


RESEARCH ARTICLE

Distributed simultaneous wireless information and power transfer in multiuser amplify-and-forward ad hoc wireless networks

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Summary

This paper studies the problem of stable node matching for distributed simultaneous wireless information and power transfer in multiuser amplify-and-forward ad hoc wireless networks. Particularly, each source node aims to be paired with another node that takes the role of an amplify-and-forward relay to forward its signal to the destination, such that the achievable rate is improved, in return of some payment made to the relaying node. Each relaying node splits its received signal from its respective source into two parts: one for information processing and the other for energy harvesting. In turn, a matching-theoretic solution based on the one-to-one *stable marriage matching* game is studied, and a distributed polynomial-time complexity algorithm is proposed to pair each source node with its best potential relaying node based on the power-splitting ratios, such that their utilities or payments are maximized while achieving network stability. For comparison purposes, an algorithm to enumerate all possible stable matchings is also devised to study the impact of different matchings on the source and relay utilities. Simulation results are presented to validate the proposed matching algorithm and illustrate that it yields sum-utility and sum-payment that are closely comparable to those of centralized power allocation and node pairing, with the added merits of low complexity, truth telling, and network stability.

KEYWORDS

amplify-and-forward, cooperation, matching theory, node pairing, sum-rate, wireless power transfer

1 | INTRODUCTION

Recently, green communications have received significant attention in the literature, in pursuit of finding effective solutions that improve energy efficiency and use. Specifically, energy harvesting has emerged as a viable approach to prolong the lifetime and ensure self-sustainability of energy-constrained wireless networks.¹ However, such approach relies on the availability of natural renewable energy resources (eg, wind, solar, motion, and vibration), which may not be always available.² In particular, scavenging energy is time-varying, intermittent, and limited in most circumstances, which makes the realization of energy-harvesting transmission schemes rather challenging. Alternatively, simultaneous wireless information and power transfer (SWIPT) has emerged as a promising technique through which radio frequency (RF) signals

radiated by transmitters can be used for simultaneous information delivery and energy harvesting.^{3,4} The application of SWIPT has greatly reduced the dependence on the power-grid supply or battery energy to create truly wireless communications, without requiring battery replacement or tethering to electricity grids. Hence, SWIPT has become more and more attractive in a variety of applications, ranging from remote monitoring, biomedical implants, wireless sensors, and the newly emerged Internet of Things. More importantly, cooperative wireless networks naturally lend themselves to SWIPT, as intermediate nodes can harvest energy from received signals and then use it to forward the users' transmissions to their intended destinations, ultimately achieving significant gains in terms of spectral efficiency, energy consumption, and interference management.⁵

Several research works have focused on the application of SWIPT in cooperative wireless networks. For instance, Nasir et al⁶ consider a three-node amplify-and-forward (AF) network, where the relay harvests energy from the received RF signal and uses it to forward the source information to the destination. Particularly, two relaying protocols have been proposed to enable energy harvesting and information processing, namely, time switching-based relaying and power splitting-based relaying. Furthermore, analytical expressions for the outage probability and ergodic capacity are derived for delay-limited and delay-tolerant scenarios, where it has been shown that the time switching-based relaying protocol achieves higher throughput than the power splitting-based relaying protocol at relatively low signal-to-noise ratio (SNR). The SWIPT has also been applied to two-way AF networks with two sources and an energy harvesting relay by Chen et al.⁷ Specifically, the authors analyze the outage probability, ergodic capacity, and the finite-SNR diversity-multiplexing trade-off. In addition, tight closed-form upper and lower bounds of the outage probability and ergodic capacity are derived, and the effect of the power-splitting (PS) ratio is also evaluated. In one study,⁸ the authors considered SWIPT in relay interference channels and developed a distributed PS game-theoretic framework to determine the PS ratios for all relays. Particularly, noncooperative games are formulated for AF and decode-and-forward (DF) networks, where each link is modeled as a player aiming to maximize its own achievable rate. Additionally, the existence and uniqueness of the Nash equilibriums of the formulated games and the convergence of the proposed algorithm have been proven. Distributed relay selection for SWIPT is studied by Yan et al⁹ for AF wireless networks, where the relays harvest energy from the source's RF signal for cooperative relaying. In particular, the authors proposed two relay selection protocols, namely, maximum harvested energy and maximum SNR, and then derived the outage probability under each protocol, where the maximum SNR protocol has been shown to outperform the maximum harvested energy protocol. The authors in one study¹⁰ study the trade-off associated with information/power transfer via relay selection with the aim of minimizing outage probability. To be specific, single- and multi-relay selection schemes based on causal and non-causal channel state information cases are considered to determine the trade-offs associated with the number of relays and the energy harvesting efficiency. The problem of optimal PS design to maximize the cooperative capacity for AF and DF protocols in a three-node cooperative relay network is studied by Yin et al.¹¹ Particularly, the closed-form optimal PS ratio is derived under the two cooperation protocols, where it has been shown that the AF protocol benefits more than the DF protocol from favorable cooperation link conditions and the cooperation link condition dominates the optimal cooperative capacity instead of direct link condition. In Liu,¹² SWIPT has been applied to a network with a single source-destination pair and multiple AF relays. In particular, the study was aimed at determining the optimal PS factor that minimizes the outage probability. A high-SNR approximation analysis based on first-order channel statistics has been performed to optimize the PS factor. After that, an algorithm to select the best relay for outage minimization is devised and compared to different relay selection schemes in terms of throughput. In Michalopoulos et al,¹³ a relay selection policy has been proposed that yields the optimal trade-off between information transmission efficiency and the amount of transferred energy in a maximum capacity/minimum outage probability sense. Moreover, the authors propose two suboptimal relay selection schemes that do not require global channel state information and derive their closed-form expressions for achievable trade-offs between energy transfer, ergodic capacity, and outage probability. Liu¹⁴ applies SWIPT in multi-relay networks using the concept of distributed space-time coding. To be specific, PS optimization problems for AF and DF relaying protocols are formulated, and efficient algorithms are proposed to find the optimal solutions. In Chu et al,¹⁵ the authors consider SWIPT in a network of multiple source-destination pairs and a single DF energy harvesting relay. Particularly, the problem of total rate maximization is studied so as to determine closed-form solutions for the optimal PS ratio and transmit power. A similar problem is considered by Ding et al,¹⁶ where a single DF relay is used to efficiently distribute its harvested energy over multiple source-destination pairs, while studying the impact of different power allocation strategies on the end-to-end transmission reliability. The SWIPT has also been considered by Chen et al¹⁷ in a network with multiple DF relays and one source-destination pair. Specifically, a closed-form expression of the outage probability is analyzed, and its approximation at high SNR is derived. Moreover, the outage performance of the multi-relay network with SWIPT is compared to conventional systems with self-powered relays, where it has been shown that the outage probability with and without SWIPT

differs by a coefficient. It is noteworthy that although cooperative relaying service from non-altruistic nodes is commonly assumed granted in ad hoc wireless networks, this assumption is far too optimistic, noting the limited energy available at these nodes. The SWIPT has been introduced as a practical solution to encourage cooperation among these nodes by compensating them via energy harvesting. This can lead to a competition among these nodes to select their cooperative partners. Hence, matching theory can be used to match network nodes so as to facilitate the pairing of source and relay nodes in SWIPT-based wireless networks, while rewarding them (in terms of utility and payment) for their cooperation.

Matching theory has recently received much attention as a promising technique for resource allocation and node selection/pairing in wireless networks. For instance, in two studies,^{18,19} the problem of energy-efficient partner selection in cooperative wireless networks is studied. In particular, the authors devised two polynomial-time complexity algorithms based on the *stable roommates matching problem* to pair nodes such that the total energy consumption to meet a target end-to-end SNR is minimized. The first algorithm is based on Irving's stable matching, which does not always guarantee a stable solution; therefore, the second algorithm is proposed to determine the maximum number of stable disjoint pairs. In one study,²⁰ the authors use the Stackelberg game model to determine the optimal time allocation between multiple primary users (PUs) and secondary users (SUs) for cooperative spectrum leasing. After that, a matching-theoretic framework is proposed for partner selection to optimize the PUs and SUs utilities in terms of transmission rate and power consumption. In addition, a distributed one-to-one matching algorithm that converges to a stable matching between the PUs and SUs is proposed, yielding considerable gains compared to the noncooperative scenario. A novel context-aware user-cell association approach for small-cell networks using matching theory is studied by Namvar et al.²¹ Particularly, the user-cell association problem is formulated as a many-to-one matching game with externalities, where the preferences of users and small-cell base-stations are strictly interdependent. In turn, a self-organizing algorithm that can dynamically update the preference lists in the presence of externalities is proposed so as to reach a stable matching between the users and their serving small-cell base-stations. A matching game-based heterogeneous network selection algorithm is proposed by Chen et al.²² to achieve a stable matching in terms of the different utilities and requirements of users and networks. In Gu et al.,²³ a comprehensive tutorial on the use of matching theory for resource management in wireless networks is presented. Specifically, a wireless-oriented classification of matching theory is developed to capture the unique features of emerging wireless networks. Moreover, for each class of matching problems, the basic challenges, solution concepts, and potential applications are provided.

In this paper, stable node matching for distributed SWIPT in multiuser AF ad hoc wireless networks is studied and modeled as a *stable marriage problem (SMP)*.^{24,25} In general, the SMP is used to determine a stable matching/pairing between two equally sized sets of players according to a certain ordering of preference, such that no two players would both prefer to have each other over their current partners. On the other hand, network stability is an important metric in the performance of wireless networks as it is concerned with user associations and network connectivity. If a network is not stable in terms of users' pairings and associations, the performance may degrade dramatically, because of excessive overheads and delays, which hamper the network efficiency and reliability.^{26,27} In our work, the SMP is considered to find a stable matching between network nodes according to their preference lists, in which each source node orders its preference of other nodes—acting as relays—in terms of the resulting utility. Moreover, the relaying nodes order their preference of source nodes according to the payment they receive in return for the cooperative service they provide. Thus, the aim is to find a one-to-one *stable* matching between the source and relaying nodes, such that there is no pair of a source node and a relaying node that both prefer each other to their partner in the matching. To this end, a distributed stable marriage matching (SMM) algorithm is proposed to find a stable matching, where no network source-relay pair both have incentive to break their bond and choose another partner over their current partner. The proposed algorithm has polynomial-time complexity of order $\mathcal{O}(N^2)$ (where N is the number of network nodes), which implies that it can be executed efficiently to *always* find a stable matching solution. The proposed SMM algorithm intrinsically enforces truth telling and thus suppresses any potential cheating behavior. For comparison purposes, the all stable matchings enumeration (ASME) algorithm has been devised to list all possible stable matchings, with time-complexity of $\mathcal{O}(N^2 + N|\mathbb{M}|)$, where \mathbb{M} is the set of all stable matchings.²⁸ Specifically, the aim of the ASME algorithm is to enumerate all stable matchings so that different pairing criteria can be applied.²⁹ Lastly, the proposed algorithms are compared with centralized source-relay selection/pairing schemes in terms of sum-utility and sum-payment.

To the best of the authors' knowledge, no prior work has applied matching theory to determine stable source-relay pairings in multiuser AF ad hoc wireless networks for SWIPT and yield solutions that are comparable with those of centralized sum-utility and sum-payment maximization. In turn, the main contributions of this work can be summarized as follows:

- Modeled the source-relay selection/pairing problem as an SMM problem, with the source utility and relay payment as selection criteria, which are defined as functions of the PS ratio.
- Proposed the distributed SMM algorithm, which matches source and relaying nodes in polynomial-time complexity. Moreover, the SMM algorithm has been shown to intrinsically enforce truth telling and thus suppress any potential cheating behavior.
- Compared the proposed distributed SMM algorithm with the ASME algorithm—which enumerates all stable matchings—and with centralized source-relay selection/pairing algorithms in terms of network sum-utility and sum-payment.

