $\mathcal{R}_i \in \mathcal{R}_{cc}$ finds that the receiver of the received PS message is not itself, it would drop the SN's data and would keep on sensing the medium. On the other hand, if the RN $\mathcal{R}_i \in \mathcal{R}_{cc}$ received a PS message that is destined for itself, it will encode both the SN's and its data with the aid of SPC and will forward the superimposed SR data frame to $\mathcal{D}$ at its precalculated transmission power of $P_{\mathcal{R}_i^{\min}}$ after an SIFS period, acting as the best RN, as shown in Fig. 2. Finally, at the DN, the classic automatic repeat request procedure will be initiated, when receiving the forwarded data and successfully decoding and combing it with the most recent direct transmission during Step I of Phase II.

2) Source Retransmission: If none of the RNs competes for a transmission opportunity or multiple RRTS messages collided at the SN, $\mathcal{S}$ directly sends its data to $\mathcal{D}$ as a replica without relaying. This transmission takes place either at the specific transmit power of $P_{\mathcal{S}-\mathrm{data}}^{(2)}$, which is capable of guaranteeing the expected rate of $\alpha C_{\mathcal{S},\mathcal{D}}^{\max}$, or failing that, it resorts to using the maximum affordable transmit power of $P_{\max}$, as shown in Table II. If $\mathcal{D}$ receives this data frame, it replies with an acknowledgment (ACK) message to $\mathcal{S}$ after successfully decoding and combining the frame with the most recent erroneous data frame broadcast by $\mathcal{S}$. If $\mathcal{S}$ does not receive any response from $\mathcal{D}$ before the timer set for waiting for an ACK message is expired, it will broadcast its data again at power of $P_{\mathcal{S}-\mathrm{data}}$ to seek cooperation, and the RN selection procedure described earlier is repeated, as shown in Table II.

TABLE II
PROCEDURE OF SN

$\mathcal{S}$ broadcasts data $Data_i$ at power P_{S-data}
$\mathcal{S}$ waits for the fixed duration of $(T_w + SlotTime)$
if $\mathcal{S}$ receives RRTS message
  sends PS message to the best RN
else
  compute power $P_{S-data}^{(2)}$
  if $P_{S-data}^{(2)} \leq P_{max}$
    send data to $\mathcal{D}$ at power $P_{S-data}^{(2)}$
  else
    send data to $\mathcal{D}$ at power P_{max}
  wait for ACK message
  if ACK timeout
    $\mathcal{S}$ broadcast data $Data_i$ again
  else
    $\mathcal{S}$ send RTS message for transmitting a new data

IV. SIMULATION RESULTS

To evaluate the achievable performance of the proposed scheme, we present our simulation results based on Omnet++. Based on the network model introduced in Section II-A, we consider two scenarios to investigate both the achievable rate and EC improvement, and to analyze the RN's behavior. In the first scenario, all the RNs are randomly distributed across the entire network area, whereas $\mathcal{S}$ and $\mathcal{D}$ have fixed positions. The network size considered ranges from $u = 5$ nodes to $u = 30$ nodes for the sake of evaluating the influence of the size of the networks on the achievable rate and EC. In the other scenario, we consider a small network supporting $u = 5$ nodes, i.e., $\mathcal{S}$, $\mathcal{D}$, and three RNs, where all the nodes have fixed positions. One of the three RNs is located at the position of $d = 1/4$ along the SD link. Another RN is in the middle of the SD link at $d = 1/2$, whereas the third RN is at the point $d = 3/4$ of the SD link. In the given two scenarios, the values of $P_{\max}$ and $P_{\mathcal{S}-\mathrm{data}}$ are 2 and 1 mW, respectively. The size of CWmin is 7, whereas SlotTime is set to 20 μs. Furthermore, the length of SIFS is

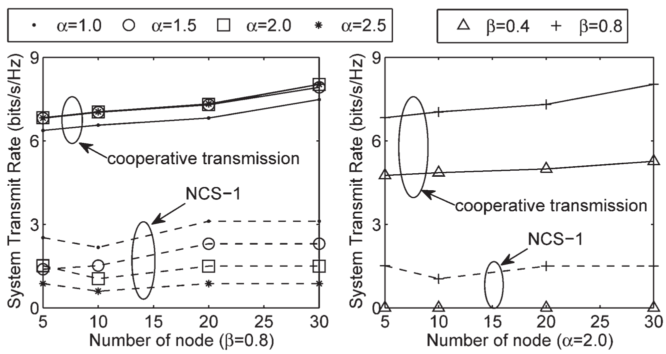


Fig. 4. System's total achievable rate improvement.

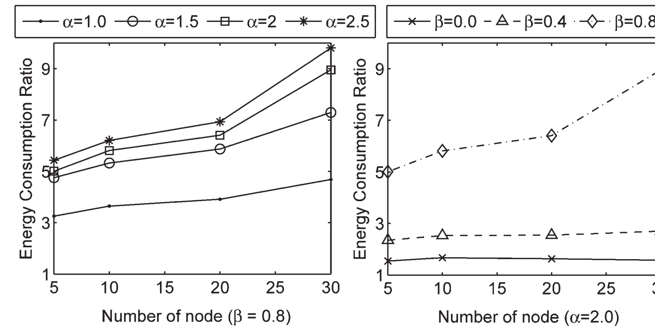


Fig. 5. Energy consumption ratio of $E_{\rm noncoop}/E_{\rm coop}$.

10 μs. The length of the data frame generated at the application layer is 1024 B. The length of the RRTS and PS messages is 20 B and 14 B, respectively, whereas that of the RTS and CTS is 24 and 18 B. The greedy factor α ranges from 1 to 3, whereas the value of β ranges from 0 to 0.8. Both α and β are predetermined for each simulation.

Two noncooperative systems are introduced as the benchmarkers of our comparisons. We compare the system's achievable total transmit rate (TTR) constituted by the sum of the SN's and RN's transmit rate to that of the noncooperative system 1 (NCS-1), which consumes the same total transmission energy as our CSLS (WW-CSLS). Additionally, we compare the total transmission EC to that of the noncooperative system 2 (NCS-2), which is capable of achieving the same TTR as our WW-CSLS. Since the SN's data is transmitted twice by itself and additionally by the best RN, if the cooperative transmission is successful, two direct transmission phases are exploited in both NCS-1 and NCS-2. When aiming for investigating the effect of our relay selection scheme, we compare the achievable performance of our WW-CSLS to that of a random CSLS (Ran-CSLS), where the best RN is randomly selected without considering the transmit power required for providing a successful cooperative transmission. To evaluate their performance, we adopt the idealized simplifying assumption that the control messages are received without errors in both NCS-1 and NCS-2, as well as in WW-CSLS. In Sections IV-E and F, we investigated a more practical network.

A. *Effect of Cooperative Transmission*

Let us now investigate the effects of cooperative transmission on the TTR and EC by comparing the performance achieved in the first scenario and NCS-1 and in NCS-2.

1) Achievable Transmit Rate: Fig. 4 compares the system's TTR, namely, the sum of both the SN's rate and the RN's rate achieved by the WW-CSLS relying on our WW cooperative MAC protocol to that of NCS-1. It is observed in Fig. 4 that, as expected, the system's achievable TTR relying on our WW-CSLS is higher than 6 bit/s/Hz, even for $\alpha = 1$ and $\beta = 0.8$, which is more than twice as high as that achieved by NCS-1, which consumes the same total transmission energy, given the same values of α and β. Additionally, for $\beta = 0.4$ and $\alpha = 2$, the system's TTR achieved by our WW-CSLS is in excess of 4 bit/s/Hz, while in fact, no successful transmissions may be supported in NCS-1 for the same values of α and β due to the system's low EC. Hence, the proposed WW cooperative MAC protocol is capable of providing a considerable TTR improvement, despite consuming low energy. As shown in Fig. 4, the system's TTR achieved by our WW-CSLS is increased, when $\mathcal{S}$ becomes greedier due to the SN's increased transmit rate requirement. Additionally, when β is increased, the best RN will be rewarded by a considerably higher rate for its own traffic, provided that the cooperation is successful. Hence, the system's TTR is increased, when the RN becomes greedier, as shown in Fig. 4. Moreover, the achievable TTR of our WW-CSLS is gradually increased, when the network becomes larger. The above investigations imply that the proposed WW cooperative MAC protocol is capable of providing significant TTR improvements.

2) Energy Consumption: Fig. 5 shows the achievable EC ratio (ECR) of $E_{\rm noncoop}/E_{\rm coop}$, where $E_{\rm coop}$ denotes the system's total transmission EC[5] for our cooperative MAC protocol and $E_{\rm noncoop}$ represents that of NCS-2, which is capable of achieving the same system's TTR as our WW-CSLS. As shown in Fig. 5, compared with NCS-2, two third of the system's total energy may be saved by exploiting the proposed WW cooperative MAC protocol, given $\beta = 0.8$. The EC $E_{\rm coop}$ of our WW-CSLS is reduced when $\mathcal{S}$ becomes greedier, which can be also characterized by the TTR of NCS-1 in Fig. 4. By contrast, the EC $E_{\rm noncoop}$ of NCS-2 is slightly increased, when $\mathcal{S}$ becomes greedier due to the slightly increased system rate of WW-CSLS. Hence, the ECR is increased, when $\mathcal{S}$ becomes greedier, as shown in Fig. 5. As β is increased, the system's ECR is increased from 1.5 to 5 for $\alpha = 2$ and $u = 5$, as shown in Fig. 5. When the RNs become greedier, fewer RNs can afford the increased power required for successfully forwarding the SPC data. However, the transmit rate achieved by the best RN is considerably increased. Hence, an increased total energy is required by NCS-2 for the sake of achieving the same system rate as our WW-CSLS. Therefore, the system's ECR of $E_{\rm noncoop}/E_{\rm coop}$ is increased when the RN becomes greedier. Based on the given discussions, the proposed WW cooperative MAC protocol is capable of achieving a considerable system rate improvement while offering a satisfactory energy efficiency.

[5]It is reasonable to focus on the transmission EC and ignore the circuit processing EC in a large network where the transmission EC is dominant in the total EC [26].

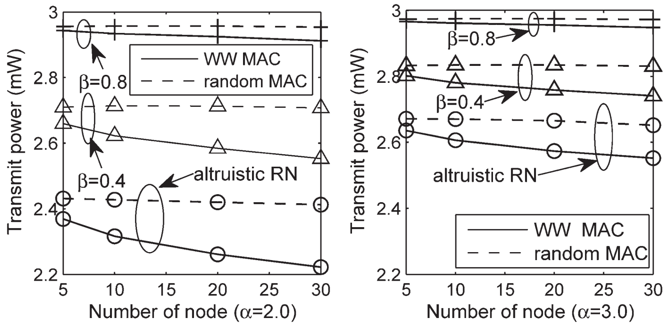


Fig. 6. System data transmit power consumed by our WW-CSLS and Ran-CSLS.

B. Effect of Relay Selection

Let us now investigate the effect of the proposed RN selection scheme by evaluating the achievable performance of our WW-CSLS and Ran-CSLS, where the best RN is randomly selected.

