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# Allocation Schemes for Relay Communications: A Multi-Band Multi-Channel Approach Using Game Theory

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Abstract—Although relay-based communication networks have greatly improved in terms of transmission coverage and capacity, they lack in the ability to choose best-quality channels among heterogeneous frequency bands. In this letter, we consider a multi-band multi-channel allocation scheme involving traditional and innovative algorithms. First, we present a centralized oracle following a bipartite graph model, and we indicate why this technique is not viable for deployment. Then, with reference to our previously published greedy approach, we explore a better online, distributed multi-band/channel allocation strategy by proposing a sequential game-theoretic algorithm. Simulation results demonstrate that our proposed game-theoretic approach significantly outperforms the traditional distributed and centralized methods.

Index Terms—Multi-band, sequential game, bipartite graph.

## I. INTRODUCTION

In conventional communication systems, relay-based network topology [1] is an established technique used for the improvement of transmission coverage and capacity. Relaying a data packet from a sender node (SN) via relay node/s (RN(s)) to a destination node (DN) can be quite advantageous, especially when considering the following two cases : 1) The channel between SN and DN does not satisfy the desired quality of service (QoS), or 2) the DN is at a great distance from the SN, hence increasing coverage but at the cost of a longer delay. In this letter, we introduce the advantages and challenges of using multi-band communication to mitigate this drawback of relay networks.

Considering the relay network depicted in Fig. 1, we assume multi-band devices supporting a variety of transceiving frequency bands (e.g., IEEE 802.11ax operating at 2.4GHz and 5GHz, millimeter wave, visible light communication, and so forth) that respond diversely to path loss, fading, mobile blocking, and other physical impairments. This results in drastically varying channel conditions across different frequency bands.

The RN traditionally waits for an SN to complete transmission on what we can denote to be $i^{\text{th}}$ channel of $j^{\text{th}}$ band ($\text{ch}_{sr}^{ij}$). Then, the same channel is used to forward the data packet to the DN, in an approach widely known as the decode and forward (DF) scheme [2]. On the other hand, in multi-band relay communication, the RN can start sending data out to the DN using the $m^{\text{th}}$ channel from a different $n^{\text{th}}$ band ($\text{ch}_{rd}^{mn}$) even before the SN-to-RN data transmission is complete. Naturally, this technique significantly reduces the latency involved in packet forwarding.

When it comes to relay-based networks, reducing communication delay is an active area of research. Relay communication using a multi-band approach was studied in [3]–[5] with the aim of reducing end-to-end packet latency. In [3], a multi-hop network was proposed whereby a centralized optimization problem was employed to make decisions in regard to routing, channel allocation and link scheduling. The work also explained how uncertain channel availability results in uncertain scheduling, which not only increases latency but also heavily overloads the system.

In [4], a relay network was designed using a truncated DF scheme with multi-band communication, which increases both the frame error and communication latency. In [5], the authors proposed a simple greedy approach for which they determined the best (i.e., the fastest) communication channel, where the signal-to-interference noise ratio of each available channel was calculated and then the packet was forwarded as per the modulation and coding table. However, there was no consideration of the case where better quality channels are unavailable for packet forwarding.

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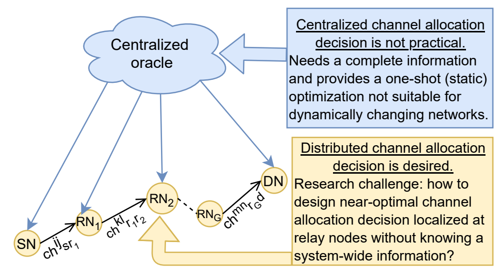


Fig. 1: Centralized vs distributed resource selection for relays.

The main contributions of this letter are the solutions we present for the latency issue in relay-based communications. We design and analyze both centralized and distributed approaches. For the former, we use graph theory [6], [7] and model the problem as a bipartite graph. We then solve it using optimization theory tools (given in section II). Graph theory is ultimately a study of relationships, and it be useful when trying to clarify and evaluate the complete dynamics of the problem. In other words, it provides a brief interpretation of a convoluted network.