The remainder of this paper is organized as follows. Section 2 presents the network model, while Section 3 discusses the utility functions of the source and relaying nodes. In Section 4, the proposed distributed SMM algorithm is outlined and discussed, while Section 5 presents the ASME algorithm. Section 6 outlines the centralized source-relay selection/pairing optimization problems, while Section 7 presents the simulation results. A few related strategic issues are discussed in Section 8, while Section 9 draws the conclusions.

2 | NETWORK MODEL

Consider an ad hoc wireless network with N (for even N) AF* half-duplex single-antenna source nodes, denoted S_i , for $i \in \{1, 2, \dots, N\}$. Each source node S_i intends to transmit its data symbol x_i to a common destination node D . Additionally, each source node S_j can be selected to act as a relay R_j (for $j \in \{1, 2, \dots, N\}$) to assist a source node S_i (for $i \neq j$) in forwarding its signal to the destination. The channel between any two nodes is modeled as narrowband Rayleigh fading with additive white Gaussian noise of zero-mean and variance N_0 . In particular, let $h_{S_i,D}$, h_{S_i,R_j} , and $h_{R_j,D}$ be the S_i - D , S_i - R_j , and R_j - D channel coefficients, which are modeled as zero-mean complex Gaussian random variables, with variances $\sigma_{S_i,D}^2$, σ_{S_i,R_j}^2 , and $\sigma_{R_j,D}^2$, respectively. The channel coefficients are assumed to be reciprocal as in time division duplexing systems (ie, $h_{S_i,R_j} = h_{S_j,R_i}$). Each source node S_i is assigned a signature waveform $c_i(t)$, which is used for multiuser detection at the destination node.¹⁸ Moreover, signature waveforms $c_i(t)$ and $c_j(t)$ have correlation coefficient $0 \leq \rho_{i,j} \leq 1$, for $i \neq j$, where $\rho_{i,i} = 1$. Without loss of generality, it assumed that $\rho_{i,j} = \rho$, $\forall j \neq i$. Also, it is assumed that the transmit power of each source S_i is given by P_{S_i} and that there is a total transmit power P per node (ie, $P_{S_i} \leq P$, $\forall i \in \{1, 2, \dots, N\}$). In addition, perfect channel state information is assumed to be available at all network nodes. Furthermore, each network node is assumed to have an energy harvesting device to harvest energy from the received signals by using PS. In turn, the harvested energy can be used by each relaying node to forward a source's information signal to the destination. Additionally, each node acting as a relay R_j splits a portion of its received signal energy $\alpha_{i,j}$ from source S_i for information processing, and the rest $1 - \alpha_{i,j}$ is for energy harvesting (which will subsequently be used for relaying).[†]

Communication between each source node and the destination is split into two transmission phases (see Figure 1), namely, the broadcasting phase (of N time slots) and the cooperation phase (of 1 multiple-access time slot). In the broadcasting phase, each source node S_i broadcasts its data symbol x_i in its assigned time slot, which is received by the destination node as well as the $N - 1$ other nodes. Specifically, the received SNR at the destination is given by

$$\gamma_i = \frac{P_{S_i} |h_{S_i,D}|^2}{N_0}. \quad (1)$$

Additionally, the harvested energy at relay R_j due to source S_i 's signal is obtained as

$$P_{S_i,R_j}(\alpha_{i,j}) \triangleq \eta(1 - \alpha_{i,j})P_{S_i} |h_{S_i,R_j}|^2, \quad (2)$$

where $\alpha_{i,j}$ is the PS ratio between source S_i and relay R_j and $0 < \eta \leq 1$ is the energy conversion efficiency.[‡] Clearly, the smaller the value of $\alpha_{i,j}$ is, the greater the harvested energy.

In the cooperation phase, the N nodes acting as relays simultaneously amplify-and-forward their received signals to the destination.[§] Particularly, each selected relay node R_j assists a source node S_i (for $i \neq j$) by forwarding its signal to the

*The AF cooperation protocol is considered in this work because of its simplicity and low complexity,³⁰ and thus, it lends itself naturally to SWIPT-based wireless networks.

†From this point onwards, each relaying node that cooperates with a source node in forwarding its signal is called a relay, which solely depends on the harvested energy for cooperative relaying.

‡For simplicity, assume normalized transmission time in each time slot, such that the terms “power” and “energy” can be used interchangeably.

§Perfect timing synchronization is assumed.

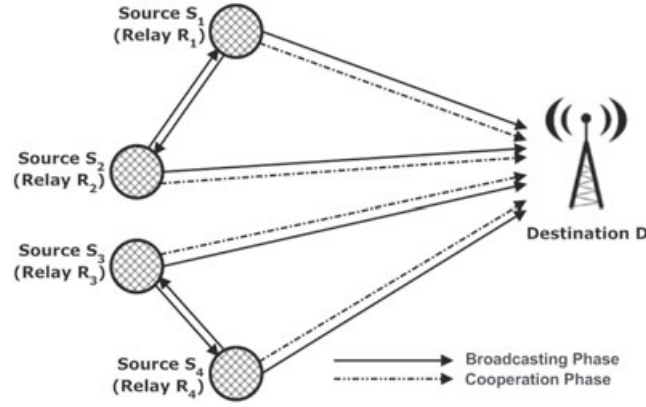


FIGURE 1 Network model with (S_1, S_2) and (S_3, S_4) paired nodes

destination D . The instantaneous SNR at the destination due to the cooperative transmission by relay R_j can be expressed as^{18,31}

$$\gamma_{ij}(\alpha_{ij}) = \frac{1}{\rho N_0} \frac{\alpha_{ij} P_{S_i} |h_{S_i, R_j}|^2 P_{S_i, R_j}(\alpha_{ij}) |h_{R_j, D}|^2}{\alpha_{ij} P_{S_i} |h_{S_i, R_j}|^2 + P_{S_i, R_j}(\alpha_{ij}) |h_{R_j, D}|^2 + N_0}, \quad (3)$$

where ρ is the noise amplification coefficient due to the use of signature waveforms, as given by

$$\rho = \frac{1 + (N - 2)\rho}{1 + (N - 2)\rho - (N - 1)\rho^2}. \quad (4)$$

Remark 1. Due to the strict monotonicity of the γ_i and $\gamma_{ij}(\alpha_{ij})$ SNR terms, $P_{S_i} = P, \forall i \in \{1, 2, \dots, N\}$.

Hence, the instantaneous achievable rate of source node S_i at the destination D via relay R_j is obtained as³²

$$\mathcal{R}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij})) = \frac{1}{N + 1} \log_2 \left(1 + \frac{P G_{S_i, D}}{N_0} + \frac{1}{\rho N_0} \frac{\alpha_{ij} P G_{S_i, R_j} P_{S_i, R_j}(\alpha_{ij}) G_{R_j, D}}{\alpha_{ij} P G_{S_i, R_j} + P_{S_i, R_j}(\alpha_{ij}) G_{R_j, D} + N_0} \right), \quad (5)$$

where $P_{S_i, R_j}(\alpha_{ij}) = \eta(1 - \alpha_{ij}) P G_{S_i, R_j}$, while $G_{S_i, D} = |h_{S_i, D}|^2$, $G_{S_i, R_j} = |h_{S_i, R_j}|^2$, and $G_{R_j, D} = |h_{R_j, D}|^2$ are the instantaneous channel gains. Therefore, the achievable rate maximizing power allocation (RM-PA) optimization problem is formulated as

RM-PA:

$$\begin{aligned} \max \quad & \mathcal{R}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij})) \\ \text{s.t.} \quad & 0 \leq \alpha_{ij} \leq 1. \end{aligned} \quad (6)$$

Problem **RM-PA** is nonconvex although it is defined over a convex set, as the rate function $\mathcal{R}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}))$ is not concave in α_{ij} .¹⁴ However, because of the strict monotonicity of the $\log_2(\cdot)$ function, problem **RM-PA** can be rewritten as

RM-PA:

$$\begin{aligned} \max \quad & \frac{1}{\rho N_0} \frac{\eta P^2 G_{S_i, R_j}^2 \alpha_{ij} (1 - \alpha_{ij}) G_{R_j, D}}{\alpha_{ij} P G_{S_i, R_j} + \eta (1 - \alpha_{ij}) P G_{S_i, R_j} G_{R_j, D} + N_0} = \frac{\mathcal{N}_{S_i, R_j}(\alpha_{ij})}{\mathcal{D}_{S_i, R_j}(\alpha_{ij})} \\ \text{s.t.} \quad & 0 \leq \alpha_{ij} \leq 1, \end{aligned} \quad (7)$$

which is still nonconvex, but can be shown to be a concave-convex fractional programming problem.³³ Particularly, it can be easily verified that the numerator $\mathcal{N}_{S_i, R_j}(\alpha_{ij})$ of the objective function is concave and nonnegative in α_{ij} , while

the denominator $\mathcal{D}_{S_i, R_j}(\alpha_{ij})$ is convex and positive. Therefore, problem **RM-PA** can be solved as a concave problem via a parametric approach, by recasting it as³⁴

RM-PA:

$$\begin{aligned} \mathcal{F}_{S_i, R_j}(\lambda) &= \max \mathcal{N}_{S_i, R_j}(\alpha_{ij}) - \lambda \mathcal{D}_{S_i, R_j}(\alpha_{ij}) \\ \text{s.t.} \quad & 0 \leq \alpha_{ij} \leq 1, \end{aligned} \quad (8)$$

with $\lambda \in \mathbb{R}$. It is straightforward to verify that $\mathcal{F}_{S_i, R_j}(\lambda)$ is concave and continuous. Moreover, the optimal solution λ^* is finite, yielding $\mathcal{F}_{S_i, R_j}(\lambda^*) = 0$. Consequently,

$$\lambda^* = \frac{\mathcal{N}_{S_i, R_j}(\alpha_{ij}^*)}{\mathcal{D}_{S_i, R_j}(\alpha_{ij}^*)} = \max_{0 \leq \alpha_{ij} \leq 1} \frac{1}{\rho N_0} \frac{\eta P^2 G_{S_i, R_j}^2 \alpha_{ij} (1 - \alpha_{ij}) G_{R_j, D}}{\alpha_{ij} P G_{S_i, R_j} + \eta (1 - \alpha_{ij}) P G_{S_i, R_j} G_{R_j, D} + N_0}, \quad (9)$$

and α_{ij}^* is the value that yields λ^* .

Remark 2. The optimal PS ratio is strictly in range of $0 < \alpha_{ij}^* < 1$, since $\gamma_{ij}(\alpha_{ij}^*) = 0$ for $\alpha_{ij}^* = 0$ and $\alpha_{ij}^* = 1$.

Finally, the optimal amount of harvested energy at relay R_j used for cooperative transmission is expressed as

$$P_{S_i, R_j}(\alpha_{ij}^*) = \eta (1 - \alpha_{ij}^*) P G_{S_i, R_j}. \quad (10)$$

Remark 3. The optimal PS ratio α_{ij}^* of each source S_i at relay R_j (for $i \neq j$) can be determined locally at each source node without the need for a centralized controller. In turn, the optimal PS solutions can be determined in a distributed manner.

3 | UTILITY FUNCTIONS

In this work, the aim is to match each source node with another relay node, such that the achievable rate of that source is maximized. In order for each source to select a relay, it must first determine its optimal PS ratio from that relay and then rank the $N - 1$ relays according to the resulting utility. On the other hand, a relay must determine the payment it should receive from each source node it is potentially to be paired with in return for forwarding the source's signal to the destination. The payment a relay receives must be a function of the PS ratio, such that its payment is maximized. Consequently, it ranks the source nodes according to the payment it may receive from each one of them and aims to be paired with the one that yields the maximum payment.