1) Transmit Power: According to the proposed WW cooperative MAC protocol, the specific RN that promises the lowest transmit power $P_{\mathcal{R}_i}$ required for successfully conveying superposition-coded data is selected as the best RN. However, the best RN is randomly selected in Ran-CSLS without considering any system parameters, such as the transmit power $P_{\mathcal{R}_i}$. Hence, the RN's transmit power $P_{\mathcal{R}_i}$ is the crucial parameter for investigating the effect of the proposed RN selection scheme. Fig. 6 quantifies the system's total data transmit power (TDTP) for our WW-CSLS and that is consumed in Ran-CSLS. The system's TDTP is defined as the sum of the SN's transmit power required for conveying its data plus the RN's transmit power necessitated for delivering the superposition-coded data.

Based on the proposed backoff algorithm, the system's TDTP consumed in the WW-CSLS is lower than that of the Ran-CSLS, as shown in Fig. 6. When the SN or RN becomes greedier, less RNs can afford the increased transmit power required to provide successful cooperative transmission assistance. This phenomenon increases the probability that the same RN is selected as the best RN in both WW-CSLS and Ran-CSLS. Hence, the difference between the TDTP of our WW-CSLS and that of Ran-CSLS is reduced when either α or β is increased, as shown in Fig. 6. Moreover, the TDTP of both WW-CSLS and of the Ran-CSLS is reduced when the network hosts more RNs due to the increased probability of having RNs, which promise to reduce the transmit power in comparison with a smaller network. However, the probability of the event that a low-quality RN, namely, one which requires a higher transmit power than other RNs, is selected as the best RN in the Ran-CSLS is increased, when the network becomes larger. Hence, compared with Ran-CSLS, an increased TDTP is saved by our WW-CSLS when the network's size is increased.

2) Achievable Transmit Rate: Fig. 7 compares the system's TTR, namely, the sum of both the SN's rate and the RN's rate achieved by our WW-CSLS to that achieved by Ran-CSLS. As shown in Fig. 7, the system's achievable TTR relying on WW-CSLS is 8 bit/s/Hz for $\beta = 0.8$ and $u = 30$, whereas a lower TTR of 6.5 bit/s/Hz is achieved by Ran-CSLS, given β and the network size. Compared with Ran-CSLS, the system's TTR can be improved by our WW-CSLS, even for lower β values and for smaller networks, e.g., for $\beta = 0.4$ and $u = 5$, as shown in Fig. 7. Based on WW-CSLS, the specific RN that promises lower transmit power of $P_{\mathcal{R}_i}$ may achieve a higher transmit rate of $\beta C^{\max}_{\mathcal{R}_i,\mathcal{D}}$ due to having an improved RD link. Hence, compared with Ran-CSLS, a higher TTR is achieved by our WW-CSLS relying on selecting the specific RN, which promises the lowest transmit power $P_{\mathcal{R}_i}$.

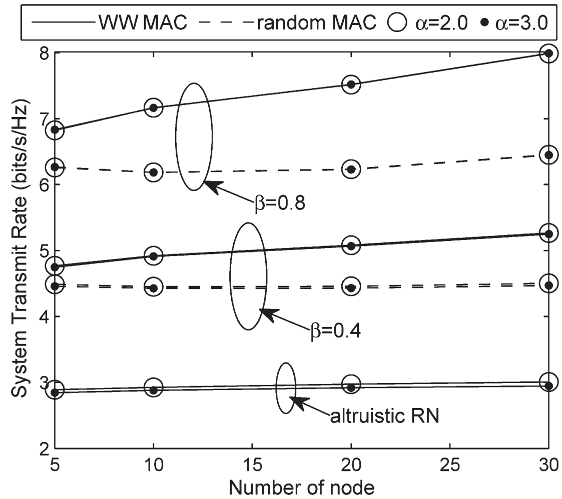


Fig. 7. System's total achievable rate improvement of our WW-CSLS and Ran-CSLS.

Observe in Fig. 7 that the proposed WW cooperative MAC protocol is capable of providing a higher TTR improvement than Ran-CSLS, when β is increased. When an RN becomes greedier, its target transmit rate is increased. This phenomenon increases the difference between the RN's transmit rate achieved by WW-CSLS and that achieved by Ran-CSLS when the RN that suffers from a low-quality RD link is selected by Ran-CSLS. Hence, the difference between the TTR of WW-CSLS and that of Ran-CSLS is increased when the RN becomes greedier. Considering the CSLS, where the RN altruistically forwards data for $\mathcal{S}$, the system's TTR is equal to the SN's rate. Hence, the system's TTR remains the same, regardless of which particular candidate RN is selected as the best RN when the RNs are altruistic, as shown in Fig. 7.

As shown in Fig. 7, the system's TTR achieved by our WW-CSLS is increased, when the network becomes larger. However, the effect of the network's size on the TTR achieved by Ran-CSLS is not as obvious as that on our WW-CSLS. When the network hosts more RNs, the number of candidate RNs may be increased. This phenomenon increases the probability that a low-quality RN having a lower transmit rate is selected as the best RN in Ran-CSLS. However, these low-quality RNs cannot win the cooperative transmission opportunity in our WW-CSLS if the specific RN promising a reduced transmit power also contends for the transmission opportunity. Hence, a higher TTR improvement is provided by the proposed WW cooperative MAC protocol, as the network becomes larger, as shown in Fig. 7. The given investigations imply that the proposed WW cooperative MAC protocol is capable of saving a substantial amount of transmit power while simultaneously

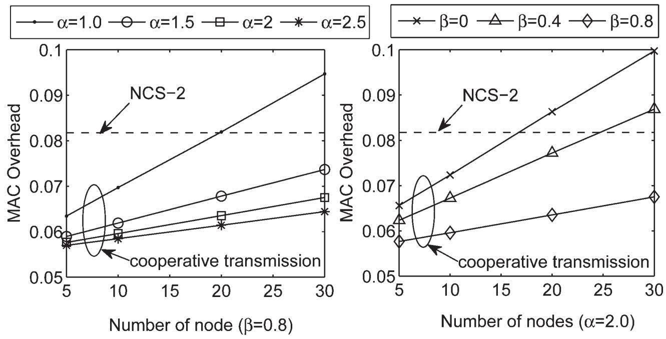


Fig. 8. MAC overhead for $\beta = 0.8$ or $\alpha = 2$.

providing significant TTR improvements compared with Ran-CSLS.

C. MAC Overhead

Fig. 8 compares the MAC overhead of the proposed cooperative MAC protocol with that of NCS-2, which is based on the RTS/CTS signaling regime of the IEEE 802.11 standards [22]. The MAC overhead is defined as the ratio of $(\mathcal{N}_{\mathrm{mac}-c} + \mathcal{N}_{\mathrm{mac}-h} + \mathcal{N}_{\mathrm{mac}-t})/\mathcal{N}_{\mathrm{mac}-d}$, where $\mathcal{N}_{\mathrm{mac}-c}$ denotes the number of bits of all MAC control messages, and $\mathcal{N}_{\mathrm{mac}-h}$ and $\mathcal{N}_{\mathrm{mac}-t}$ represent the number of header and tailing bits of the MAC data frame, respectively. Furthermore, $\mathcal{N}_{\mathrm{mac}-d}$ denotes the number of bits in the payload data packet, including the headers introduced by the higher layers. Observe in Fig. 8 that the MAC overhead of the proposed WW cooperative MAC protocol decreases, when either α or β increases, because the number of candidate RNs is reduced, whereas the SN or the RN becomes greedier. Compared with the traditional RTS/CTS scheme specified in the IEEE 802.11 standards [22], the RRTS message and the PS message are introduced into our WW-CSLS to assist with RN selection if cooperation can be exploited. However, compared with NCS-2, the RN's data can be also transmitted with the aid of cooperation in WW-CSLS. Since the length of the RN's data frames is higher than that of the extra control messages, the MAC overhead introduced by our WW protocol is lower than that of the NCS-2 when the network size is smaller than $u = 20$. Although the overhead of our WW-CSLS becomes higher than that of NCS-2 when the network hosts more than $u = 20$ nodes, the MAC overhead introduced by our WW protocol always remains lower than 0.1 for $\beta = 0.8$ or $\alpha = 2$.

D. Relay Behavior

To investigate the behavior of the relays, we analyze both the transmission probability and the achievable rate improvement of each RN for the configuration of $\alpha = 2$ in the network hosting $u = 5$ nodes, as shown in Fig. 9(a) and (b). Upon increasing β, the transmission probability of the RNs at "$d =$ 1/4" and "$d = 1/2$" decreases, whereas that of the RN at "$d = 3/4$" increases, as shown in Fig. 9(a). The RN at "$d =$ 3/4" always benefits from the highest transmission probability, whereas the RN at "$d = 1/4$" has the lowest probability of cooperative opportunities. As a benefit of its highest transmission probability, the RN at "$d = 3/4$" maintains the highest

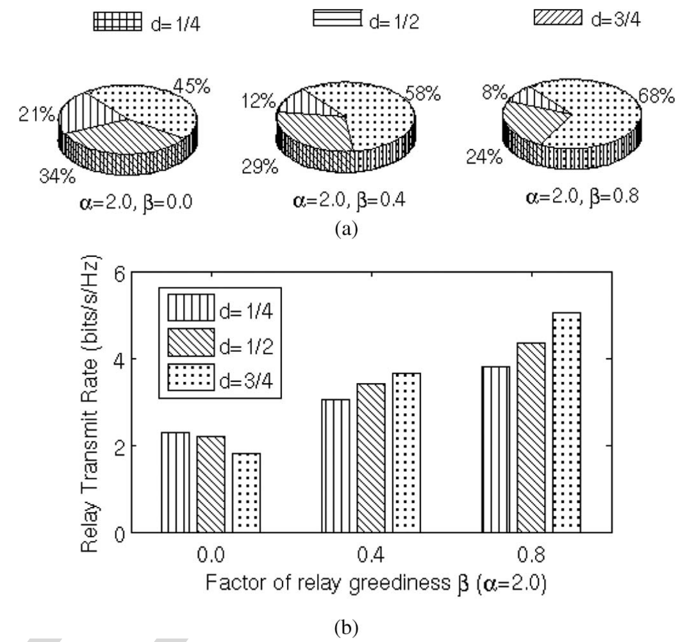


Fig. 9. RN transmission probability and the achievable rate improvement in a network hosting $u = 5$ nodes, namely, $\mathcal{S}$, $\mathcal{D}$, and three RNs. (a) Relay transmission probability. (b) Relay achievable rate.

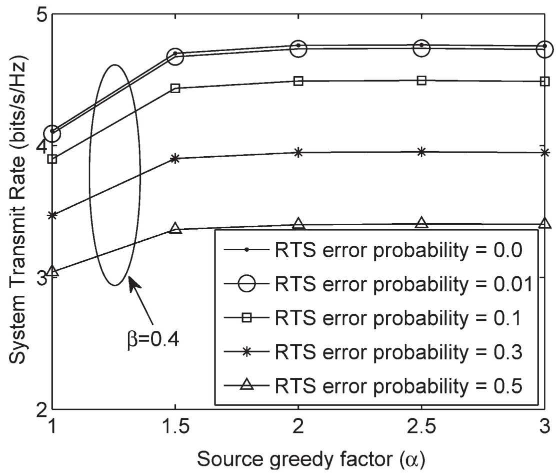
achievable rate improvement, which is above 5 bits/s/Hz for $\beta = 0.8$ and $\alpha = 2$. The achievable RN-rate improvement at "$d = 1/4$" is lower than that of the RN at "$d = 1/2$," as shown in Fig. 9(b). However, when the three RNs altruistically dedicate themselves solely to forwarding data frames for $\mathcal{S}$ $(\beta = 0)$, the achievable RN-rate improvement at "$d = 1/4$" is higher than that of the other relays. Naturally, if the RNs become selfish, their improved transmission probability leads to an increased total throughput.