Previously in [8], we modeled and solved a time-sensitive multi-band relay communication model using a distributed greedy algorithm. Our customized greedy heuristic can be considered a benchmark for intuitive, distributed solutions to the optimization problem. However, due to its greedy nature, there is room for further improvement, notably in the solution framework, which we investigate here using game theory (given in section III). Although game theory has been studied for resource allocation in other similar radio systems [9], [10], they have not been examined under the pressures of multi-band communication (e.g., buffer overflow, increased latency).

As seen in Fig. 1, when a centralized oracle makes decisions for all network entities including RNs, the decision-making process requires a non-deterministic amount of time with a significant increase in the number of nodes. This results in a more complex, time-consuming, and static optimization, which is not a practically viable solution. Therefore, designing a practical band/channel selection method that minimizes the degradation of QoS parameters (e.g., communication delay, throughput, available power/energy, available buffer) in relay-based communication emerges as the key research problem and contribution in this letter. Our approach hinges on the design of a distributed, online decision making technique that allows RNs to select heterogeneous bands/channel based on the prevalent channel and traffic conditions, thereby improving decreasing delay (from SN to DN) and increasing throughput. Simulation results in favour of our proposed technique are reported in section IV.

## II. CONSIDERED CENTRALIZED SYSTEM MODEL AND PROBLEM DESCRIPTION

Here we present the centralized system model, which is based on a balanced bipartite graph. We then formally formulate the optimization problem. As shown in Fig. 1, the system model assumes one central node (CN), acting as an oracle and having complete information of the network, i.e., spectrum sensing results [11]; signal to noise ratio (SNR) estimation of free channels; buffer size; available power; distance between interconnecting SN, RN/s and DN; and so forth. In addition, the CN is responsible for making decisions and allocating resources, such as power and frequency.

***Bipartite Graph-based Oracle:*** The relay-based network can be represented as a combinatorial, constraint-weighted bipartite graph matching problem $C = \{\mathcal{G}, \mathcal{Q}, \mathcal{E}\}$ consisting of two disassociated sets of vertices $\mathcal{G}$, $\mathcal{Q}$, and a set of edges $\mathcal{E} = \mathcal{G} \times \mathcal{Q}$. An edge $\mathrm{X_{gq}}$ connects a vertex $RN_g \in \mathcal{G} = \{RN_1, RN_2, ..., RN_{\mathcal{G}}\}$ with a vertex $(P, f)_q \in \mathcal{Q} = \{(P, f)_1, (P, f)_2, ..., (P, f)_{\mathcal{Q}}\}$ and has an associated weight $\mathrm{U}gq$, where $(P, f)$ represents a power level and available channel frequency pair.

The objective is to find a matching $\mathrm{X} \subseteq \mathcal{E}$ that associates every vertex in $\mathcal{G}$ with a vertex in $\mathcal{Q}$. In a bipartite graph, perfect matching can be attained when the cardinalities of the vertex sets are equal (i.e., $|\mathcal{G}| = |\mathcal{Q}|$) [12]. The vertices $\mathrm{RN_g}$ represent the RNs that belong to the same set $\mathcal{G}$, whereas the vertices $(P, f)_q$ represent the allocatable resources, which are denoted by set $\mathcal{Q}$. In this work, we consider the packet time span $\mathbf{U}_{g,q}$ to be the weight of the edge connecting the $g^{th}$ RN to the $q^{th}$ $(P, f)$ pair. Here, $\mathbf{U}_{g,q} = \mathrm{F}/(\mathrm{B}\log 2(1 + \mathrm{SNR_{gq}}))$, F is the packet size in bits, B is the bandwidth of the resource and $\mathrm{SNR_{qg}}$ is the function of the $q^{th}$ $(P, f)$ pair connected to the $g^{th}$ RN. The goal is to choose the edges/connections that grant minimum weights, i.e., to find $\mathrm{X_{gq}} \in \{0, 1\}$, where 0 means discarding the connection and 1 means keeping it.