3.1 | Source utility

Since each source S_i aims at maximizing its achievable rate when it uses power $P_{S_i, R_j}(\alpha_{ij}^*)$ from relay R_j , the utility function \mathcal{U}_{S_i, R_j} of source S_i when it is paired with relay R_j is given by³⁵

$$\mathcal{U}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*)) = \Delta \mathcal{R}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*)) - \mathcal{P}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*)), \quad (11)$$

where $\mathcal{P}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*))$ is the payment relay R_j receives when it is paired with source S_i (as will be detailed shortly) and $\Delta \mathcal{R}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*))$ is the improvement in the transmission rate due to the cooperative transmission by relay R_j , as given by³⁵

$$\Delta \mathcal{R}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*)) = \frac{1}{N + 1} \log_2 \left(1 + \frac{P_{S_i, R_j}(\alpha_{ij}^*) \Omega_{ij}(\alpha_{ij}^*)}{P_{S_i, R_j}(\alpha_{ij}^*) + \Upsilon_{ij}(\alpha_{ij}^*)} \right), \quad (12)$$

where

$$\Omega_{ij}(\alpha_{ij}^*) = \frac{\alpha_{ij}^* PG_{S_i, R_j}}{\rho (PG_{S_i, D} + N_0)}, \quad (13)$$

and

$$\Upsilon_{ij}(\alpha_{ij}^*) = \frac{\alpha_{ij}^* PG_{S_i, R_j} + N_0}{G_{R_j, D}}. \quad (14)$$

Remark 4. The greater the utility $\mathcal{U}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*))$ of source S_i is, the more preferred is relay R_j to source S_i (for $i \neq j$).

3.2 | Relay utility

When selecting the payment function of each relay R_j , it is important to ensure that the payment function stays bounded for all values of $0 \leq \alpha_{ij} \leq 1$. More importantly, the payment function must equal zero at the extreme values of α_{ij} (ie, when α_{ij} is equal to 0 or 1). This is because both these values will yield an instantaneous SNR value of $\gamma_{ij}(\alpha_{ij}) = 0$, and thus, the rate improvement of source S_i will equal to zero (as per Remark 2), in which case the cooperative transmission reduces to direct transmission. Thus, in this work, the utility function of relay R_j is defined in terms of the payment it receives—as a function of α_{ij} —when it is paired with source S_i , as given by

$$\begin{aligned} \mathcal{P}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij})) &\triangleq \xi_{R_j} \ln(1 + \mu_{R_j} P_{S_i, R_j}(\alpha_{ij}))^{\alpha_{ij}} \\ &= \xi_{R_j} \ln(1 + \mu_{R_j} \eta (1 - \alpha_{ij}) PG_{S_i, R_j})^{\alpha_{ij}}, \end{aligned} \quad (15)$$

where $\mu_{R_j} > 0$ is a constant controlling the rate at which the payment function increases with the increase in $P_{S_i, R_j}(\alpha_{ij})$ (ie, the steepness between the minimum and maximum payment values). Moreover, the parameter $\xi_{R_j} > 0$ is used to control the maximum value of the payment. Without any loss of generality, let $\mu_{R_j} = \mu_R$ and $\xi_{R_j} = \xi_R$, $\forall j \in \{1, 2, \dots, N\}$. Examples of the payment function values are given in Figure 2, where it can be seen that different values of ξ_R and μ_R yield different maximum payments for different optimal PS ratios α_{ij}^* .

Remark 5. The payment function $\mathcal{P}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}))$ is concave in α_{ij} , $\forall i, j \in \{1, 2, \dots, N\}$ and $j \neq i$. In turn, it is straightforward for relay R_j to determine the optimal PS ratio α_{ij}^* that maximizes its payment function.

Remark 6. The greater the payment $\mathcal{P}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij}^*))$ relay R_j receives, the more preferred is source S_i to relay R_j (for $i \neq j$).

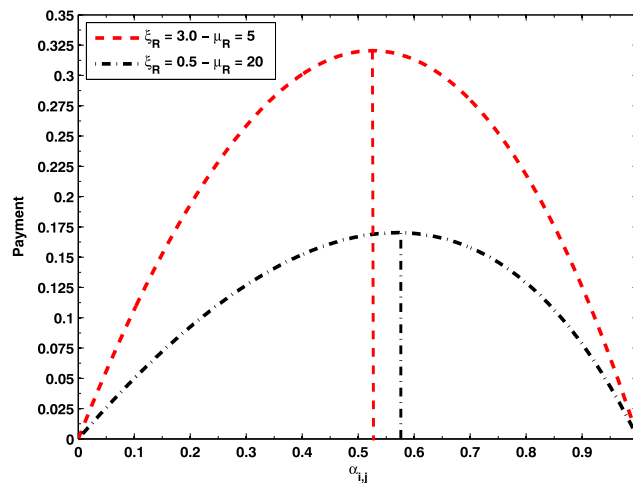


FIGURE 2 Numerical examples of the payment function $\mathcal{P}_{S_i, R_j}(P_{S_i, R_j}(\alpha_{ij})) = \xi_R \ln(1 + \mu_R \eta (1 - \alpha_{ij}) PG_{S_i, R_j})^{\alpha_{ij}}$ for $\eta = 0.95$, $P = 0.1$ W and $G_{S_i, R_j} = 1$

Based on Remarks 4 and 6, it is clear that the higher the payment of relay R_j is, the lower is the utility of source S_i (and vice versa). Hence, the source and relay nodes have conflicting demands in terms of the resulting utility and received payments, which requires a matching-theoretic solution. Moreover, based on the defined utility and payment functions of the source and relay nodes, one must keep in mind the following. There are two possible ways of obtaining the values of the optimal PS ratio, depending whether the source or relay nodes initiate the matching process (as will be discussed in the following section). Specifically, if the source nodes are to propose the matching to relay nodes, then each source S_i must determine the optimal PS ratio $\alpha_{i,j}^*$ from relay R_j (as per (9)) and then determine its corresponding utility as given by (11), for which relay R_j receives a corresponding payment (which may not be optimal to the relay). This is referred to as the *sources-optimal* (SO) scenario. On the other hand, if the relay nodes are to propose the matching to the source nodes, then each relay R_j would determine the optimal PS ratio that maximizes its payment from source S_i (as per (15)), which may not necessarily be optimal to that source node. This is referred to as the *relays-optimal* (RO) scenario. More importantly, the optimal PS ratio determined by the source node may not necessarily be equal to that calculated by the relay.

It should be noted that the focus of this work is not analyze or determine the PS ratio that is optimal to both the source and relay nodes, as this would require some form of a noncooperative game-theoretic solution. For instance, a Stackelberg game can be used to model the dynamic interaction between a source node and each potential relaying node.³⁶ Particularly, the game is formulated such that the source node pays a relay node to improve its achievable rate improvement, while each relay can charge the source node a certain price per unit power for forwarding its signal. Moreover, a distributed iterative algorithm may be devised in order for each source and relay node to reach an equilibrium of the Stackelberg game. However, doing so may require a solution of a nonconvex optimization problem, which may not have a closed-form solution or entails excessive computations. Such approach may introduce significant communication and computational overheads in multiuser AF ad hoc wireless networks. Therefore, in our work, instead of dynamically modeling the interaction between each source node S_i and the $N - 1$ potential relaying nodes R_j (for $j \neq i$), each source node S_i can determine its optimal PS ratio (via the reformulated problem **RM-PA**) when paired with relay R_j and thus obtain the rate improvement (or utility), while relay R_j can determine the maximum payment it receives in return for the cooperative transmission via the predefined pricing function in (15).³⁷ Clearly, this approach reduces the computational complexity and communication overheads significantly at the expense of possibly some suboptimality.

4 | STABLE MARRIAGE MATCHING ALGORITHM

In this section, the distributed SMM algorithm is devised, which is based on the SMP.²⁵

4.1 | Definitions

An instance of the SMP consists of a set of sources (men) and a set of relays (women). The members of each set would like to be matched to exactly one member of the opposite set, such that by the end of the matching process, no two members of opposite sets would like to be with each other more than their current partner. This requires that every member of each set to rank—in descending order of preference—the members of the opposite set. In the original SMP, each node's preference list must include *all* members of the opposite set. However, in our context, rather than having two distinct sets of nodes, the same N network nodes take two different roles: sources and relays. Particularly, each source (relay) ranks the other $N - 1$ relays (sources) in descending order of preference (since a source will not act as a relay for its own signal, and hence, it excludes itself from its preference list).

To design the distributed SMM algorithm, a few definitions must first be stated.

Definition 1. (Matching)

A matching \mathcal{M} is a set of $N/2$ disjoint network source-relay pairs. If source S_i and relay R_j are paired in \mathcal{M} (ie, (S_i, R_j) are partners in \mathcal{M}), then one can write $S_i = \mathcal{M}(R_j)$ and $R_j = \mathcal{M}(S_i)$, where $\mathcal{M}(R_j)$ and $\mathcal{M}(S_i)$ are the \mathcal{M} -partners of nodes R_j and S_i , respectively.[¶]

[¶]A matching is a one-to-one correspondence between the source and relay nodes.

Definition 2. (Preference)

If source S_i prefers relay R_j to R_l , then $R_j \succ_{S_i} R_l$. In a similar manner, if relay R_j prefers source S_i to S_k , then $S_i \succ_{R_j} S_k$.

Definition 3. (Preference List)

Let $\mathbb{P}_{S_i} = \{R_j^{(1)}, \dots, R_l^{(N-1)}\}$ be the preference list of source S_i , where $R_j^{(1)}(R_l^{(N-1)})$ stipulates that relay $R_j(R_l)$ is the most (least) preferred to source S_i . Similarly, $\mathbb{P}_{R_j} = \{S_i^{(1)}, \dots, S_k^{(N-1)}\}$ is the preference list of relay R_j , where $S_i^{(1)}(S_k^{(N-1)})$ indicates that source $S_i(S_k)$ is the most (least) preferred to relay R_j .

Definition 4. (Preference Matrix)

Let \mathbb{P}_S be an $N \times (N - 1)$ matrix, where the i^{th} row (for $i \in \{1, 2, \dots, N\}$) represents the preference list \mathbb{P}_{S_i} of source S_i . Similarly, \mathbb{P}_R denotes the $N \times (N - 1)$ matrix, where the j^{th} row (for $j \in \{1, 2, \dots, N\}$) gives the preference list \mathbb{P}_{R_j} of relay R_j .

Definition 5. (Blocking Pair)

A source S_i and relay R_j form a *blocking pair* for matching \mathcal{M} (expressed as (S_i, R_j) blocks \mathcal{M}) if the following 3 conditions are met: (1) $\mathcal{M}(S_i) \neq R_j$ but S_i and R_j are acceptable to each other; (2) $R_j \succ_{S_i} \mathcal{M}(S_i)$ or S_i is single in \mathcal{M} ; and (3) $S_i \succ_{R_j} \mathcal{M}(R_j)$ or R_j is single in \mathcal{M} .³⁸

Definition 6. (Stable Marriage)

A matching is *stable* if it does not have any blocking pair.