E. Effect of Erroneous RTS Message

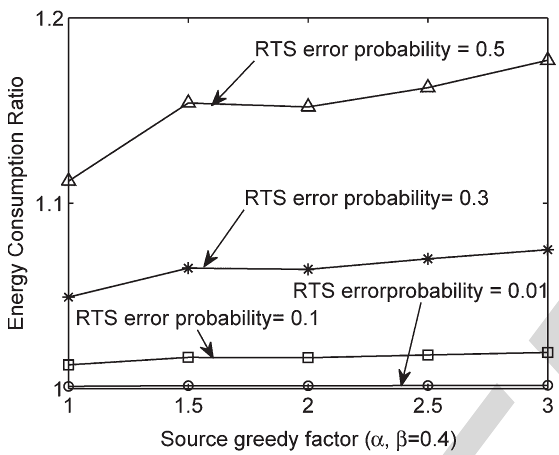
The contention caused by hidden SNs or RNs may corrupt the transmission of data and control messages. Apart from the effects of corrupted RTS messages, the erroneous transmission of both other control messages and of data have been considered in our WW cooperative MAC protocol. Hence, the effect of corrupted RTS messages on the system's transmit rate and on the ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$ that are achieved by our WW-CSLS are evaluated, as shown in Fig. 10(a) and (b). The variable $E_{\mathrm{rts-error}}$ denotes the system's total EC for WW-CSLS, where the RTS message may be corrupted. Furthermore, $E_{\mathrm{error-free}}$ is the system's total EC for WW-CSLS, where error-free control messages are assumed. It is observed in Fig. 10(a) and (b) that, when the RTS error probability is increased, the system's TTR is decreased, and an increased total system energy is dissipated by our WW-CSLS because having more potentially erroneous RTS transmissions reduces the probability of successful transmission, and the extra RTS message retransmissions consume extra energy.

F. Effect of Imperfect Channel Estimation

To evaluate the overall system performance of our WW cooperative protocol in a more practical scenario, we now

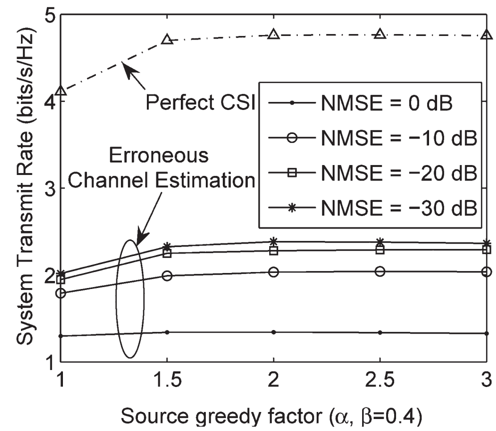


(a)

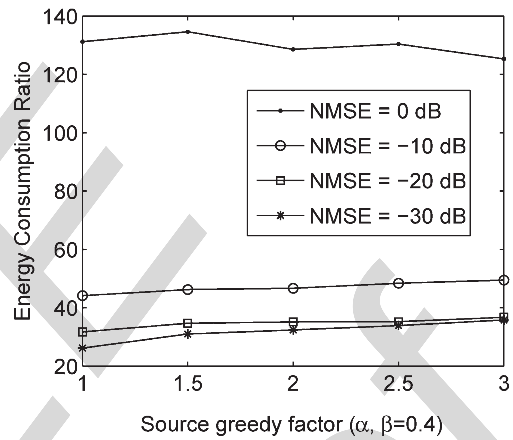


(b)

Fig. 10. System's total achievable transmit rate and system's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$ versus the SN's greedy factor parameterized with different RTS message error probabilities. (a) System's TTR. (b) System's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$.



(a)



(b)

Fig. 11. System's total achievable transmit rate and system's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$ versus the SN's greedy factor parameterized with different channel estimation NMSEs when $\beta = 0.4$. (a) System's TTR. (b) System's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$.

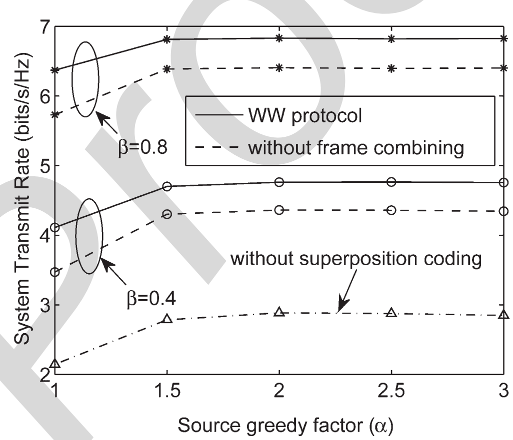


Fig. 12. System's total achievable transmit rate versus the SN's greedy factor both with and without SPC and SIC and frame combining.

introduce Gaussion-distributed CSI estimation errors into our WW-CSLS, instead of relying on the idealized simplifying assumption of perfect CSI. The normalized mean square error (NMSE) of the Gaussian channel estimation errors was defined as $10\log(E\{\|h-\hat{h}\|^2\}/E\{\|h\|^2\})$ in decibels [27]. Compared with the performance achieved by assuming perfect CSI, the realistic imperfect channel estimation reduces the system's attainable transmit rate and dramatically increases the system's ECR of $E_{\mathrm{error}}/E_{\mathrm{perfect}}$, as shown in Fig. 11(a) and (b), respectively. Variable E_{error} denotes the system's energy consumed by the CSLS relying on realistic imperfect channel estimation, whereas E_{perfect} denotes when perfect CSI is assumed. Based on the given discussions, it is necessary to develop a more robust cooperative MAC protocol to reduce the impact of realistic imperfect channel estimation.

G. *Effect of Either Superposition Coding or Frame Combining*

To evaluate the achievable TTR improvement jointly attained by SPC and SIC, we compare the system's TTR achieved by our WW-CSLS with that of the cooperative system operating without exploiting these techniques, as shown in Fig. 12. Since there are two data frames jointly conveyed by the RN to $\mathcal{D}$ in our WW-CSLS, the best RN, which does not exploit SPC, is assumed to forward only the SN's data instead of the SPC data. As shown in Fig. 12, the system's TTR may be increased from 2.9 to 6.9 bits/s/Hz for $\alpha = 2$ and $\beta = 0.8$ by jointly exploiting the SPC and SIC. Hence, these techniques are capable of significantly improving the system's transmit rate. To improve the SN's transmit rate, $\mathcal{D}$ invokes frame combining for amalgamating both the direct and relayed SN data after successfully separating the SN's and RN's data. Fig. 12 shows the system's TTR improvement achieved by exploiting frame combining.

V. Conclusion

In this paper, we have formulated a distributed WW cooperative framework for striking a tradeoff between the achievable system rate improvement and EC and for granting transmission opportunities for the unlicensed RNs. Furthermore, a WW cooperative MAC layer protocol was proposed for implementing our DWWCF. When compared with the corresponding noncooperative system, the proposed scheme is capable of providing a considerable transmit rate and transmission EC improvements. This was achieved with the aid of joint SPC at the RN for both the SN's and RN's data and by combining the SD and RD signals at the DN. Our future work will consider similar interference-limited scenarios relying on a more robust cooperative MAC design.

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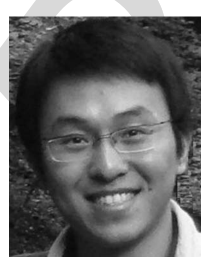

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AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = Please provide keywords.
AQ2 = Please provide expanded form of OF.
AQ3 = What is the first initial of author Asaduzzaman?

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Cooperative Medium Access Control Based on Spectrum Leasing

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***Abstract*—Based on cooperative spectrum leasing, a distributed "win–win" (WW) cooperative framework is designed to encourage the licensed source node (SN) to lease some part of its spectral resources to the unlicensed relay node (RN) for the sake of simultaneously improving the SN's achievable rate and for reducing the energy consumption (EC). The potential candidate RNs carry out autonomous decisions concerning whether to contend for a cooperative transmission opportunity, which could dissipate some of their battery power, while conveying their traffic in light of their individual service requirements. Furthermore, a WW cooperative medium-access-control (MAC) protocol is designed to implement the proposed distributed WW cooperative framework. Simulation results demonstrate that our WW cooperative MAC protocol is capable of providing both substantial rate improvements and considerable energy savings for the cooperative spectrum leasing system.**

***Index Terms*—Author, please supply index terms/keywords for your paper. To download the IEEE Taxonomy go to http://www.ieee.org/documents/taxonomy_v101.pdf.** AQ1

I. Introduction

COOPERATIVE communications techniques have recently attracted substantial research attention [1] as a benefit of their significant throughput improvements, energy savings, and coverage enhancements. However, these benefits may be eroded by the conventional higher layer protocols, which were designed for classic noncooperative systems. Hence, it is important to design appropriate medium-access-control (MAC) protocols to support cooperative physical layer techniques.

In contrast with the legacy wireless MAC protocols, cooperative MAC protocols aim to cooperatively schedule the medium access of all nodes while allowing the relay nodes (RNs) to buffer and forward the others' data frames using the broadcast nature of the wireless network, instead of ignoring these data frames. There are numerous contributions in the literature on designing cooperative MAC protocols, most of which aim to maximize the throughput [2]–[6], including the widely recognized CoopMAC of [7]. However, a potential impediment of the CoopMAC is that its energy efficiency was traded off against the throughput benefits claimed. Therefore, [8]–[12] aimed to minimize the energy consumption (EC) by developing energy-efficient cooperative MAC protocols. To jointly consider these conflicting design objectives, Luo *et al.* [13] and Zhou *et al.* [14] designed meritorious algorithms to improve the achievable throughput and to simultaneously enhance the energy efficiency achieved.

However, the aforementioned cooperative MAC protocols, such as CoopMAC, were developed based on the common assumption that the relays agree to altruistically forward the data of the source node (SN). This unconditional altruistic behavior is unrealistic to expect from mobile stations. In fact, a greedy RN behavior is likely to be the norm in spectrum leasing [15], where the licensed SN intends to lease some part of its spectral resources to the unlicensed RN in exchange for appropriate "remuneration." In this spectrum leasing system, the unlicensed RNs also have an incentive to support the SN to achieve its quality-of-service (QoS) target in exchange for a transmission opportunity. This cooperation allows both the SN and the RN to satisfy its individual requirement. Based on this cooperative spectrum leasing system, some early theoretical studies have been conducted in [16]–[21]. Bearing in mind the greedy behavior of the mobile RNs, meritorious game-theoretic frameworks were proposed in [16]–[19] to maximize the SN's *transmit rate* while simultaneously satisfying the requirements of the RNs. Based on game theory, Hafeez and Elmirghani [20] and Jayaweera *et al.* [21] aimed to minimize the *EC* of cooperative spectrum leasing systems by designing beneficial game-aided strategies. However, the joint optimization of the transmit rate and of the EC has not been considered in these existing works. Furthermore, the design of an appropriate cooperative MAC protocol for practically implementing the theoretical framework was not discussed in [16]–[21].

Against this backdrop, the contributions of this paper are as follows.