***Problem Formulation:*** Let $\mathcal{G}$ contain the actual number of RNs plus dummy RNs in order to construct a balanced bipartite problem [12]. Then, let $\mathcal{Q}$ denote the number of power level pairs and available free channels. Let **U**, **T**, **SNR**, and **BO** be $\mathcal{G} \times \mathcal{Q}$ matrices. Here, **U** = **T** and it contains the outcomes of all the edges and is equal to the time span of the forwarded data packet against each power frequency pair. **BO** is the buffer overflow matrix against each edge, and **SNR** denotes the corresponding SNR for each pair. Let **P** and **f** be the row vectors of size $\mathcal{Q}$, representing the corresponding power values and available channel frequencies for all the pairs, respectively. Now, our considered problem can be formally modeled as an optimization problem as follows

$$\min \quad \sum_{g=1}^{\mathcal{G}} \sum_{q=1}^{\mathcal{Q}} \mathbf{X}_{g,q} \cdot \mathbf{U}_{g,q}, \tag{1a}$$

s. t.

$$\sum_{g=1}^{\mathcal{G}} \sum_{q=1}^{\mathcal{Q}} \mathbf{X}_{g,q} \cdot \mathbf{BO}_{g,q} = 0, \tag{1b}$$

$$\sum_{q=1}^{\mathcal{Q}} \mathbf{X}_{g,q} \cdot \mathbf{P}_q \leq P_{avail}, \quad \forall g, \tag{1c}$$

$$\mathbf{X}_{g,q} + \mathbf{X}_{g+1,q} \leq 1, \quad \forall q, g, \tag{1d}$$

$$\sum_{q=1}^{\mathcal{Q}} \mathbf{X}_{g,q} \cdot \mathbf{SNR}_{\mathrm{g,q}} \geq \mathrm{SNR_{min}}, \quad \forall \mathrm{g}, \tag{1e}$$

$$\sum_{q=1}^{\mathcal{Q}} \mathbf{X}_{g,q} = 1 \quad \forall g, \tag{1f}$$

$$\mathbf{X}_{g,q} \in \{0, 1\}, \tag{1g}$$

where, $\mathbf{X}_{g,q}$ is a $\mathcal{G} \times \mathcal{Q}$ matrix, the binary decision variables for which are unknown. The objective function (1a) aims to minimize the sum of all the forwarded packets' time spans. The equality constraint (1b) checks if all the RNs have a buffer overflow equal to zero. The inequality constraint (1c) aims to keep the power usage level with the available power of the RNs. On the other hand, the inequality constraint (1d) forces the system to use a multi-band/channel setting. Constraint (1e) maintains the QoS of each forwarded data packet. The equality constraint (1f) compels each RN to pick exactly a single power frequency pair to keep forwarding the data packet. Constraint (1g) is for characterizing the unknown matrix **X** as a Boolean variable.

***Oracle-based multi-band allocation to RNs:*** The steps of the aforementioned centralized bipartite graph-based oracle for an optimal multi-band/channel allocation to the RNs are enumerated here. First, the CN accesses its central spectrum-sensing results and generates $(P, f)$ pairs with all possible combinations of power levels and available channel frequencies. After generating these pairs, the CN collects information on the packet size F directly from the SN (using any information channel). Then, the CN collects information on the distances between each RN and the power available for each.

Next, the CN generates matrices for the time span, buffer overflow, and SNR against each power frequency pair for each RN. After this, it generates the equality and inequality matrices for an optimization solver. The solver returns the solution matrix to the CN, which then gets forwarded to each RN. In addition to the problem's solution, the CN now has the scheduling times for the packets of each RN, and it shares that information with all RNs. The SN commences transmitting and each RN, at this point, already knows which power frequency is to be selected in order to forward the received data packet to the DN.