4.2 | Algorithm design

The basic SMP involves determining—for any instance of preference matrices \mathbb{P}_S and \mathbb{P}_R —a stable matching such that there exists no pair of nodes who prefer each other to their current partners. The SMM algorithm can be devised depending on whether the source or the relay nodes propose the matching/pairing to the other nodes. Thus, the SMM algorithm is either SO if the source nodes propose pairings according to their preference lists or otherwise RO. In what follows, the SO-SMM algorithm is outlined for solving the SMP, which is based on a series of iterations.[†] Particularly, at each iteration, each source proposes to its most preferred relay to which it has not already proposed (which may or may not already be paired). In turn, each relay considers all proposals it receives from the sources (as well as its currently paired-to source, if such exists) and accepts (or retains) a pairing with the most preferable among them. Once a relay becomes paired-to a source, it remains paired, while it can improve its position by rejecting its currently paired-to source for another. On the other hand, a paired source may be abandoned by its paired-to relay and become unpaired (single) again; in which case, it resumes the sequence of proposals, starting with the next relay on its list. Moreover, a relay's pairing status changes only once from single to paired, and thereafter, its ranking of its paired source can only improve. However, a source's status may change multiple times between unpaired and paired, while the ranking of its paired-to relay can only worsen. This process repeats until all sources (and consequently all relays) become matched, at which point all pairings are final and a stable marriage is obtained. The SO stable matching marriage algorithm is outlined in Algorithm 1, which is adapted from the Gale-Shapley algorithm.²⁴

It is noteworthy that the SO-SMM algorithm involves a sequence of proposals from the sources to the relays, yielding a matching that is SO (and hence *relays-pessimal*). This can be seen by noting that the algorithm is characterized by a monotonicity of sources' and relays' rankings of their assigned partners. Furthermore, even though relays can reject one source for another, relays passively react to the sources' proposals, while sources actively make proposals on their own. Consequently, the SO-SMM algorithm serves the wellbeing of sources and not that of relays. In turn, in the resulting stable matching, each source gets the highest (and each relay gets the lowest) preference it could get in any stable solution. If the roles of the sources and relays are reversed (ie, the RO-SMM algorithm), then the algorithm will produce an RO (and thus *sources-pessimal*) matching.

Additionally, the following remarks can be made in relation to the output of the SMM algorithm.²⁵

[†]The RO-SMM algorithm can be obtained by letting the relays propose the pairings according to their preference lists and thus is identical to the operation of its SO-SMM counterpart.

Remark 7. In the sources- (relays-) optimal stable matching, each relay (source) has the worst partner it can have in any stable matching. Moreover, in this stable matching, each source (relay) is paired with the best relay (source) that it can have in any stable matching.

Remark 8. The order of sources (relays) proposals does not affect the resulting stable matching produced by the sources- (relays-) optimal algorithm.

Algorithm 1: Sources-optimal stable marriage matching (SO-SMM)

Input: Preference matrices \mathbb{P}_S and \mathbb{P}_R .

```

1  WHILE (some source  $S$  is unmatched or has not run out of nodes to propose to)
2    Let  $R$  be the first relay on source  $S$ 's list to which  $S$  has not yet proposed;
3    IF relay  $R$  is single
4      Match  $S$  and  $R$  to each other;
5    ELSE
6      IF  $R$  prefers  $S$  to its currently paired to source  $S'$ 
7        Match  $S$  and  $R$  to each other, and set  $S'$  to be free;
8        Return to Step 2 and set  $S = S'$ ;
9      ELSE
10        $R$  rejects  $S$ , and  $S$  remains single;
11     END IF
12   END IF
13 END WHILE

```

Output: Stable matching \mathcal{M} .

4.3 | Properties

The proposed SMM algorithm possesses several properties, which are discussed in the following sections.

4.3.1 | Existence

In Gale et al,²⁴ it has been proved that for any instance of the SMP, there is at least one stable solution.

4.3.2 | Convergence

The SMM algorithm is guaranteed to converge with time-complexity $\mathcal{O}(N^2)$; and upon convergence, the disjoint pairs of sources and relays constitute a stable matching.²⁵ Particularly, in the worst-case scenario of the SO-SMM algorithm, each of the N sources may possibly propose to each of the $N - 2$ relays, with a single proposal made to the last $(N - 1)$ th relay. Thus, the total number of proposals is equal to $N(N - 2) + 1$. By analogy, this is also the case for the RO-SMM algorithm.

4.3.3 | Optimality

Due to the fact that for a stable matching solution resulting from the SO-SMM algorithm there is no other matching (stable or not) where every source has a relay which it strictly prefers to its current paired-to relay, then the SO stable matching solution is weak Pareto-optimal.²⁵ A similar statement can be made for the RO stable matching.

4.3.4 | Uniqueness

If the SMM algorithm produces SO and RO matchings that are identical, then the resulting stable matching is unique. Otherwise, there may be other stable matchings in between, as will be discussed in the following section.

4.3.5 | Truth telling

It should be noted that in the SMM algorithm, the sources/relays may be tempted to be dishonest about their preferences. That is, a source/relay can cheat (and thus may benefit) by reporting false preferences. However, it has been proved that there is no mechanism for the SMM algorithm in which truth telling is a dominant strategy for the sources or relays.³⁹

Moreover, it has been demonstrated that the chance that a player (source or relay) can benefit from being dishonest is extremely limited, especially, if all the other players are honest/truthful.^{40,41} Additionally, it is impossible that every cheating relay/source gets a chance to improve the rank of its partner while no one gets hurt. This is because the best match a relay/source can receive from the SO-SMM (RO-SMM) algorithm is its optimal stable source/relay with respect to its true preference list and others' announced true preference lists. Consequently, when the other players are truthful, almost surely, a given player's best strategy is to tell the truth. This signifies that it is always hard to incentivize some players to falsify their lists when all the other players are honest. Hence, the best strategy for each player is to stick to the SMM algorithm and be honest (ie, truth telling is intrinsically the dominant strategy).^{**} Finally, in the SMM algorithm—which yields the optimal stable outcome for the sources (or relays)—truthful revelation of preference is a dominant strategy for all the sources (or relays).

5 | ALL STABLE MATCHINGS ENUMERATION ALGORITHM

It should be noted that the problem of finding a stable and optimal matching for both source and relay nodes is known to be NP-complete since an instance of the SMP can have exponentially many stable matchings.⁴² Therefore, in this work, it was elected to implement a simpler algorithm, namely, the ASME algorithm to enumerate all stable matchings between the SO and RO matching solutions. On the basis of the determined matching solutions, the solution that maximizes the sources sum-utility (or the relays sum-payment) can be selected or any other matching that may yield a fair solution to both the sources and relays.³⁸

To that end, let the SO stable matching be denoted \mathcal{M}_S , while that of the RO stable matching be \mathcal{M}_R . Thus, the set of all possible stable matchings for any instance of the SMP forms a distributive lattice, with the \mathcal{M}_S and \mathcal{M}_R matchings forming the two extreme ends of the lattice. In turn, the ASME algorithm finds at least one stable matching solution for a given SMP, and the unique matching solution occurs when $\mathcal{M}_S = \mathcal{M}_R$. On the other hand, let \mathcal{M} be a stable matching for an instance of an SMP. Now, for each source in a matching \mathcal{M} that is not the same source in the RO matching (ie, $\mathcal{M}(S) \neq \mathcal{M}_R(S)$), define the successor relay for S with respect to \mathcal{M} as $\mathcal{W}_M(S)$, which is the first relay R on S 's list such that R prefers S to $\mathcal{M}(R)$ following $\mathcal{M}(S)$. Consequently, such relay exists if $\mathcal{M}(S) \neq \mathcal{M}_R(S)$, since $\mathcal{M}_R(S)$ is a valid partner; otherwise, $\mathcal{W}_M(S)$ would not exist (ie, when $\mathcal{M}(S) = \mathcal{M}_R(S)$). So, if the \mathcal{M}_S and \mathcal{M}_R matchings are different, then the main idea behind the ASME algorithm is to find and *expose* all the “rotations” for the SMP in hand.²⁸ To elaborate, the following definitions are stated.

Definition 7. (Rotation)

A rotation in a stable matching \mathcal{M} is an ordered and cyclic sequence of pairs $\pi = \{(S^{(0)}, R^{(0)}), \dots, (S^{(r-1)}, R^{(r-1)})\}$, such that $\mathcal{M}(S^\tau) = R^\tau$ and $\mathcal{W}_M(S^\tau) = R^{\tau+1}$, for all τ and $\tau + 1$ taken modulo r (for $r \geq 2$ and $0 \leq \tau \leq r - 1$), where r is the number of pairs in the rotation.

Definition 8. (Stable Pair)

Given an instance of the SMP, a source-relay pair (S, R) is called a *stable pair* if and only if source S is paired to relay R in some stable matching.

Definition 9. (Rotation Precedence)

Let there be two distinct rotations π and π' . Then, a rotation π is said to *precede* π' if and only if π eliminates a pair (S, R) , and π' moves source S to a relay R' such that source S strictly prefers R to R' .²⁸ Consequently, if π precedes π' , then π' cannot possibly become exposed until π is eliminated.

Definition 10. (Directed Acyclic Graph)

Let \mathcal{G} be a directed acyclic graph, where the nodes of \mathcal{G} are in one-to-one correspondence with a set of rotations. Additionally, for any two nodes π and π' , there is a directed edge from π to π' if and only if rotation π precedes rotation π' . In turn, π precedes π' if and only if π reaches π' by a directed path in \mathcal{G} .²⁸

^{**}This result is equivalent to saying that in a noncooperative game, it is always a Nash equilibrium for all nodes to reveal their true preferences.³⁹

On the basis of the above definitions, to eliminate an exposed rotation from a stable matching \mathcal{M} , then nodes S^τ and $R^{\tau+1}$ must be paired for all S^τ in the rotation (where it should be noted that $\tau + 1$ is taken modulo r); otherwise, the pairs are left unchanged, and hence, the resulting matching is also stable. Generally speaking, every stable matching $\mathcal{M} \neq \mathcal{M}_R$ has at least one exposed rotation, and each stable matching is defined by a set of rotations that must be eliminated to generate it.²⁵

Remark 9. Every stable matching is obtained by starting with the SO and successively (and systematically) eliminating a sequence of exposed rotations until the RO matching is reached.

5.1 | Algorithm description

The operation ASME algorithm is based on the following 3 phases.

Phase 1: In this phase, all the different rotations and stable pairs that appear in all matchings are determined. Additionally, this phase outputs several matchings but not all of them are necessarily stable; however, the matchings found contain all possible stable pairs, as every stable pair appears in at least one of the matchings.²⁸ Moreover, this phase is dependent on the following two functions:

- *Break_Matching:* The *Break_Matching*(\mathcal{M}, S) function is successively used to transform (starting with) the SO matching $\mathcal{M}_0 \triangleq \mathcal{M}_S$ into the RO matching \mathcal{M}_R .⁴³ Specifically, this function breaks the matching of source S and a relay R paired in matching \mathcal{M} under the SMM algorithm. The source S is freed, while the relay will only accept a new proposal from a source it prefers to S . The *Break_Matching*(\mathcal{M}, S) is executed with source S proposing to the relay following R in its list under matching \mathcal{M} , which triggers a series of proposals, rejects and acceptances as per the SMM algorithm. Furthermore, every matching \mathcal{M}' can be obtained via a series of *Break_Matching* executions, starting with the SO matching \mathcal{M}_S . Moreover, if rotation π precedes π' , then phase 1 finds rotation π before π' . Hence, moving to matching \mathcal{M}' occurs after matching \mathcal{M} by the *Break_Matching* function. This function terminates either when some source is rejected by all relays or when relay R receives a proposal from a source S' preferred over S . Consequently, the sequence of proposals is completely determined as the next proposal is always made by the free source S . As a result, no source gets a partner relay more preferable in its list, and no relay gets a partner source lower in its list.
- *Pause_Break_Matching:* The *Pause_Break_Matching* function serves the purpose of *pausing* the execution of the *Break_Matching* function at certain points when the next stable matching in the sequence is output. To be specific, this function pauses when the proposal sequence generated by going from matching \mathcal{M}_0 to \mathcal{M}_R outputs a rotation. At each pause, the rotation is output and the next stable matching in the sequence is generated by making the changes designated by the rotation. Therefore, such function allows the transformation from matching \mathcal{M}_0 to \mathcal{M}_R by exposing rotations and running a sequence of proposals, acceptance and rejections as per the *Break_Matching* operation.

Phase 2: This phase is concerned with creating the directed acyclic graph \mathcal{G} , which contains all rotations as its nodes, whereas the edges define the precedence of the rotations. Specifically, graph \mathcal{G} can be constructed by processing each source S 's list, starting from its partner in \mathcal{M}_0 until \mathcal{M}_R .