1) We first formulate a distributed "win–win" (WW) cooperative framework (DWWCF) to encourage the SN to lease part of its spectral resources to the unlicensed RN for the sake of improving the SN's *transmit rate* and for simultaneously reducing the SN's *EC* while ensuring that the unlicensed RNs are capable of securing a transmission opportunity for *their own traffic* and for satisfying their QoS. Furthermore, the proposed DWWCF selects the

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best RN for the sake of *minimizing the system's transmit power*.

2) Second, a WW cooperative MAC protocol is developed to *practically implement* our DWWCF in a cooperative spectrum leasing system (CSLS) by designing the required *signaling procedures* to implement the negotiation between the SN and the greedy RN. Similarly, the *frame structure* of both the data and control messages is also conceived to convey all the required information. Hence, the proposed WW cooperative MAC protocol is a throughput- and energy-oriented protocol rather than a single-objective cooperative MAC protocol, such as CoopMAC [7], which is a throughput-oriented protocol. Furthermore, the proposed WW cooperative MAC protocol is designed for more realistic scenario having rewarded RNs rather than altruistic RNs, which was considered in most existing cooperative MAC protocol, such as the CoopMAC [7]. To simplify the signaling procedures at the MAC layer, the proposed WW cooperative MAC protocol relies on a *distributed RN selection scheme*, rather than either centralized or table-based RN selection scheme, which was exploited by many cooperative MAC protocols, such as CoopMAC [7], allowing the SN to select the best RN relying on the global information in the SN's CoopTable.

3) Additionally, in contrast with the RN's time/frequency slot reservation strategy of [17], superposition coding (SPC) is invoked at the RN for jointly encoding both the SN's and RN's data based on a cooperative spectrum leasing system. Fortunately, the resultant interference can be eliminated at the destination node (DN) using successive interference cancelation (SIC) to separate the SN's and RN's data while beneficially amalgamating both the direct and relayed components using frame combining.

The remainder of this paper is organized as follows. The network's architecture and our DWWCF are introduced in Section II. Section III describes the proposed WW cooperative MAC protocol, whereas in Section IV, the attainable performance of our scheme is quantified. Finally, we conclude in Section V.

II. System Model and Distributed Win-Win Cooperative Framework

A. System Model

Before embarking on outlining our DWWCF, we introduce our network topology and outline our assumptions.

As shown in Fig. 1, we consider a cooperative network having a single SN $\mathcal{S}$ and a total of N RNs in the set $\mathcal{R} = \{\mathcal{R}_1, \ldots, \mathcal{R}_N\}$, as well as a common DN $\mathcal{D}$, where $\mathcal{D}$ may be a base station (BS) or an ad hoc cluster head. Both $\mathcal{S}$ and $\mathcal{D}$ are granted access to the licensed spectrum, whereas the N RNs are not licensees. To simplify our investigations, we made the following assumptions. All the channels involved are assumed to undergo quasi-static Rayleigh fading; hence, the complex-valued fading envelope remains constant during a transmission burst,[1] whereas it is faded independently between the consecutive transmission bursts. Within a given transmission burst, the duplex bidirectional channels between a pair of actively communicating nodes are assumed to be identical, whereas the channels of any of the remaining links are independent. We assume perfect channel estimation for all nodes concerning their own channels,[2] but no knowledge of the remaining links is assumed. Additionally, the nodes' own position information is perfectly known at each node. We consider the effects of free-space path loss that is modeled by $\rho = \lambda^2/16\pi^2 d^\eta$, where λ represents the wavelength, d is the transmitter-to-receiver distance and η denotes the path-loss exponent, which is 2. All nodes are assumed to be limited by the same maximum transmit power $P_{\max}$.

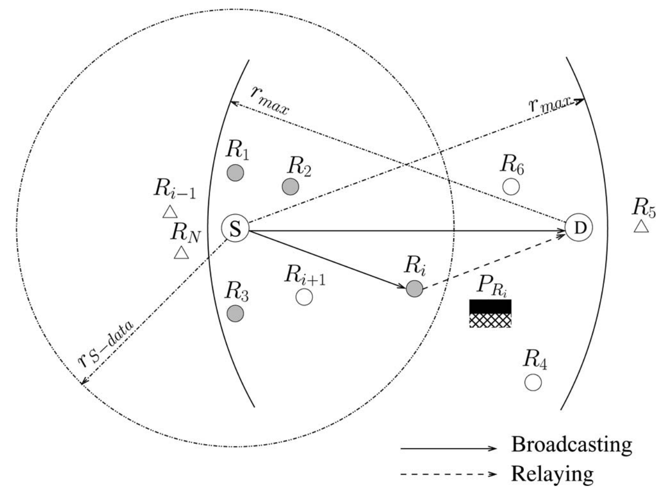

Fig. 1. Cooperative topology consists of one SN $\mathcal{S}$, one DN $\mathcal{D}$, and a total of N RNs $\mathcal{R} = \{\mathcal{R}_1, \ldots, \mathcal{R}_N\}$.

B. Distributed WW Cooperative Framework

1) SN's Behavior: Rather than relying on monetary remuneration, $\mathcal{S}$ in our DWWCF intends to lease part of its spectrum to the RNs in exchange for cooperatively supporting the source's transmission. Based on the RN's assistance, $\mathcal{S}$ is capable of successfully conveying its data at a *reduced* transmit power of $P_{\mathcal{S}-\mathrm{data}}$ and an *increased* transmit rate of $\alpha C^{\max}_{\mathcal{S},\mathcal{D}} (\alpha \geq 1)$, which is the SN's target transmit rate. In greater detail, α is the ratio of the desired and affordable throughput termed as the SN's "factor of greediness," whereas $C^{\max}_{\mathcal{S},\mathcal{D}}$ is the maximum achievable rate of the source-to-destination (SD) link, which can be formulated as $C^{\max}_{\mathcal{S},\mathcal{D}} = \log_2(1 + (\rho_{\mathcal{S},\mathcal{D}} |h_{\mathcal{S},\mathcal{D}}|^2 P_{\max}/P_N))$, where P_N is the power of the additive white Gaussian noise, whereas $|h_{\mathcal{S},\mathcal{D}}|$ denotes the magnitude of the flat Rayleigh channel between $\mathcal{S}$ and $\mathcal{D}$. Furthermore, $\rho_{\mathcal{S},\mathcal{D}}$ is the free-space path-loss gain between $\mathcal{S}$ and $\mathcal{D}$. If $\mathcal{S}$ cannot acquire any cooperative transmission assistance, it directly transmits its data to $\mathcal{D}$ at a higher transmit power

[1] We define a transmission burst as a single transmission attempt, excluding any subsequent retransmission attempts.

[2] The effect of realistic imperfect channel estimation is evaluated in Section IV-F.

$P_{\mathcal{S}}^{nc}$ and lower transmit rate $R_{\mathcal{S}}^{nc}$. Hence, $\mathcal{S}$ has two Objective Functions (OF) in our DWWCF, which may be formulated as

$$\mathrm{OF}_{\mathcal{S}1} = \max\left\{\xi_{\mathcal{S}} \cdot R_{\mathcal{S}}^{req} + (1-\xi_{\mathcal{S}}) \cdot R_{\mathcal{S}}^{nc}\right\} \quad (1)$$

$$\mathrm{OF}_{\mathcal{S}2} = \min\left\{\xi_{\mathcal{S}} \cdot P_{\mathcal{S}-\mathrm{data}} + (1-\xi_{\mathcal{S}}) \cdot P_{\mathcal{S}}^{nc}\right\} \quad (2)$$

subject to $R_{\mathcal{S}}^{req} = \alpha C_{\mathcal{S},\mathcal{D}}^{\max} > R_{\mathcal{S}}^{nc}$ and $\alpha \geq 1$, as well as $P_{\mathcal{S}-\mathrm{data}} < P_{\mathcal{S}}^{nc}$, where $\xi_{\mathcal{S}}$ denotes the cooperative probability of SN.

2) RN's Behavior: According to our DWWCF, the RN has an incentive to forward data for $\mathcal{S}$ for the sake of accessing the SN's spectrum to convey its own traffic. The selfish RN $\mathcal{R}_i$ reserves a certain fraction of $\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$ $(0 < \beta < 1)$ of the Relay-to-Destination (RD) channel's capacity for conveying its own traffic, where β is the RN's "factor of greediness" and $C_{\mathcal{R}_i,\mathcal{D}}^{\max}$ is given by: $C_{\mathcal{R}_i,\mathcal{D}}^{\max} = \log_2(1 + (\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\max}/P_N))$, while $|h_{\mathcal{R}_i,\mathcal{D}}|$ denotes the magnitude of the flat Rayleigh channel between $\mathcal{R}_i$ as well as $\mathcal{D}$, and $\rho_{\mathcal{R}_i,\mathcal{D}}$ is the free-space path-loss gain between $\mathcal{R}_i$ and $\mathcal{D}$. Based on our DWWCF, each RN $\mathcal{R}_i$ carries out autonomous decisions concerning its own cooperative strategy by optimizing its own OF, which may be formulated as

$$\mathrm{OF}_{\mathrm{RN}1} = \max\left\{\xi_{\mathcal{R}_i} \cdot \beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}\right\} \quad (3)$$

subject to $0 < \beta < 1$, where $\xi_{\mathcal{R}_i}$ denotes the probability that RN $\mathcal{R}_i$ is granted the transmission opportunity.

When the RNs provide cooperative transmission assistance, extra energy is dissipated when relaying data for $\mathcal{S}$. Hence, another OF is designed in our DWWCF to select the best RN, which may be formulated as

$$\mathrm{OF}_{\mathrm{RN}2} = \min \sum_{i=1}^{N} \left\{\xi_{\mathcal{R}_i} \cdot P_{\mathcal{R}_i}\right\} \quad (4)$$

subject to $\sum_{i=1}^{N} \xi_{\mathcal{R}_i} \leq 1$, and $P_{\mathcal{R}_i} \leq P_{\max}$, where $P_{\mathcal{R}_i}$ is the RN's transmit power required for successfully forwarding the SN's data and for simultaneously conveying its own data. Based on the above OFs, it is quite a challenge to mathematically solve these optimization problems in our DWWCF. Hence, we designed a WW cooperative MAC protocol to implement our DWWCF.

III. Win-Win Cooperative Medium Access Control Protocol Description

Based on the request-to-send/clear-to-send (RTS/CTS) signaling of the legacy IEEE 802.11 protocol, a WW cooperative MAC protocol is developed to implement our DWWCF, which is formulated in Section II-B. The proposed signaling procedure is detailed in Fig. 2, which includes three phases, as detailed in the following.

A. Phase I: Initialization

Before $\mathcal{S}$ transmits any data frame, it issues an RTS message to $\mathcal{D}$ at the maximum transmission power $P_{\max}$ to reserve the shared channel, as shown in Fig. 2. When $\mathcal{D}$ correctly receives the RTS message, it replies with a CTS message, employing the same transmission power $P_{\max}$. The instantaneous transmission ranges of the sources are shown in Fig. 1. To elaborate a little further, we include the transmitter's position information into the RTS and CTS signaling frame; thus, any RNs in the set $\mathcal{R}$, which can overhear both the RTS and CTS messages, will be aware of the imminently forthcoming transmission and of the position information on $\mathcal{S}$ and $\mathcal{D}$. Based on the knowledge of their own position and on the position of the SN and the DN, these RNs are capable of calculating the distances from both the SN and the DN to themselves. These RNs, which are denoted by filled or hollow circles in Fig. 1, form a potential cooperative RN set $\mathcal{R}_c \subset \mathcal{R}$.