Phase 3: In this phase, a tree \mathcal{T} showing all stable matchings and their exposed rotations is created from graph \mathcal{G} . This tree is used to instruct the order in which rotations must be eliminated to find each stable matching solution. Particularly, in this tree, every node is a stable matching, and every edge is a rotation that must be eliminated to get to that matching (ie, there is a one-to-one correspondence between the nodes in \mathcal{T} and the set of all stable matchings).^{††} Hence, the stable matching corresponding to a node is determined by traversing the path from the root to that node, with moves made according to the rotations on the path. At the end of this phase, the list of all stable matching solutions \mathbb{M} is output.

^{††} Each node has a larger label than any of its predecessors.

The ASME algorithm is outlined in Algorithm 2, which is followed by the *Break_Matching* and *Pause_Break_Matching* functions.

Algorithm 2: All stable marriage enumeration

Input: Preference matrices \mathbb{P}_S and \mathbb{P}_R .

Phase 1:

- 1 Determine the SO matching and set $\mathcal{M}_0 = \mathcal{M}_S$, and also determine the RO matching \mathcal{M}_R .
- 2 Set $i = 1$ (all relays are unmarked at this point).
- 3 IF $\mathcal{M}_i = \mathcal{M}_R$
- 4 Stop, and output all stable matching solutions;
- 5 ELSE
- 6 Unmark all relays, and let S be the first source whose partner relay in \mathcal{M}_i is different from that in \mathcal{M}_R ;
- 7 Let $\mathcal{M} = \mathcal{M}_i$, mark relay R the partner of source S , and perform *Break_Matching*(\mathcal{M}, S) with the following rules;
- 8 (a) During the *Break_Matching*(\mathcal{M}, S), mark any unmarked relay that accepts a proposal;
- 9 (b) Go to *Pause_Break_Matching*(\mathcal{M}, S) when a marked relay R' (which could be R) receives a proposal from a source S' that it prefers to its current partner in \mathcal{M}_i ;
- 10 END IF

Phase 2: To generate graph \mathcal{G} , follow the next two rules:

Rule 1:

- 11 Let $\mathcal{R}(S) = \{R^{(0)}, R^{(1)}, \dots, R^{(r)}\}$ be the set of relays in descending order of preference by source S , such that for each $0 \leq i \leq r-1$, $(S, R^{(i)})$;
- 12 For $0 \leq i \leq r-1$, let π_i be the rotation containing the pair $(S, R^{(i)})$, and let $\Pi(S)$ be the set of these rotations;
- 13 For i from 0 to $r-2$, the directed cyclic graph \mathcal{G} contains an edge from π_i to π_{i+1} .

Rule 2:

- 14 IF (S, R) is a nonstable pair eliminated by a rotation π
- 15 S prefers R to any other relay R' in any other pair (S, R') eliminated by π ;
- 16 END IF
- 17 IF there are relays $R^{(i)}$ and $R^{(i+1)}$ in $\mathcal{R}(S)$ such that S prefers $R^{(i)}$ to R , and S prefers R to $R^{(i+1)}$
- 18 \mathcal{G} contains an edge from π to π_i ;
- 19 END IF

Phase 3: To build tree \mathcal{T} , start at the root and expand any unexpanded node u as follows:

- 20 Let e be the last edge on the path from the root to node u , and let $\varpi(u)$ be the rotations along the path from the root to that node in \mathcal{T} ;
- 21 Let $\varpi(u)'$ be the set of maximal rotations when all the rotations in $\varpi(u)$ are eliminated from \mathcal{G} , and let $\varpi(u)''$ be the rotations in $\varpi(u)'$ with label that is larger than that on edge e ;
- 22 Node u is expanded by adding $|\varpi(u)''|$ edges out of node u with a distinct rotation $\varpi(u)''$;

Output: Set of all stable matching solutions \mathbb{M} .

Function 1: *Break_Matching*(\mathcal{M}, S)

Input: Source S to break the pairing with relay R under matching \mathcal{M} .

- 1 Set source S free.
- 2 Run Algorithm 1.

Output: Some stable matching \mathcal{M}_i .

Function 2: Pause_Break_Matching

```

1 Let  $Q$  be the set containing  $R'$  and all the relays that became marked since the last time  $R'$  was marked;
2 Let the next matching  $\mathcal{M}_{i+1}$  be the matching in which relay  $R'$  is paired with source  $S'$ , and all other relays in  $Q$  are paired with
   their partners in the current status of  $Break\_Matching(\mathcal{M}, S)$ , and all other relays are paired to their partners in  $\mathcal{M}_i$ ;
3 Output rotation  $\pi_i$  and matching  $\mathcal{M}_{i+1}$ ;
4 Set  $i = i + 1$  and unmark all relays in  $Q$ ;
5 IF  $R = R'$ 
6   Relay  $R'$  accepts the proposal from  $S'$ 
7   Return to Step 3 in Algorithm 2 and end  $Break\_Matching(\mathcal{M}, S)$ ;
8 ELSE
9   Relay  $R'$  compares  $S'$  to its current partner in  $\mathcal{M}$ ;
10  IF relay  $R'$  rejects the proposal from  $S'$ 
11    Mark  $R'$ , return to Step 7 in Algorithm 2, and continue  $Break\_Matching(\mathcal{M}, S)$ ;
12  ELSE
13    Return to Step 7 in Algorithm 2, and continue  $Break\_Matching(\mathcal{M}, S)$ ;
14  END IF
15 END IF

```

5.2 | Properties

5.2.1 | Convergence

The ASME algorithm is guaranteed to converge, since that if the stable matching solution is unique (ie, $\mathcal{M}_S = \mathcal{M}_R$), then it terminates at step 4 immediately after executing the SMM algorithm twice (as per step 1). However, if there are multiple stable matching solutions, then the algorithm will output one matching solution after the other according to the precedence relationship between the different rotations, until the RO matching is reached.

5.2.2 | Complexity

It should be noted that phase 1 has time-complexity of $\mathcal{O}(N^2)$. Additionally, all rotations can be found in $\mathcal{O}(N^2)$ time-complexity. Moreover, the construction of \mathcal{G} in phase 2 requires time-complexity of $\mathcal{O}(N^2)$ as the graph \mathcal{G} contain only one copy of any edge. Furthermore, the complexity of generating tree \mathcal{T} in phase 3 is N for every stable matching solution there is in \mathbb{M} , and thus yields $\mathcal{O}(N |\mathbb{M}|)$, where $|\cdot|$ indicates the cardinality of the parameter set.^{‡‡} It has been shown in Gusfield²⁸ that the overall complexity of the ASME algorithm is $\mathcal{O}(N^2 + N |\mathbb{M}|)$.

6 | CENTRALIZED JOINT POWER ALLOCATION AND NODE PAIRING

In this section, the centralized joint power allocation and node pairing optimization problems are formulated. Particularly, the optimization problems are formulated according to the following criteria:

- Sum-utility maximization (SUM): Pair every two nodes such that network sum-utility is maximized.
- Sum-payment maximization (SPM): Every two nodes are paired so as to maximize sum-payment of all network nodes.

To this end, a binary decision variable must first be defined. Particularly, let \mathcal{I}_{S_i, R_j} be a binary decision variable that takes the value of 1 if relay R_j (for $j \neq i$) is paired with source S_i , and 0 otherwise. Moreover, the utility function of each source node S_i must be redefined as follows:

$$\mathcal{U}_{S_i}(\mathcal{I}_{S_i}, \alpha_i) = \Delta \mathcal{R}_{S_i}(\mathcal{I}_{S_i}, \alpha_i) - \mathcal{P}_{S_i}(\mathcal{I}_{S_i}, \alpha_i), \quad (16)$$

^{‡‡}It is important to emphasize that an instance of the SMP can have an exponential number of stable matching solutions.⁴²

where \mathcal{I}_{S_i} and α_i are given by $\mathcal{I}_{S_i} = [\mathcal{I}_{S_i,R_1}, \dots, \mathcal{I}_{S_i,R_{i-1}}, \mathcal{I}_{S_i,R_{i+1}}, \dots, \mathcal{I}_{S_i,R_N}]$ and $\alpha_i = [\alpha_{i,1}, \dots, \alpha_{i,i-1}, \alpha_{i,i+1}, \dots, \alpha_{i,N}]$, respectively. Additionally, $\Delta\mathcal{R}_{S_i}(\mathcal{I}_{S_i}, \alpha_i)$ and $\mathcal{P}_{S_i}(\mathcal{I}_{S_i}, \alpha_i)$ are expressed as

$$\Delta\mathcal{R}_{S_i}(\mathcal{I}_{S_i}, \alpha_i) = \frac{1}{N+1} \log_2 \left(1 + \sum_{j=1, j \neq i}^N \mathcal{I}_{S_i, R_j} \cdot \frac{P_{S_i, R_j}(\alpha_{i,j}) \Omega_{i,j}(\alpha_{i,j})}{P_{S_i, R_j}(\alpha_{i,j}) + Y_{i,j}(\alpha_{i,j})} \right) \quad (17)$$

and

$$\mathcal{P}_{S_i}(\mathcal{I}_{S_i}, \alpha_i) = \xi_R \sum_{j=1, j \neq i}^N \mathcal{I}_{S_i, R_j} \cdot \ln(1 + \mu_R P_{S_i, R_j}(\alpha_{i,j}))^{\alpha_{i,j}}, \quad (18)$$

respectively. The centralized sum-utility maximizing (**C-SUM**) and sum-payment maximizing (**C-SPM**) joint power allocation and node pairing problems are formulated as mixed integer nonlinear programming problems, as given by

$$\begin{aligned} \max \quad & \sum_{i=1}^N f_{S_i}(\mathcal{I}_{S_i}, \alpha_i) \\ \text{s.t.} \quad & \sum_{j=1, j \neq i}^N \mathcal{I}_{S_i, R_j} = 1, \quad \forall i \in \{1, 2, \dots, N\}, \end{aligned} \quad (19a)$$

$$\sum_{i=1, i \neq j}^N \mathcal{I}_{S_i, R_j} = 1, \quad \forall j \in \{1, 2, \dots, N\}, \quad (19b)$$

$$0 \leq \alpha_{i,j} \leq \mathcal{I}_{S_i, R_j}, \quad \forall i, j \in \{1, 2, \dots, N\} \text{ for } i \neq j, \quad (19c)$$

$$\mathcal{I}_{S_i, R_j} \in \{0, 1\}, \quad \forall i, j \in \{1, 2, \dots, N\} \text{ for } i \neq j, \quad (19d)$$

where

$$f_{S_i}(\mathcal{I}_{S_i}, \alpha_i) = \begin{cases} \mathcal{U}_{S_i}(\mathcal{I}_{S_i}, \alpha_i), & \text{for C-SUM} \\ \mathcal{P}_{S_i}(\mathcal{I}_{S_i}, \alpha_i), & \text{for C-SPM.} \end{cases} \quad (20)$$

Now, in the above optimization problem, the first constraint ensures that each source S_i is paired with only one relay R_j , while the second constraint ensures each relay is paired with only one source (ie, one-to-one matching). The third constraint enforces that if source S_i is paired with relay R_j (ie, $\mathcal{I}_{S_i, R_j} = 1$), then the PS ratio must satisfy $0 < \alpha_{i,j} \leq 1$; otherwise, $\alpha_{i,j} = 0$. The last constraint defines the values the binary decision variables take.

Remark 10. The formulated **C-SUM** and **C-SPM** problems are network sum-utility and network sum-payment optimal, respectively. Additionally, both problems are NP-hard and thus are difficult to solve accurately because of their excessive computational complexity.^{44,45}

Remark 11. Obtaining analytical solutions to the **C-SUM** and **C-SPM** problems is extremely complex and mathematically intractable and thus is beyond the scope of this paper. Hence, such problems can be solved using global optimization software packages.

Remark 12. Neither of the formulated optimization problems necessarily ensure that the resulting node pairings are stable.

7 | SIMULATION RESULTS

In this section, the proposed SMM and ASME algorithms are evaluated and compared with the centralized power allocation and node pairing optimization problems in terms of the network sum-utility and sum-payment. The network nodes are located as illustrated in Figure 3, where there are $N = 8$ network (source/relay) nodes. Furthermore, the channel variance between any two nodes is given by $\sigma^2 = d^{-\nu}$, where d and ν are the inter-node distance and path-loss exponent, respectively. Moreover, the simulations are averaged over 10^5 independent instances of randomly generated channel

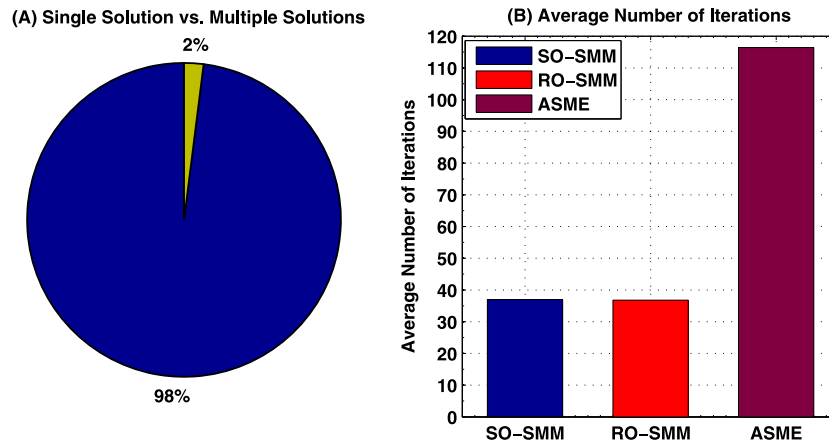


FIGURE 4 (A) Single solution vs multiple solutions and (B) average number of iterations of the SMM and ASME algorithms

requires an average of 116 iterations to find all stable matching solutions (if any exist). Figure 4 indicates that for the specified network topology, multiple stable solutions are rare; however, much higher time-complexity is required to find such solutions if they exist. More importantly, if the **ASME** is executed in a network instance where there is a unique solution, then its complexity would be twice that of any of the **SMM** algorithms. This is because the **ASME** algorithm executes the **SO-SMM** and **RO-SMM** algorithms to determine whether the SO matching is identical to the RO matching, as given in Algorithm 2.

In Figure 5A, the rate improvement of each network node is presented. Particularly, one can see that source/relay nodes 3 and 4 achieve relatively higher rate improvement than the other network nodes, under the different **SMM** and **ASME** algorithms. This is attributed to the location of these two nodes, as they are positioned approximately in the center of the network, which implies less path-loss and channel noise to the neighboring nodes and destination. That is to say, the closer the position of a node to the other nodes and the destination is, the lesser the loss (and thus the higher the rate improvement). On the contrary, nodes 5 and 8 achieve the lowest rate improvement among the network nodes, as they are relatively farther in the network from the other nodes and the destination. In Figure 5B, the average payment each node receives from the other paired-to nodes is demonstrated. Specifically, it is evident that nodes 3 and 4 receive the highest payments, and again, this is attributed to their location as they are frequently paired with the closer nodes. On the other hand, nodes 5 and 8 receive the lowest payment as they are farther from the destination, and the payment they receive when paired with the closer-to-destination nodes is low. Finally, Figure 5C illustrates the utility achieved by each node, where it is evident that nodes 3 and 4 achieve the highest utility, while nodes 5 and 8 achieve the lowest. This is in agreement with the rate improvement results given in Figure 5A, since they are more dominant than the payment values.^{¶¶} Generally speaking, the network nodes achieve higher rate improvement under the **SO-SMM** algorithm than its **RO-SMM** counterpart, but vice versa in terms of the payment. This is because the **SO-SMM** algorithm is SO as it aims at increasing the rate improvement, while the **RO-SMM** algorithm is RO in the sense that it pairs the nodes according to the payments they receive. Finally, the **O-ASME-SU** and **O-ASME-SP** algorithms are superior to their **SO-SMM** and **RO-SMM** counterparts, as they enumerate all possible solutions (if any exist) and select the one that yields the highest sum-utility or sum-payment, respectively.

Figure 6 illustrates the average source nodes pairings under the **SO-SMM** algorithm. One can see from Figure 6A that node S_1 is paired with node S_3 about 54% of the time, while it is paired with nodes S_7 and S_8 the least. This is also confirmed by noting that node S_3 is paired with node S_1 about 47% of the time (see Figure 6B). A similar observation can be made in Figure 6C, where node S_5 is paired with node S_6 about 44% of the time, while node S_6 is paired with node S_5 about 45% of the time (see Figure 6D). Generally speaking, each node aims to be paired with a node that is closer to the destination, and also, the closer the nodes to each other, the higher the average node pairing. Similar observations can be made to the proposing relays under the **RO-SMM** algorithm (see Figure 7).^{||}

^{¶¶}Recall that Utility = Rate Improvement – Payment.

^{||}Similar results have been observed for nodes $S_2(R_2)$, $S_4(R_4)$, $S_7(R_7)$, and $S_8(R_8)$, but are eliminated because of space limitation. Also, the results for node pairings under the **ASME** algorithms are similar to those of the **SMM** algorithms and thus are not presented.

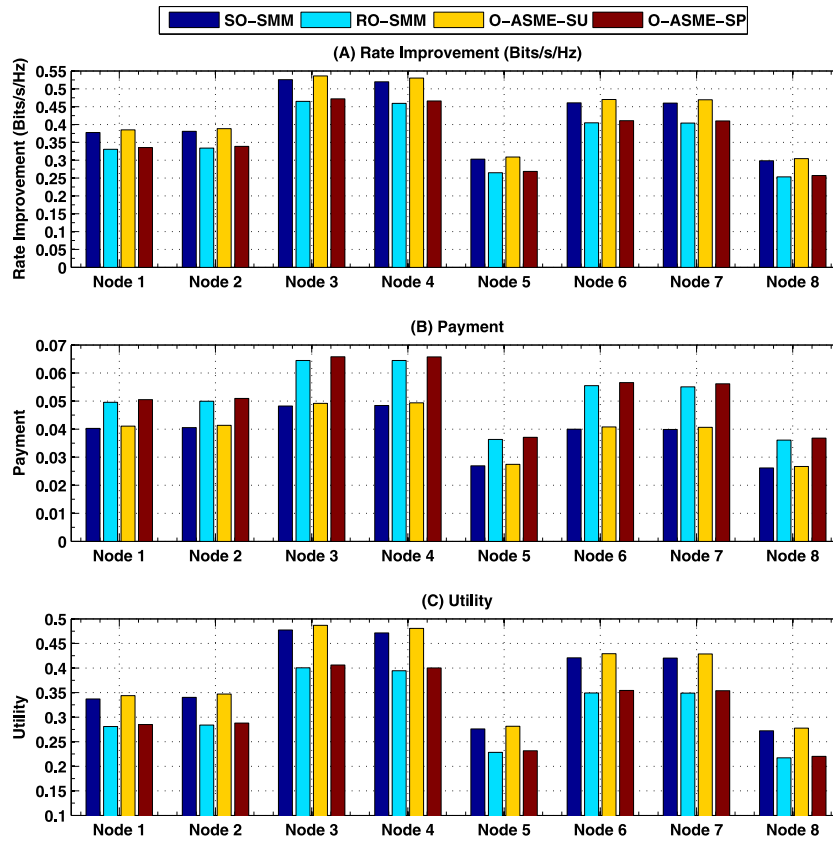


FIGURE 5 (A) Rate improvement (Bits/s/Hz), (B) payment, and (C) utility

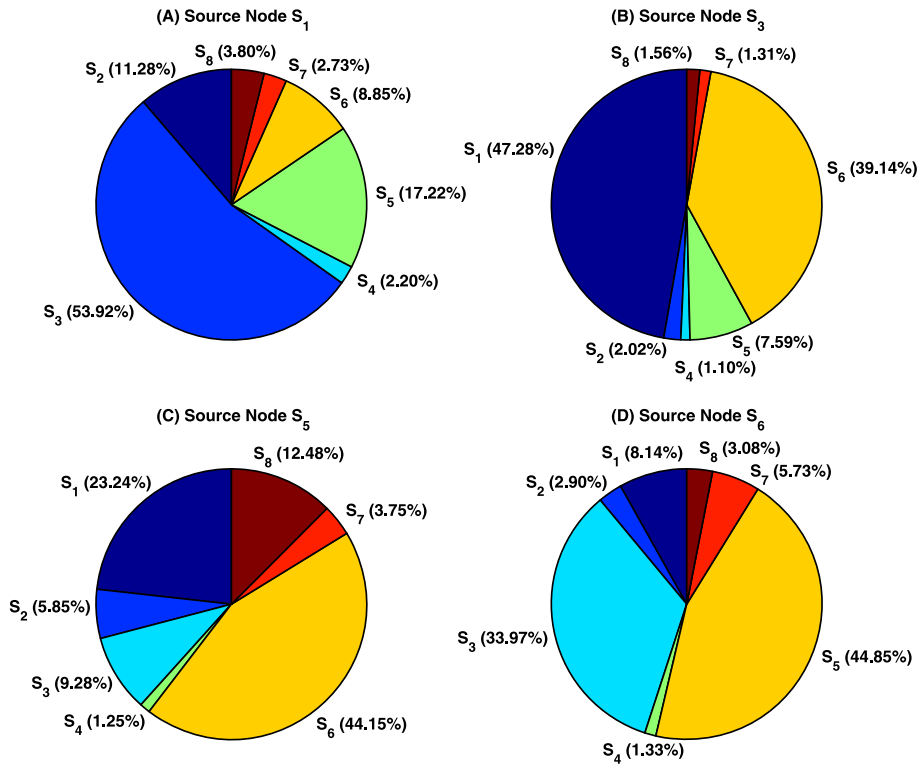


FIGURE 6 Average source nodes' pairings for (A) source node S₁, (B) source node S₃, (C) source node S₅, and (D) source node S₆—SO-SMM algorithm

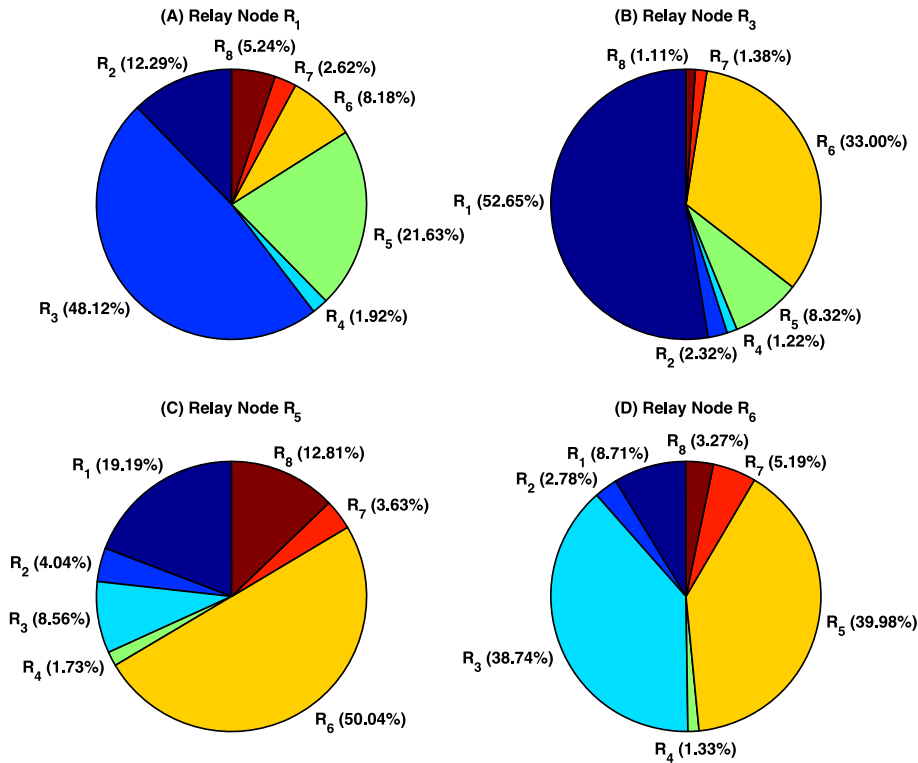


FIGURE 7 Average relay nodes' pairings for (A) relay node R_1 , (B) relay node R_3 , (C) relay node R_5 , and (D) relay node R_6 —RO-SMM algorithm