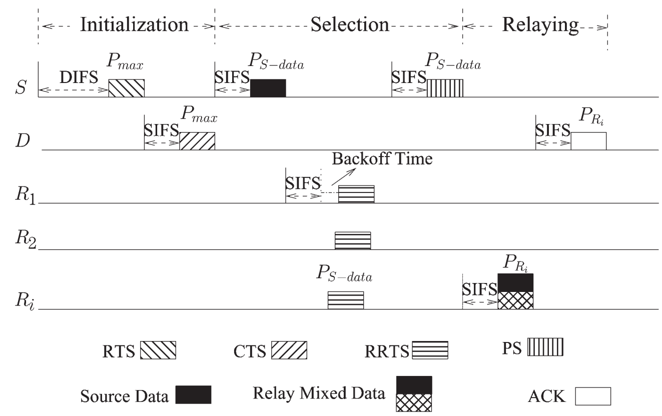

Fig. 2. Overall signaling procedure. RTS: Request-to-send. CTS: Clear-to-send. RRTS: Relay-request-to-send. PS: Please-send. ACK: Acknowledgement. DIFS: Distributed interframe space. SIFS: Short interframe space.

B. Phase II: Relay Selection

Following the initialization phase, the RN selection procedure is constituted by a data transmission and two beacon message exchanges, as detailed in the following.

1) Step I—Invitation for Cooperation: If $\mathcal{S}$ does not receive a CTS message from $\mathcal{D}$, it would retransmit the RTS message as specified in the legacy IEEE 802.11 protocol [22]. In contrast, if $\mathcal{S}$ receives a CTS message from $\mathcal{D}$, it broadcasts its data frame after a short interframe space (SIFS) interval at *reduced* power of $P_{\mathcal{S}-\mathrm{data}}$ and *its target transmit rate* of $\alpha C_{\mathcal{S},\mathcal{D}}^{\max}$ $(\alpha \geq 1)$, as shown in Fig. 2. As a result, both $\mathcal{D}$ and the RNs in the set $\mathcal{R}_c$ will hear this broadcast. When α is higher than unity, the SN's data cannot be successfully transmitted to $\mathcal{D}$ in its entirety. However, $\mathcal{D}$ will store this data frame and exploits the classic Chase combining scheme [23] to combine it with the duplicated data frame independently transmitted by the potential candidate relays, for the sake of achieving rate improvements. Therefore, the SN's aggregated rate achieved by using Chase combining may be expressed as [24]

$$\alpha C_{\mathcal{S},\mathcal{D}}^{\max} = \log_2\left(1 + \gamma_{\mathcal{S},\mathcal{D}}^{(1)} + \gamma_{\mathcal{R}_i}^{\mathcal{S}}\right) \quad (5)$$

subject to $\alpha \geq 1$, where $\gamma_{\mathcal{S},\mathcal{D}}^{(1)}$ denotes the receiver's signal-to-interference-plus-noise ratio (SINR) related to the direct transmission during the broadcast phase. Furthermore, $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ represents the receive SINR of the SN's data frame, which is transmitted during the relaying phase to be introduced. Based

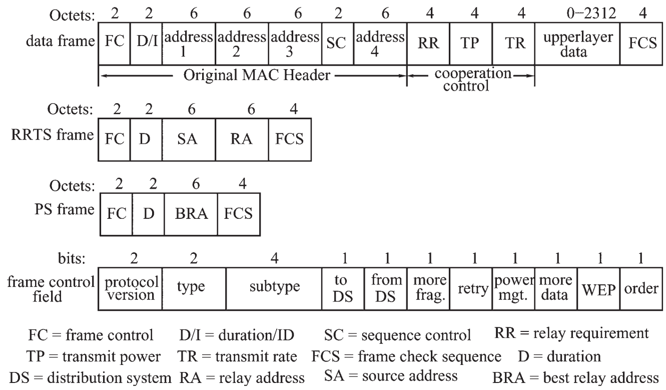

Fig. 3. Formats of the data frames, the RRTS message, and the PS message.

on the estimated channel state information (CSI) of the SD link, $\mathcal{S}$ first calculates the receive SINR of $\gamma_{\mathcal{S},\mathcal{D}}^{(1)}$ achieved by the direct transmission during the broadcast phase. Then, based on $\gamma_{\mathcal{S},\mathcal{D}}^{(1)}$ and (5), $\mathcal{S}$ calculates the receive SINR of $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$, which must be guaranteed by the best RN and includes the value of $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ into the relay requirement (RR) field of its data frame for implicitly informing the RNs of the SN's transmit requirement $\alpha C_{\mathcal{S},\mathcal{D}}^{\max}$. The RNs in the vicinity, which correctly receive the SN's data frame, are capable of inferring the value of $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ by reading the RR field of the appropriately designed cooperative MAC data frame, as shown in Fig. 3.[3]

2) Step II—Contend for Cooperation: For clarity, we break the discussion of this step into several subtopics, namely, the cooperative decision, the backoff algorithm, and contention message derivation.

Cooperation decision: If a particular RN $\mathcal{R}_i \in \mathcal{R}_c$ erroneously receives the data frame from $\mathcal{S}$, $\mathcal{R}_i$ would drop this data frame and would keep on sensing the channel, as shown in Table I. On the other hand, if cooperative RN $\mathcal{R}_i \in \mathcal{R}_c$ correctly receives a data frame from $\mathcal{S}$, it calculates the transmit power $P_{\mathcal{R}_i}^{\mathcal{S}}$ necessitated to satisfy the SN-rate requirement and the transmit power $P_{\mathcal{R}_i}^{\mathcal{R}}$ required to guarantee a throughput of $\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$. If the sum of transmit power $P_{\mathcal{R}_i} = P_{\mathcal{R}_i}^{\mathcal{S}} + P_{\mathcal{R}_i}^{\mathcal{R}}$ is higher than $P_{\max}$, $\mathcal{R}_i$ has to give up contending for the cooperative opportunity and drop this SN's data frame, as shown in Table I. On the other hand, if $P_{\mathcal{R}_i}$ does not exceed $P_{\max}$, $\mathcal{R}_i$ would send a relay-request-to-send (RRTS) message to $\mathcal{S}$ after waiting for a SIFS interval and its backoff time, which is calculated based on the proposed backoff algorithm for the sake of contending for a transmission opportunity, as shown in Table I. The RRTS message in Fig. 2 informs $\mathcal{S}$ about the RN's correct reception and its intention to cooperate. Hence, the specific RNs, which decide to contend for the transmission opportunity form a smaller contending set of $\mathcal{R}_{cc} \in \mathcal{R}_c$. These RNs are represented by the filled circles in Fig. 1. It is noted that the value of $P_{\mathcal{R}_i}$ is not included in the RRTS message in Fig. 3 since the proposed backoff algorithm can identify the different values of $P_{\mathcal{R}_i}$ promised by the contending RNs.

Backoff algorithm: To minimize the total transmit power of the RNs, which is formulated by (4), we design a backoff algorithm to select the best RN. As shown in Fig. 2, before issuing the RRTS message, the RN $\mathcal{R}_i \in \mathcal{R}_{cc}$ has to wait for a SIFS interval and for subsequent backoff duration of $T_{\mathcal{R}_i,\mathrm{bo}}$, which is defined as $T_{\mathcal{R}_i,\mathrm{bo}} = \varphi_{\mathcal{R}_i} T_w$, where $T_w = \mathrm{CWmin} \cdot \mathrm{SlotTime}$ is the contention window (CW) length,[4] with CWmin being the minimum CW duration specified in the IEEE802.11 standards [22]. The coefficient $\varphi_{\mathcal{R}_i}$ is defined as $\varphi_{\mathcal{R}_i} = P_{\mathcal{R}_i^{\min}}/P_{\max}$. Hence, the specific candidate RN, which promises the lowest transmit power, may first transmit its RRTS message as a benefit of its shortest backoff time. In each RN selection phase, $\mathcal{S}$ has to wait for a fixed period of $(T_w + \mathrm{SlotTime})$ to collect the responses of the potential candidate RNs. If $\mathcal{S}$ correctly receives the RRTS message before its fixed waiting duration times out, it selects the transmitter of that specific RRTS, which was the first one to be correctly received as the best RN, without considering the RRTS messages arriving later and without comparing the specific transmit power promised by the individual candidate RNs. Hence, the best RN is selected in a distributed manner both without a centralized controller and without any information exchange between the candidate RNs. Since the value of $P_{\mathcal{R}_i^{\min}}$ promised by the candidate RN $\mathcal{R}_i$ is always lower than $P_{\max}$, the backoff time allocated to $\mathcal{R}_i$ will not exceed the SN's fixed waiting duration of $(T_w + \mathrm{SlotTime})$. Hence, all the candidate RNs may issue their RRTS messages before $\mathcal{S}$ stops waiting for the responses.

Contention message derivation: According to our backoff algorithm, the specific RN promising the lowest power may be granted the transmission opportunity to minimize the total transmit power of RNs. Hence, the greedy RN has to minimize its transmit power by *only* satisfying its rate requirement of $\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$ to wait for a shorter backoff time,

TABLE I
PROCEDURE OF THE RN SUBMISSION COOPERATIVE DECISION

if erroneously receive data frame $Data_i$ from $\mathcal{S}$
drop data frame $Data_i$
else
read the RN requirement $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$
calculate the values of $P_{\mathcal{R}_i}^{\mathcal{S}}$, $P_{\mathcal{R}_i}^{\mathcal{R}}$ and $P_{\mathcal{R}_i}$
if $P_{\mathcal{R}_i} \le P_{max}$
calculate its backoff time $T_{\mathcal{R}_i,bo}$
backoff for $T_{\mathcal{R}_i,bo}$ interval
if $T_{\mathcal{R}_i,bo}$ timeout
send RRTS to $\mathcal{S}$
wait for PS message
else
keep backoff
else
drop data frame $Data_i$

[3]Apart from the cooperative control fields of the data frame, as shown in Fig. 3, the remaining fields are the same as those of the data frame specified in the IEEE 802.11 standards [22].

[4]In the IEEE 802.11 standard, a SlotTime consists of the time required to physically sense the medium and to declare the channel as "clear," as well as the MAC processing delay, the propagation delay, and the "receiver/transmitter turn-around time," which is the time required for the physical layer to change from receiving to transmitting at the start of the first bit [22].

which is calculated based on the proposed backoff algorithm. Therefore, we have

$$P_{\mathcal{R}_i^{\min}}\left(P_{\mathcal{R}_i}^{\mathcal{S}}, P_{\mathcal{R}_i^{\min}}^{\mathcal{R}} \middle| \alpha, \beta\right) = P_{\mathcal{R}_i}^{\mathcal{S}} + P_{\mathcal{R}_i^{\min}}^{\mathcal{R}} \tag{6}$$

subject to the condition of $C_{\mathcal{R}_i}^{\mathcal{R}} = \beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$ and $\alpha > 1$, as well as $0 < \beta < 1$.