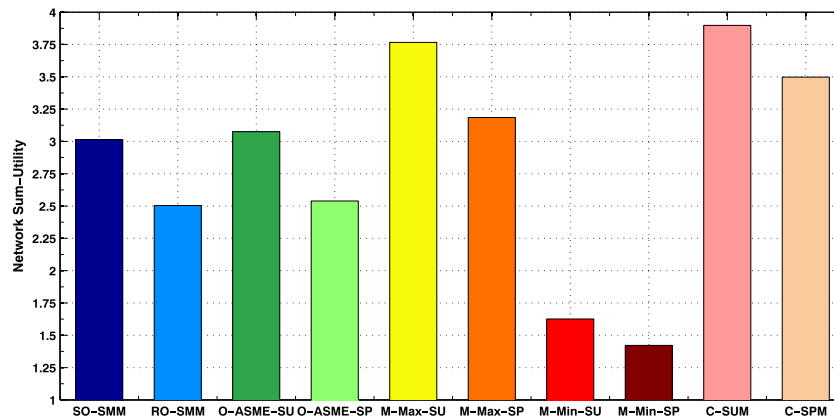


FIGURE 8 Comparison of network sum-utility

Figure 8 illustrates the network sum-utility of the different schemes. Specifically, it can be seen that the **O-ASME-SU** outperforms the **SO-SMM** algorithm. However, it should be noted that the difference in sum-utility of the **SO-SMM** algorithm in comparison with the **O-ASME-SU** is marginal, since the occurrence of multiple solutions is rather rare (as demonstrated in Figure 4). It is also clear that the **RO-SMM** algorithm yields a lower network sum-utility than its **SO-SMM**. This is because it matches the relays according to their payments rather than their utilities. This is also observed in the **O-ASME-SU** and **O-ASME-SP** algorithms. The **M-Max-SU** scheme is superior to its **M-Min-SU** counterpart, since the former scheme matches nodes such that their sum-utility is maximized, while the latter scheme maximizes the minimum sum-utility and thus trades off SUM for fairness. A similar observation can be made to the **M-Max-SP** and **M-Min-SP** schemes, which yield lower sum-utility as they pair nodes according to their sum-payment. On the other hand, and as would be expected, the **C-SUM** scheme yields the best sum-utility performance and is superior to the **C-SPM** scheme. Lastly, it should be noted that all schemes—other than the **SMM** and **ASME** algorithms—do not necessarily result in stable node matchings.

Figure 9 presents a comparison of the network sum-payment. In particular, the **RO-SMM** algorithm yields comparable sum-payment to that of the **O-ASME-SP**. More importantly, the **RO-SMM** and **O-ASME-SP** algorithms yield higher network sum-payment than their **SO-SMM** and **O-ASME-SU** counterparts, as they pair nodes according to the payments they receive. One can also see that the **M-Max-SP** scheme is superior to the **M-Min-SP**. The **C-SPM** scheme yields the highest sum-payment value, as would be expected.

The network sum-rate improvement under the different node matching schemes is compared in Figure 10. Similar observations to those made in Figure 8 can be seen in Figure 10. This is because the network sum-utility is equivalent to the network sum-rate improvement minus the network sum-payment, where network sum-rate improvement value is more dominant (in terms of magnitude) than the sum-payment.

In the following simulation results, the truth-telling property of the **SMM** algorithms is verified in terms of the network sum-utility and sum-payment. Particularly, the following cases are considered:

Case 1: **SO-SMM** with cheating sources and truthful relays.

Case 2: **SO-SMM** with truthful sources and cheating relays.

Case 3: **RO-SMM** with cheating sources and truthful relays.

Case 4: **RO-SMM** with truthful sources and cheating relays.

The cheating behavior is assumed by the odd-numbered nodes (ie, $S_1(R_1)$, $S_3(R_3)$, $S_5(R_5)$, and $S_7(R_7)$), while the even-numbered nodes ($S_2(R_2)$, $S_4(R_4)$, $S_6(R_6)$, and $S_8(R_8)$) are assumed to be truthful. Specifically, the cheating behavior of a source S_i is modeled by falsifying its PS ratio $\tilde{\alpha}_{ij}$ from relay R_j . Two scenarios are considered, whereby the cheating source can under-demand or over-demand its PS ratio, as given by

$$\tilde{\alpha}_{ij} = \begin{cases} U \left[0, \alpha_{ij}^* \right], & \text{under-demand,} \\ U \left[\alpha_{ij}^*, 1 \right], & \text{over-demand,} \end{cases} \quad (21)$$

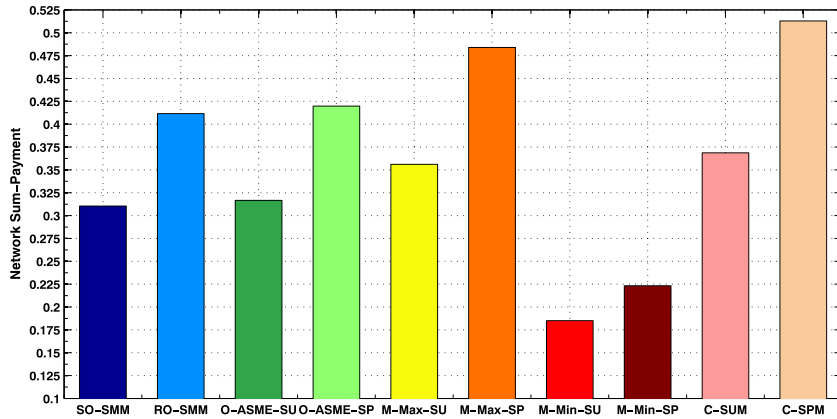


FIGURE 9 Comparison of network sum-payment

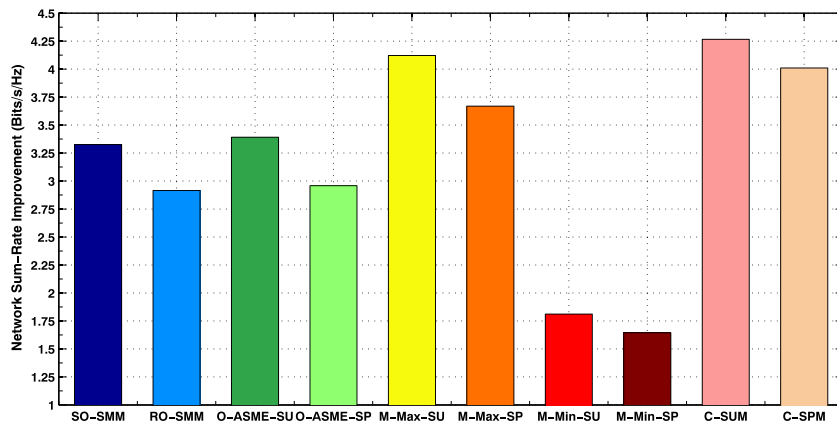


FIGURE 10 Comparison of network sum-rate improvement

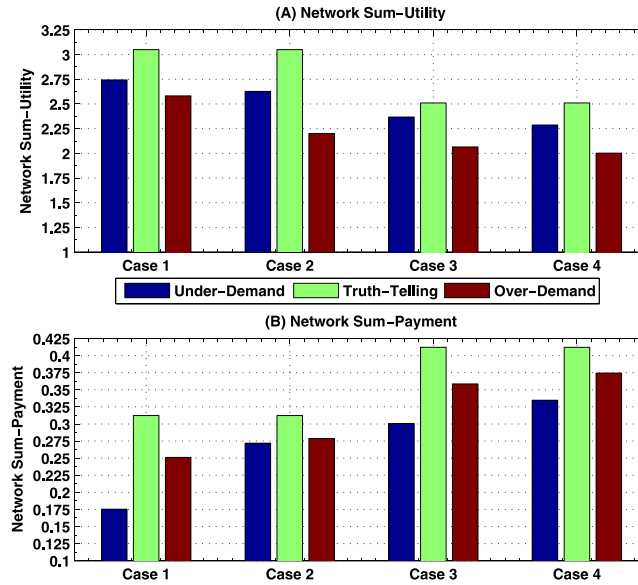


FIGURE 11 (A) Network sum-utility and (B) network sum-payment

where $U[a, b]$ denotes a uniformly distributed value on the interval $[a, b]$. Similarly, the cheating behavior by a relay R_j is modeled by falsifying the payment their demands from source S_i as $\mathcal{P}_{S_i, R_j} \left(P_{S_i, R_j} \left(\tilde{\alpha}_{i,j}^* \right) \right)$, where $\tilde{\alpha}_{i,j}^*$ is given by (21).

Figure 11 shows the network sum-utility and network sum-payment, respectively, where the cheating behavior (under-demand or over-demand) is compared to the scenario of truth telling (ie, all source and relay nodes are honest). It is clear that truth telling yields the highest network sum-rate and sum-payment, as opposed to the cases when some nodes cheat by falsifying (under- or over-demanding) their PS ratios. For instance, under case 1, when the cheating sources under-demand their PS ratios (ie, $\tilde{\alpha}_{i,j} < \alpha_{i,j}^*$), this increases the allocated harvested energy (as per (10)), but at the same time decreases the resulting instantaneous SNR, the achievable rate improvement, and the utility. On the other hand, when a cheating source over-demands its PS ratio, it would still get a lower SNR value and thus a lower utility when compared to the case of the truth telling. A similar justification can be applied to the other cases for the network sum-utility and sum-payment results. This confirms that the best strategy for all source and relay nodes is to be honest, and there should be no incentive for any of the nodes to falsify their demands. That is, since each node knows its own preferences and the matching procedure of the **SO-SMM** or **RO-SMM** algorithm, then such algorithm encourages the nodes to reveal their true preferences. In turn, it is a dominant strategy for each node to follow the **SMM** algorithms and truthfully report its preferences.

8 | DISCUSSION

In this section, a few relevant strategic issues pertaining to the stable marriage algorithms are discussed.

8.1 | Optimal stable matchings

In this work, it has been shown that the **SO-SMM** algorithm yields a stable matching that is SO (and simultaneously relays-pessimal). Similarly, if the roles of the source and relay nodes are exchanged, the resulting stable matching obtained via the **RO-SMM** algorithm is RO but sources-pessimal. This entails finding an appropriate criterion for stable matching optimality. Several optimality criteria have been discussed in Iwama et al³⁸ to maximize the average satisfaction of all players, such as the regret cost, egalitarian cost, and sex-equalness cost, which yield minimum regret, minimum egalitarian, and sex-equal SMPs, respectively. For the first two problems, polynomial-time algorithms have been proposed,^{28,48} while the last problem is known to be NP-hard,⁴⁹ but for which approximation algorithms exist.²⁹ However, in our work, the novel **ASME** algorithm has been devised to enumerate all possible stable matching solutions and then select the one that maximize the network sum-utility or sum-payment.