Let us now consider how to find $P_{\mathcal{R}_i}^{\mathcal{S}}$ and $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$ of (6). In our design, the RN employs SPC for jointly encoding both the SN's and its own data. $\mathcal{D}$ then extracts the SN's data from the relayed composite signal with the aid of SIC. Finally, the extracted relayed component and the direct component are combined. Assuming that $\mathcal{D}$ treats the RN's data frame as interference, the receive SINR $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ of the SN's data frame relayed by the RN is given by $\gamma_{\mathcal{R}_i}^{\mathcal{S}} = (\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\mathcal{R}_i}^{\mathcal{S}})/(P_N + \rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\mathcal{R}_i}^{\mathcal{R}})$. After successfully retrieving the SN's data frame, $\mathcal{D}$ becomes capable of decoding the RN's data frame by removing the SN's interference with the aid of a SIC scheme [25]. Hence, the achievable rate of the RN may be formulated as $C_{\mathcal{R}_i}^{\mathcal{R}} = \log_2(1 + (\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2 P_{\mathcal{R}_i}^{\mathcal{R}}/P_N))$. According to the relaying strategy employed, the RN calculates the minimum power required for the rate $C_{\mathcal{R}_i}^{\mathcal{R}}$ to reach $\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}$. Thus, the value of $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$ is explicitly given as $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}} = ((2^{\beta C_{\mathcal{R}_i,\mathcal{D}}^{\max}} - 1)P_N)/(\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2)$, which is subjected to $0 < \beta < 1$. Likewise, based on the metrics of $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ and $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$, the RN is capable of calculating the transmit power $P_{\mathcal{R}_i}^{\mathcal{S}}$ required for successfully delivering the SN's data at a throughput of $\alpha C_{\mathcal{S},\mathcal{D}}^{\max}$, which is given by $P_{\mathcal{R}_i}^{\mathcal{S}} = \gamma_{\mathcal{R}_i}^{\mathcal{S}}((P_N/\rho_{\mathcal{R}_i,\mathcal{D}}|h_{\mathcal{R}_i,\mathcal{D}}|^2) + P_{\mathcal{R}_i^{\min}}^{\mathcal{R}})$, where $\gamma_{\mathcal{R}_i}^{\mathcal{S}}$ has been given in Step I. Based on the given derivation, $\mathcal{R}_i$ calculates the value of $P_{\mathcal{R}_i}^{\min}$ as the sum of $P_{\mathcal{R}_i}^{\mathcal{S}}$ and $P_{\mathcal{R}_i^{\min}}^{\mathcal{R}}$.

3) Step III—Accept for Cooperation: After waiting for the fixed duration of $(T_w + \text{SlotTime})$ specified by the proposed backoff algorithm and for a subsequent SIFS interval, $\mathcal{S}$ replies to the best RN $\mathcal{R}_{\hat{i}}$ associated with the first RRTS message that was correctly received by sending a please-send (PS) message if $\mathcal{S}$ correctly received the RRTS message during its fixed waiting period of $(T_w + \text{SlotTime})$, as shown in Fig. 2 and Table II. The format of the PS frame is characterized in Fig. 3. Since the SN sends its data frame and PS message at the same transmission power of $P_{\mathcal{S}-\text{data}}$, all the RNs, which have correctly received the data frame from the SN will overhear the PS message. This guarantees that only the best RN forwards its data frame to $\mathcal{D}$ during the data-forwarding phase.

C. Phase III: Cooperative Transmission

In this phase, the best RN $\mathcal{R}_{\hat{i}}$ forwards the superimposed SR data to $\mathcal{D}$ if $\mathcal{S}$ successfully selects the best RN. Otherwise, $\mathcal{S}$ retransmits its data frame to $\mathcal{D}$, as shown in Fig. 2 and Table II.

1) Data Forwarding and Relay Retransmission: If RN $\mathcal{R}_i \in \mathcal{R}_{cc}$ finds that the receiver of the received PS message is not itself, it would drop the SN's data and would keep on sensing the medium. On the other hand, if the RN $\mathcal{R}_i \in \mathcal{R}_{cc}$ received a PS message that is destined for itself, it will encode both the SN's and its data with the aid of SPC and will forward the superimposed SR data frame to $\mathcal{D}$ at its precalculated transmission power of $P_{\mathcal{R}_i^{\min}}$ after an SIFS period, acting as the best RN, as shown in Fig. 2. Finally, at the DN, the classic automatic repeat request procedure will be initiated, when receiving the forwarded data and successfully decoding and combing it with the most recent direct transmission during Step I of Phase II.

TABLE II
PROCEDURE OF SN

$\mathcal{S}$ broadcasts data $Data_i$ at power P_{S-data}
$\mathcal{S}$ waits for the fixed duration of $(T_w + SlotTime)$
if $\mathcal{S}$ receives RRTS message
sends PS message to the best RN
else
compute power $P_{S-data}^{(2)}$
if $P_{S-data}^{(2)} \le P_{max}$
send data to $\mathcal{D}$ at power $P_{S-data}^{(2)}$
else
send data to $\mathcal{D}$ at power P_{max}
wait for ACK message
if ACK timeout
$\mathcal{S}$ broadcast data $Data_i$ again
else
$\mathcal{S}$ send RTS message for transmitting a new data

2) Source Retransmission: If none of the RNs competes for a transmission opportunity or multiple RRTS messages collided at the SN, $\mathcal{S}$ directly sends its data to $\mathcal{D}$ as a replica without relaying. This transmission takes place either at the specific transmit power of $P_{\mathcal{S}-\text{data}}^{(2)}$, which is capable of guaranteeing the expected rate of $\alpha C_{\mathcal{S},\mathcal{D}}^{\max}$, or failing that, it resorts to using the maximum affordable transmit power of $P_{\max}$, as shown in Table II. If $\mathcal{D}$ receives this data frame, it replies with an acknowledgment (ACK) message to $\mathcal{S}$ after successfully decoding and combining the frame with the most recent erroneous data frame broadcast by $\mathcal{S}$. If $\mathcal{S}$ does not receive any response from $\mathcal{D}$ before the timer set for waiting for an ACK message is expired, it will broadcast its data again at power of $P_{\mathcal{S}-\text{data}}$ to seek cooperation, and the RN selection procedure described earlier is repeated, as shown in Table II.

IV. Simulation Results

To evaluate the achievable performance of the proposed scheme, we present our simulation results based on Omnet++. Based on the network model introduced in Section II-A, we consider two scenarios to investigate both the achievable rate and EC improvement, and to analyze the RN's behavior. In the first scenario, all the RNs are randomly distributed across the entire network area, whereas $\mathcal{S}$ and $\mathcal{D}$ have fixed positions. The network size considered ranges from $u = 5$ nodes to $u = 30$ nodes for the sake of evaluating the influence of the size of the networks on the achievable rate and EC. In the other scenario, we consider a small network supporting $u = 5$ nodes, i.e., $\mathcal{S}$, $\mathcal{D}$, and three RNs, where all the nodes have fixed positions. One of the three RNs is located at the position of $d = 1/4$ along the SD link. Another RN is in the middle of the SD link at $d = 1/2$, whereas the third RN is at the point $d = 3/4$ of the SD link. In the given two scenarios, the values of $P_{\max}$ and $P_{\mathcal{S}-\text{data}}$ are 2 and 1 mW, respectively. The size of CWmin is 7, whereas SlotTime is set to 20 μs. Furthermore, the length of SIFS is

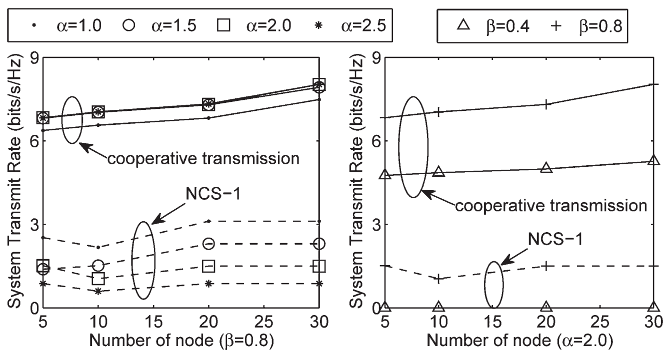

Fig. 4. System's total achievable rate improvement.

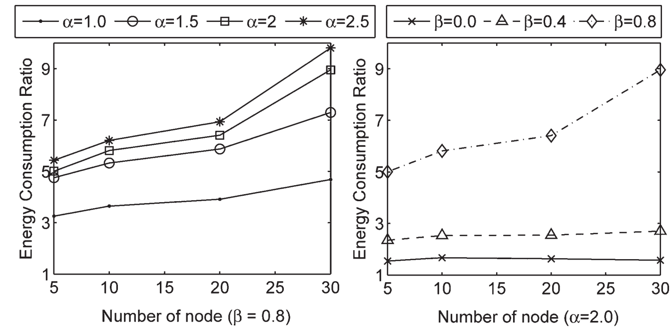

Fig. 5. Energy consumption ratio of $E_{\text{noncoop}}/E_{\text{coop}}$.

10 μs. The length of the data frame generated at the application layer is 1024 B. The length of the RRTS and PS messages is 20 B and 14 B, respectively, whereas that of the RTS and CTS is 24 and 18 B. The greedy factor α ranges from 1 to 3, whereas the value of β ranges from 0 to 0.8. Both α and β are predetermined for each simulation.

Two noncooperative systems are introduced as the benchmarkers of our comparisons. We compare the system's achievable total transmit rate (TTR) constituted by the sum of the SN's and RN's transmit rate to that of the noncooperative system 1 (NCS-1), which consumes the same total transmission energy as our CSLS (WW-CSLS). Additionally, we compare the total transmission EC to that of the noncooperative system 2 (NCS-2), which is capable of achieving the same TTR as our WW-CSLS. Since the SN's data is transmitted twice by itself and additionally by the best RN, if the cooperative transmission is successful, two direct transmission phases are exploited in both NCS-1 and NCS-2. When aiming for investigating the effect of our relay selection scheme, we compare the achievable performance of our WW-CSLS to that of a random CSLS (Ran-CSLS), where the best RN is randomly selected without considering the transmit power required for providing a successful cooperative transmission. To evaluate their performance, we adopt the idealized simplifying assumption that the control messages are received without errors in both NCS-1 and NCS-2, as well as in WW-CSLS. In Sections IV-E and F, we investigated a more practical network.

A. *Effect of Cooperative Transmission*

Let us now investigate the effects of cooperative transmission on the TTR and EC by comparing the performance achieved in the first scenario and NCS-1 and in NCS-2.

1) Achievable Transmit Rate: Fig. 4 compares the system's TTR, namely, the sum of both the SN's rate and the RN's rate achieved by the WW-CSLS relying on our WW cooperative MAC protocol to that of NCS-1. It is observed in Fig. 4 that, as expected, the system's achievable TTR relying on our WW-CSLS is higher than 6 bit/s/Hz, even for $\alpha = 1$ and $\beta = 0.8$, which is more than twice as high as that achieved by NCS-1, which consumes the same total transmission energy, given the same values of α and β. Additionally, for $\beta = 0.4$ and $\alpha = 2$, the system's TTR achieved by our WW-CSLS is in excess of 4 bit/s/Hz, while in fact, no successful transmissions may be supported in NCS-1 for the same values of α and β due to the system's low EC. Hence, the proposed WW cooperative MAC protocol is capable of providing a considerable TTR improvement, despite consuming low energy. As shown in Fig. 4, the system's TTR achieved by our WW-CSLS is increased, when $\mathcal{S}$ becomes greedier due to the SN's increased transmit rate requirement. Additionally, when β is increased, the best RN will be rewarded by a considerably higher rate for its own traffic, provided that the cooperation is successful. Hence, the system's TTR is increased, when the RN becomes greedier, as shown in Fig. 4. Moreover, the achievable TTR of our WW-CSLS is gradually increased, when the network becomes larger. The above investigations imply that the proposed WW cooperative MAC protocol is capable of providing significant TTR improvements.

2) Energy Consumption: Fig. 5 shows the achievable EC ratio (ECR) of $E_{\text{noncoop}}/E_{\text{coop}}$, where E_{coop} denotes the system's total transmission EC[5] for our cooperative MAC protocol and E_{noncoop} represents that of NCS-2, which is capable of achieving the same system's TTR as our WW-CSLS. As shown in Fig. 5, compared with NCS-2, two third of the system's total energy may be saved by exploiting the proposed WW cooperative MAC protocol, given $\beta = 0.8$. The EC E_{coop} of our WW-CSLS is reduced when $\mathcal{S}$ becomes greedier, which can be also characterized by the TTR of NCS-1 in Fig. 4. By contrast, the EC E_{noncoop} of NCS-2 is slightly increased, when $\mathcal{S}$ becomes greedier due to the slightly increased system rate of WW-CSLS. Hence, the ECR is increased, when $\mathcal{S}$ becomes greedier, as shown in Fig. 5. As β is increased, the system's ECR is increased from 1.5 to 5 for $\alpha = 2$ and $u = 5$, as shown in Fig. 5. When the RNs become greedier, fewer RNs can afford the increased power required for successfully forwarding the SPC data. However, the transmit rate achieved by the best RN is considerably increased. Hence, an increased total energy is required by NCS-2 for the sake of achieving the same system rate as our WW-CSLS. Therefore, the system's ECR of $E_{\text{noncoop}}/E_{\text{coop}}$ is increased when the RN becomes greedier. Based on the given discussions, the proposed WW cooperative MAC protocol is capable of achieving a considerable system rate improvement while offering a satisfactory energy efficiency.

[5]It is reasonable to focus on the transmission EC and ignore the circuit processing EC in a large network where the transmission EC is dominant in the total EC [26].

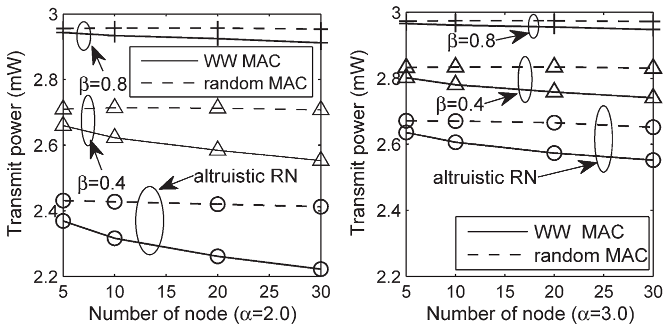

Fig. 6. System data transmit power consumed by our WW-CSLS and Ran-CSLS.

B. Effect of Relay Selection

Let us now investigate the effect of the proposed RN selection scheme by evaluating the achievable performance of our WW-CSLS and Ran-CSLS, where the best RN is randomly selected.

1) Transmit Power: According to the proposed WW cooperative MAC protocol, the specific RN that promises the lowest transmit power $P_{\mathcal{R}_i}$ required for successfully conveying superposition-coded data is selected as the best RN. However, the best RN is randomly selected in Ran-CSLS without considering any system parameters, such as the transmit power $P_{\mathcal{R}_i}$. Hence, the RN's transmit power $P_{\mathcal{R}_i}$ is the crucial parameter for investigating the effect of the proposed RN selection scheme. Fig. 6 quantifies the system's total data transmit power (TDTP) for our WW-CSLS and that is consumed in Ran-CSLS. The system's TDTP is defined as the sum of the SN's transmit power required for conveying its data plus the RN's transmit power necessitated for delivering the superposition-coded data.

Based on the proposed backoff algorithm, the system's TDTP consumed in the WW-CSLS is lower than that of the Ran-CSLS, as shown in Fig. 6. When the SN or RN becomes greedier, less RNs can afford the increased transmit power required to provide successful cooperative transmission assistance. This phenomenon increases the probability that the same RN is selected as the best RN in both WW-CSLS and Ran-CSLS. Hence, the difference between the TDTP of our WW-CSLS and that of Ran-CSLS is reduced when either α or β is increased, as shown in Fig. 6. Moreover, the TDTP of both WW-CSLS and of the Ran-CSLS is reduced when the network hosts more RNs due to the increased probability of having RNs, which promise to reduce the transmit power in comparison with a smaller network. However, the probability of the event that a low-quality RN, namely, one which requires a higher transmit power than other RNs, is selected as the best RN in the Ran-CSLS is increased, when the network becomes larger. Hence, compared with Ran-CSLS, an increased TDTP is saved by our WW-CSLS when the network's size is increased.

2) Achievable Transmit Rate: Fig. 7 compares the system's TTR, namely, the sum of both the SN's rate and the RN's rate achieved by our WW-CSLS to that achieved by Ran-CSLS. As shown in Fig. 7, the system's achievable TTR relying on WW-CSLS is 8 bit/s/Hz for $\beta = 0.8$ and $u = 30$, whereas a lower TTR of 6.5 bit/s/Hz is achieved by Ran-CSLS, given β and the network size. Compared with Ran-CSLS, the system's TTR can be improved by our WW-CSLS, even for lower β values and for smaller networks, e.g., for $\beta = 0.4$ and $u = 5$, as shown in Fig. 7. Based on WW-CSLS, the specific RN that promises lower transmit power of $P_{\mathcal{R}_i}$ may achieve a higher transmit rate of $\beta C^{\max}_{\mathcal{R}_i,\mathcal{D}}$ due to having an improved RD link. Hence, compared with Ran-CSLS, a higher TTR is achieved by our WW-CSLS relying on selecting the specific RN, which promises the lowest transmit power $P_{\mathcal{R}_i}$.

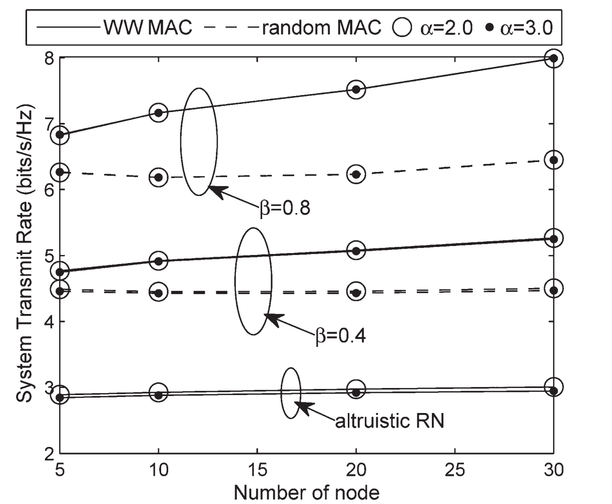

Fig. 7. System's total achievable rate improvement of our WW-CSLS and Ran-CSLS.

Observe in Fig. 7 that the proposed WW cooperative MAC protocol is capable of providing a higher TTR improvement than Ran-CSLS, when β is increased. When an RN becomes greedier, its target transmit rate is increased. This phenomenon increases the difference between the RN's transmit rate achieved by WW-CSLS and that achieved by Ran-CSLS when the RN that suffers from a low-quality RD link is selected by Ran-CSLS. Hence, the difference between the TTR of WW-CSLS and that of Ran-CSLS is increased when the RN becomes greedier. Considering the CSLS, where the RN altruistically forwards data for $\mathcal{S}$, the system's TTR is equal to the SN's rate. Hence, the system's TTR remains the same, regardless of which particular candidate RN is selected as the best RN when the RNs are altruistic, as shown in Fig. 7.

As shown in Fig. 7, the system's TTR achieved by our WW-CSLS is increased, when the network becomes larger. However, the effect of the network's size on the TTR achieved by Ran-CSLS is not as obvious as that on our WW-CSLS. When the network hosts more RNs, the number of candidate RNs may be increased. This phenomenon increases the probability that a low-quality RN having a lower transmit rate is selected as the best RN in Ran-CSLS. However, these low-quality RNs cannot win the cooperative transmission opportunity in our WW-CSLS if the specific RN promising a reduced transmit power also contends for the transmission opportunity. Hence, a higher TTR improvement is provided by the proposed WW cooperative MAC protocol, as the network becomes larger, as shown in Fig. 7. The given investigations imply that the proposed WW cooperative MAC protocol is capable of saving a substantial amount of transmit power while simultaneously

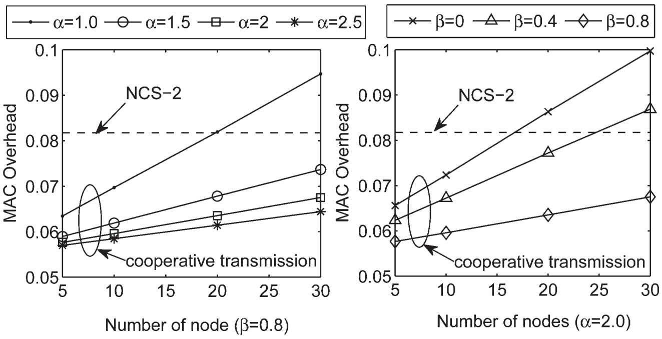

Fig. 8. MAC overhead for $\beta = 0.8$ or $\alpha = 2$.

providing significant TTR improvements compared with Ran-CSLS.

C. MAC Overhead

Fig. 8 compares the MAC overhead of the proposed cooperative MAC protocol with that of NCS-2, which is based on the RTS/CTS signaling regime of the IEEE 802.11 standards [22]. The MAC overhead is defined as the ratio of $(\mathcal{N}_{\text{mac}-c} + \mathcal{N}_{\text{mac}-h} + \mathcal{N}_{\text{mac}-t})/\mathcal{N}_{\text{mac}-d}$, where $\mathcal{N}_{\text{mac}-c}$ denotes the number of bits of all MAC control messages, and $\mathcal{N}_{\text{mac}-h}$ and $\mathcal{N}_{\text{mac}-t}$ represent the number of header and tailing bits of the MAC data frame, respectively. Furthermore, $\mathcal{N}_{\text{mac}-d}$ denotes the number of bits in the payload data packet, including the headers introduced by the higher layers. Observe in Fig. 8 that the MAC overhead of the proposed WW cooperative MAC protocol decreases, when either α or β increases, because the number of candidate RNs is reduced, whereas the SN or the RN becomes greedier. Compared with the traditional RTS/CTS scheme specified in the IEEE 802.11 standards [22], the RRTS message and the PS message are introduced into our WW-CSLS to assist with RN selection if cooperation can be exploited. However, compared with NCS-2, the RN's data can be also transmitted with the aid of cooperation in WW-CSLS. Since the length of the RN's data frames is higher than that of the extra control messages, the MAC overhead introduced by our WW protocol is lower than that of the NCS-2 when the network size is smaller than $u = 20$. Although the overhead of our WW-CSLS becomes higher than that of NCS-2 when the network hosts more than $u = 20$ nodes, the MAC overhead introduced by our WW protocol always remains lower than 0.1 for $\beta = 0.8$ or $\alpha = 2$.