8.2 | Optimal cheating in the stable marriage problem

The issue of cheating in the preferences (by manipulating the PS ratio) has been considered and shown not to be beneficial for the cheating source/relay nodes. However, there are several strategies in which sources (or relays) can cheat and force the resulting matching towards their optimal matching. For instance, each relay node follows the **RO-SMM** algorithm and submits its true preference lists, but it declares sources that rank below its relay-optimal partner as unacceptable.⁵⁰ However, this can be eliminated by forcing each node to expose their complete preference list during the execution of the **SMM** algorithm. In one study,⁴⁰ the authors developed a coalition strategy with deterministic and randomized cheating strategies to determine a nonempty set of cheating nodes can get better partners with the other honest nodes not becoming worse off. However, it was shown that it is impossible for every cheating node to improve its utility/payment while no other node is hurt. That is, a cheating node must be willing to take some risk and end up with a lower utility/payment and thus is incentive-incompatible.

8.3 | Stable marriage problem with incomplete lists and ties

It should be noted that the case of preference lists with ties never occurs in our network model, since the channel coefficients are random, and thus the probability of two PS ratio values (and hence the instantaneous SNR, achievable rates and payments) being equal is zero. On the other hand, the preference lists defined in this work are complete, since each network node populates its preference list with descendingly ordered $N - 1$ nodes, as stated in Section 4. However, there may be other network models where each node has specific requirements that lead to their preference lists being incomplete and only accepts a subset of the other $N - 1$ nodes (ie, not all the other $N - 1$ nodes are included in the preference list).⁵¹ This corresponds to the case of unacceptable partners; examples of that include, but-not-limited to, a node that yields a rate improvement that does not meet a target minimum value or a payment value that is too low or too high. Fortunately, a polynomial-time algorithm has been devised by Gale et al,⁵² which determines whether a stable matching exists, and if so, it finds one. Although this case is interesting, it is not considered in this work and thus will be deferred to future work.

9 | CONCLUSIONS

In this paper, the problem of stable source-relay matching in multiuser AF ad hoc wireless networks has been studied to facilitate distributed SWIPT. To that end, a distributed polynomial-time complexity SMM algorithm has been proposed to pair each source node with a relaying node such that its achievable rate is improved in return for some payment made to the relaying node. The source and relaying nodes are matched with each other on the basis of optimal PS ratios so as to maximize their utilities or payments while achieving network stability. Moreover, the proposed SMM algorithm has been shown to intrinsically enforce truth telling and thus suppress any potential cheating behavior. Additionally, an algorithm for the enumeration of all possible stable matchings has been devised to determine the best matching to the source and relaying nodes. The proposed algorithms have been compared with other matching schemes as well as centralized power allocation and node pairing problems, where it has been shown that they yield closely comparable sum-utility and sum-payment performance with the added merits of low complexity and network stability. Finally, light has been shed on some strategic issues related to the proposed stable matching algorithms.

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REFERENCES

1. Ulukus S, Yener A, Erkip E, et al. Energy harvesting wireless communications: a review of recent advances. *IEEE J Sel Areas Commun.* 2015;33(3):360-381.
2. Ku ML, Li W, Chen Y, Liu KJR. Advances in energy harvesting communications: past, present and future challenges. *IEEE Commun Surv Tutor.* 2016;18(2):1384-1412.
3. Varshney L. Transporting information and energy simultaneously. *Proc IEEE Int Symp Inf Theory (ISIT)*. 2008:1612-1616.
4. Zhou X, Zhang R, Ho CK. Wireless information and power transfer: architecture design and rate-energy tradeoff. *IEEE Trans Commun.* 2013;61(11):4754-4767.
5. Krikidis I, Timotheou S, Nikolaou S, Zheng G, Ng DWK, Schober R. Simultaneous wireless information and power transfer in modern communication systems. *IEEE Commun Mag.* 2014;52(11):104-110.

6. Nasir AA, Zhou X, Durrani S, Kennedy RA. Relaying protocols for wireless energy harvesting and information processing. *IEEE Trans Wireless Commun.* 2013;12(7):3622-3636.
7. Chen Z, Xia B, Liu H. Wireless information and power transfer in two-way amplify-and-forward relaying channels. *Proc IEEE Global Conf Signal Inf Process (GlobalSIP)*. 2014:167-172.
8. Chen H, Jiang Y, Ma Y, Vucetic B. Distributed power splitting for swipt in relay interference channels using game theory. *IEEE Trans Wireless Commun.* 2015;14(1):410-420.
9. Yan J, Zhang C, Gao Z. Distributed relay selection protocols for simultaneous wireless information and power transfer. *Proc IEEE Int Symp Pers, Indoor, Mobile Radio Commun (PIMRC)*. 2014:474-479.
10. Butt MM, Nasir A, Mohamed A, Guizani M. Trading wireless information and power transfer: relay selection to minimize the outage probability. *Proc IEEE Global Conf Signal Inf Process (GlobalSIP)*. 2014:253-257.
11. Yin S, Qu Z, Zhang L. Wireless information and power transfer in cooperative communications with power splitting. *Proc IEEE Global Commun Conf (GLOBECOM)*. 2015:1-6.
12. Liu K.-H.. Outage-optimal relay selection for energy-harvesting relays based on power splitting. *Proc IEEE Int Conf Wireless Commun Signal Process (WCSP)*. 2015:1-6.
13. Michalopoulos DS, Suraweera HA, Schober R. Relay selection for simultaneous information transmission and wireless energy transfer: a tradeoff perspective. *IEEE J Sel Areas Commun.* 2015;33(8):1578-1594.
14. Liu Y. Wireless information and power transfer for multirelay-assisted cooperative communication. *IEEE Commun Lett.* 2016;20(4):784-787.
15. Chu Z, Johnston M, Goff SL. SWIPT for wireless cooperative networks. *IET Electron Lett.* 2015;51(6):536-538.
16. Ding Z, Perlaza SM, Esnaola I, Poor HV. Simultaneous information and power transfer in wireless cooperative networks. *Proc Int ICST Conf Commun Networking China (CHINACOM)*. 2013:252-55.
17. Chen Z, Xu P, Ding Z, Dai X. Cooperative transmission in simultaneous wireless information and power transfer networks. *IEEE Trans Veh Technol.* 2016;65(10):8710-8715.
18. Baidas MW, Afghah MM. Energy-efficient partner selection in cooperative wireless networks: a matching-theoretic approach. *Int J Commun Syst (IJCS)*. 2016;29(8):1451-1470.
19. Baidas MW, Afghah MM. A matching-theoretic approach to energy-efficient partner selection in wireless networks. *Proc IEEE Int Wireless Commun Mobile Comput (IWCMC)*. 2015:1260-1265.
20. Namvar N, Afghah F. Spectrum sharing in cooperative cognitive radio networks: a matching-game framework. *Proc Annual Conf Inf Sci Syst (CISS)*. 2015:1-5.
21. Namvar N, Saad W, Maham B, Valentin S. A context-aware matching game for user association in wireless small cell networks. *Proc IEEE Int Conf Acoust, Speech Signal Process (ICASSP)*. 2014:439-443.
22. Chen M, Li F, Wang J. A game theoretical approach of network selection algorithm in heterogeneous wireless networks. *Proc IET Int Commun Conf Wireless Mobile Comput (CCWMC)*. 2011:148-153.
23. Gu Y, Saad W, Bennis M, Debbah M, Han Z. Matching theory for future wireless networks: fundamentals and applications. *IEEE Commun Mag.* 2015;53(5):52-59.
24. Gale D, Shapley LS. College admissions and the stability of marriage. *Am Math Mon.* 1962;69(1):9-15.
25. Gusfield D, Irving RW. *The Stable Marriage Problem: Structure and Algorithms*. Cambridge, MA: MIT Press; 1989.
26. Tan HX, Seah WKG. Limiting control overheads based on linked stability of improved performance. *Proc 3rd Int Conf Wired/Wireless Internet Commun.* 2005:258-268.
27. Xu Y, Wang W. Topology stability analysis and its application in hierarchical mobile ad hoc networks. *IEEE Trans Veh Technol.* 2009;86(9):1546-1560.
28. Gusfield D. Three fast algorithms for four problems in stable marriage. *SIAM J Comput.* 1987;16(1):111-128.
29. Iwama K, Miyazaki S, Yanagisawa H. Approximation algorithms for the sex-equal stable marriage problem. *ACM Trans Algorithms.* 2010;7(1):2-17.
30. Liu KJR, Sadek AK, Su W, Kwasinski A. *Cooperative Communications and Networking*. New York: Cambridge University Press; 2008.
31. Baidas MW, MacKenzie AB. Many-to-many space-time network coding for amplify-and-forward cooperative networks: node selection and performance analysis. *EURASIP J Wireless Commun Networking*. 2014:1-17.
32. Baidas MW, MacKenzie AB. An auction mechanism for power allocation in multi-source multi-relay cooperative wireless networks. *IEEE Transactions on Wireless Communications*. 2012;11(9):3250-3260.
33. Boyd S, Vandenberghe L. *Convex Optimization*. New York, NY, USA: Cambridge University Press; 2004.
34. Floudas CA, Pardalos PMM. *Encyclopedia of Optimization*. 2nd ed. New York, NY, USA: Springer; 2009.
35. Baidas MW, MacKenzie AB. Auction-based power allocation for many-to-one cooperative wireless networks. *Proc IEEE Int Wireless Commun Mobile Comput (IWCMC) Conf*. 2011:1677-1682.
36. Wang B, Han Z, Liu KJR. Distributed relay selection and power control for multiuser cooperative communication networks using Stackelberg game. *IEEE Trans Mobile Comput.* 2009;8(7):975-990.
37. Kahng H-K. *Information Networking: Networking Technologies for Broadband and Mobile Networks*. New York, NY, USA: Springer; 2004.
38. Iwama K, Miyazaki S. A survey of the stable marriage problem and its variants. *Proc Int Conf Inf Educ Res Knowledge-Circulating Soc.* 2008:131-136.

39. Roth AE. The economics of matching: stability and incentives. *Math Oper Res.* 1982;7(4):617-628.
40. Huang C-C. How hard is it to cheat in the gale-shapley stable matching algorithm? Tech. Rep. TR2005-565, Dartmouth College, Department of Computer Science; 2005.
41. Huang C.-C. Cheating by men in the Gale-Shapley stable matching algorithm. *Lect Notes Comput Sci - Algorithms (Springer).* 2006;4168:418-431.
42. Irving RW, Leather P. The complexity of counting stable marriages. *SIAM J Comput.* 1986;15(3):655-667.
43. McVitie DG, Wilson LB. The stable marriage problem. *Commun ACM.* 1971;14(7):486-490.
44. Bonami P, Kilinc M, Linderoth J. Algorithms and software for convex mixed integer nonlinear programs. *The IMA Volumes Math Appl.* 2012;154:1-39.
45. Nowak I. *Relaxation and Decomposition Methods for Mixed Integer Nonlinear Programming.* Birkhauser Verlag, Basel: Springer Science and Business Media; 2005.
46. Schlueter M. MIDACO software performance on interplanetary trajectory benchmarks. *Adv Space Res.* 2014;54(4):744-754.
47. Rasheed T, Ahmed MH, Dobre OA, Jerjawi W, Saad M. User pairing in cooperative wireless network coding with network performance optimization. *EURASIP J Wireless Commun Networking.* 2013:137.
48. Irving RW, Leather P, Gusfield D. An efficient algorithm for the “optimal” stable marriage. *J ACM.* 1987;34(3):532-543.
49. Kato A. Complexity of the sex-equal stable marriage problem. *Jpn J Ind Appl Math (JJIAM).* 1993;10(1):1-19.
50. Gale D, Sotomayor M. Ms. Machiavelli and the stable matching problem. *Americal Math Mon.* 1985;92(4):261-268.
51. Iwama K, Manlove D, Miyazaki S, Morita Y. Stable marriage with incomplete lists and ties. *Int Colloquium Automata, Languages Program.* 1999;1644:443-452.
52. Gale D, Sotomayor M. Some remarks on the stable matching problem. *Discrete Appl Math.* 1985;11(3):223-232.

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