D. Relay Behavior

To investigate the behavior of the relays, we analyze both the transmission probability and the achievable rate improvement of each RN for the configuration of $\alpha = 2$ in the network hosting $u = 5$ nodes, as shown in Fig. 9(a) and (b). Upon increasing β, the transmission probability of the RNs at "$d =$ 1/4" and "$d = 1/2$" decreases, whereas that of the RN at "$d = 3/4$" increases, as shown in Fig. 9(a). The RN at "$d =$ 3/4" always benefits from the highest transmission probability, whereas the RN at "$d = 1/4$" has the lowest probability of cooperative opportunities. As a benefit of its highest transmission probability, the RN at "$d = 3/4$" maintains the highest

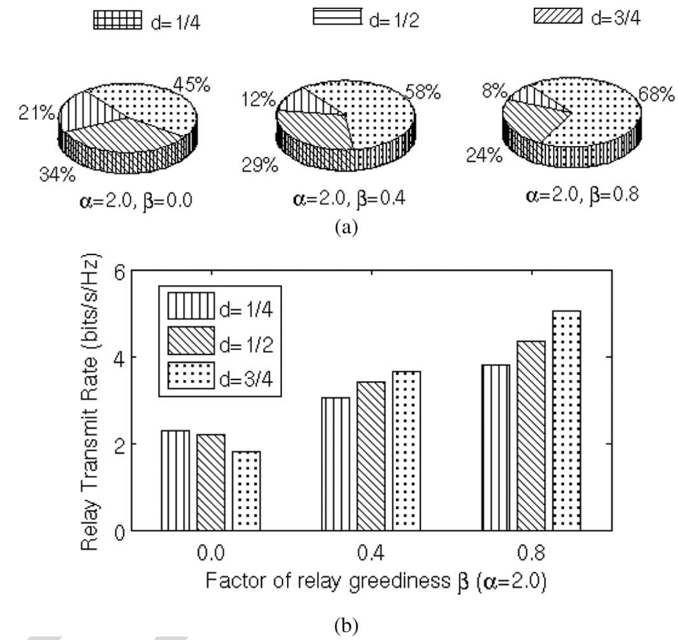

Fig. 9. RN transmission probability and the achievable rate improvement in a network hosting $u = 5$ nodes, namely, $\mathcal{S}$, $\mathcal{D}$, and three RNs. (a) Relay transmission probability. (b) Relay achievable rate.

achievable rate improvement, which is above 5 bits/s/Hz for $\beta = 0.8$ and $\alpha = 2$. The achievable RN-rate improvement at "$d = 1/4$" is lower than that of the RN at "$d = 1/2$," as shown in Fig. 9(b). However, when the three RNs altruistically dedicate themselves solely to forwarding data frames for $\mathcal{S}$ ($\beta = 0$), the achievable RN-rate improvement at "$d = 1/4$" is higher than that of the other relays. Naturally, if the RNs become selfish, their improved transmission probability leads to an increased total throughput.

E. Effect of Erroneous RTS Message

The contention caused by hidden SNs or RNs may corrupt the transmission of data and control messages. Apart from the effects of corrupted RTS messages, the erroneous transmission of both other control messages and of data have been considered in our WW cooperative MAC protocol. Hence, the effect of corrupted RTS messages on the system's transmit rate and on the ECR of $E_{\text{rts}-\text{error}}/E_{\text{error}-\text{free}}$ that are achieved by our WW-CSLS are evaluated, as shown in Fig. 10(a) and (b). The variable $E_{\text{rts}-\text{error}}$ denotes the system's total EC for WW-CSLS, where the RTS message may be corrupted. Furthermore, $E_{\text{error}-\text{free}}$ is the system's total EC for WW-CSLS, where error-free control messages are assumed. It is observed in Fig. 10(a) and (b) that, when the RTS error probability is increased, the system's TTR is decreased, and an increased total system energy is dissipated by our WW-CSLS because having more potentially erroneous RTS transmissions reduces the probability of successful transmission, and the extra RTS message retransmissions consume extra energy.

F. Effect of Imperfect Channel Estimation

To evaluate the overall system performance of our WW cooperative protocol in a more practical scenario, we now

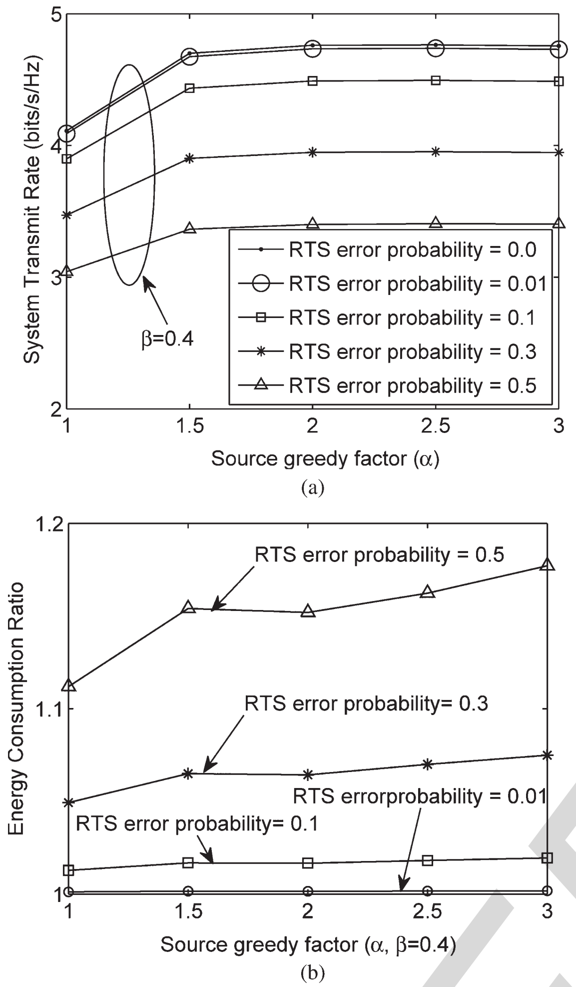

Fig. 10. System's total achievable transmit rate and system's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$ versus the SN's greedy factor parameterized with different RTS message error probabilities. (a) System's TTR. (b) System's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$.

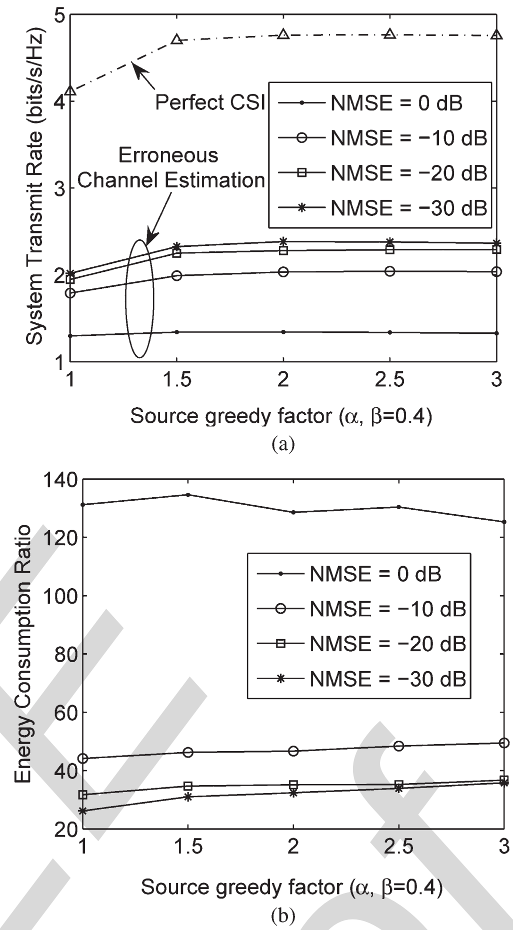

Fig. 11. System's total achievable transmit rate and system's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$ versus the SN's greedy factor parameterized with different channel estimation NMSEs when $\beta = 0.4$. (a) System's TTR. (b) System's ECR of $E_{\mathrm{rts-error}}/E_{\mathrm{error-free}}$.

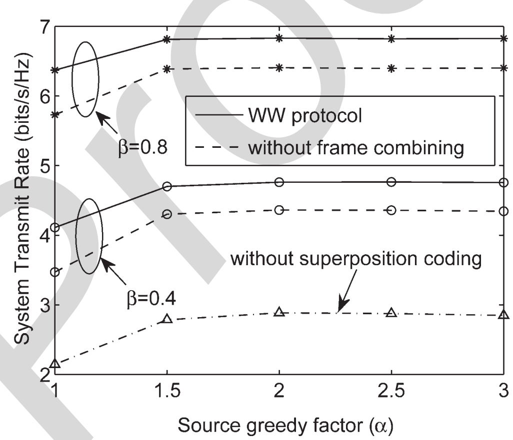

Fig. 12. System's total achievable transmit rate versus the SN's greedy factor both with and without SPC and SIC and frame combining.

introduce Gaussion-distributed CSI estimation errors into our WW-CSLS, instead of relying on the idealized simplifying assumption of perfect CSI. The normalized mean square error (NMSE) of the Gaussian channel estimation errors was defined as $10\log(E\{\|h-\hat{h}\|^2\}/E\{\|h\|^2\})$ in decibels [27]. Compared with the performance achieved by assuming perfect CSI, the realistic imperfect channel estimation reduces the system's attainable transmit rate and dramatically increases the system's ECR of $E_{\mathrm{error}}/E_{\mathrm{perfect}}$, as shown in Fig. 11(a) and (b), respectively. Variable E_{error} denotes the system's energy consumed by the CSLS relying on realistic imperfect channel estimation, whereas E_{perfect} denotes when perfect CSI is assumed. Based on the given discussions, it is necessary to develop a more robust cooperative MAC protocol to reduce the impact of realistic imperfect channel estimation.

G. Effect of Either Superposition Coding or Frame Combining

To evaluate the achievable TTR improvement jointly attained by SPC and SIC, we compare the system's TTR achieved by our WW-CSLS with that of the cooperative system operating without exploiting these techniques, as shown in Fig. 12. Since there are two data frames jointly conveyed by the RN to $\mathcal{D}$ in our WW-CSLS, the best RN, which does not exploit SPC, is assumed to forward only the SN's data instead of the SPC data. As shown in Fig. 12, the system's TTR may be increased from 2.9 to 6.9 bits/s/Hz for $\alpha = 2$ and $\beta = 0.8$ by jointly exploiting the SPC and SIC. Hence, these techniques are capable of significantly improving the system's transmit rate. To improve the SN's transmit rate, $\mathcal{D}$ invokes frame combining for amalgamating both the direct and relayed SN data after successfully separating the SN's and RN's data. Fig. 12 shows the system's TTR improvement achieved by exploiting frame combining.

V. Conclusion

In this paper, we have formulated a distributed WW cooperative framework for striking a tradeoff between the achievable system rate improvement and EC and for granting transmission opportunities for the unlicensed RNs. Furthermore, a WW cooperative MAC layer protocol was proposed for implementing our DWWCF. When compared with the corresponding noncooperative system, the proposed scheme is capable of providing a considerable transmit rate and transmission EC improvements. This was achieved with the aid of joint SPC at the RN for both the SN's and RN's data and by combining the SD and RD signals at the DN. Our future work will consider similar interference-limited scenarios relying on a more robust cooperative MAC design.

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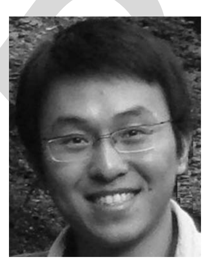

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AUTHOR QUERIES

AUTHOR PLEASE ANSWER ALL QUERIES

AQ1 = Please provide keywords.
AQ2 = Please provide expanded form of OF.
AQ3 = What is the first initial of author Asaduzzaman?

END OF ALL QUERIES