While this centralized optimization algorithm requires an oracle (i.e., a full knowledge on the system), it is not progressive with respect to the individual RNs. It is not possible for the optimization problem to incorporate the ability to assess local buffer overflow conditions at the RNs because it depends on the previous nodes' decisions regarding data rate. In the centralized model, all decisions are taken at once by the central node, and therefore, it can only check the buffer overflow condition for all the nodes at once. With an increasing number of RNs, however, this approach takes non-deterministic time and adds exponential latency to the system. This type of approach would only be suitable for devices with limited power, where it is capable of finding the global optimal solution for the network with infinite buffer sizes. Due to such impracticality, a distributed algorithm would make for a more effective solution.

## III. PROPOSED GAME THEORETIC DISTRIBUTED MULTI-BAND/CHANNEL SELECTION ALGORITHM

This section presents the distributed system model based on game theory. A sequential game does not allow players to make a move at the same time. In other words, the players take turns making decisions [13]. In our case, a particular RN can start transmitting at a particular power in some channel (makes a decision) only after it starts receiving the packet from the previous node. Importantly, the later players must have some information of the earlier ones' choices; otherwise the difference in time

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would have no strategic effect. In our case, the packet header received from the previous node provides this information to the particular RN.

Perfect information is often, and erroneously, used interchangeably with complete information; however, here we make an important distinction. In this model, we assume that RNs receive perfect information in the packet header from the previous node. In our case, we do not use complete information, i.e., all RNs having information regarding the entire network as considered with the centralized oracle. Hence, we construct a sequential combinatorial game with perfect information, not with complete information, using the following representation [14] and entities:

1) Players: In our case, the RNs are regarded as players.
2) The information available to each player: Here, RNs hold information about the packet size/length and the rate at which data is received.
3) Actions: These are the choices available to each RN at the point of decision. These include selecting a power value pair out of $\mathcal{P}$ possible power values $P = [P_1, P_2, ..., P_{\mathcal{P}}]$ and $\mathcal{F}$ available channels $f = [f_1, f_2, ..., f_{\mathcal{F}}]$, at which the data can be forwarded to the next player.
4) The payoffs for each outcome: Here, the payoff is represented as a Boolean. Either all the constraints are met or not against each power and frequency channel pair.

In game theory, these elements are typically used, along with strategies available for each player. Here, each RN's strategy is to choose a power frequency pair that satisfies the utility function and fulfills all constraints. The utility function of the modeled game is to reduce the forwarded packet's time span.

The sequential aspects, characterized by the extensive form representation can also be depicted as a decision tree as seen in Fig. 2. The decision tree demonstrates the possible ways of playing our considered game. $D_{sr1}$ denotes the initial data rate chosen by the source/SN in accordance with its own channel condition. To trigger the relay communication, this value is considered the starting/initial point for the necessary algorithm to be designed.

***Reformulation of the Original Problem:*** Now, we transform the original optimization problem in eq. (1a) into the distributed game model for some $g^{th}$ player (RN) as follows

$$U = \min \quad T_{g,(g+1)}(P_{g,(g+1)}, f_{g,(g+1)}), \tag{2a}$$
$$\text{s. t. } (po \in \{0, 1\})$$
$$BO(\mathcal{D}_{(g-1)}, \text{buffsize}_\text{g}) = 0, \tag{2b}$$
$$f_{(g-1),g} \neq f_{g,(g+1)} \tag{2c}$$
$$\text{SNR}_{\text{g},(\text{g}+1)} \geq \text{SNR}_{\text{min}} \tag{2d}$$
$$0 \leq P_{g,(g+1)} \leq P_{g,avail}, \tag{2e}$$

where

$$T_{g,(g+1)} = \frac{\text{F}}{\mathcal{D}_{g,(g+1)}} \tag{3}$$
$$\mathcal{D}_{g,(g+1)} = B \log_2(1 + \text{SNR}_{\text{g},(\text{g}+1)}) \tag{4}$$
$$\text{SNR}_{\text{g},(\text{g}+1)} = \frac{\text{P}_{\text{g},(\text{g}+1)}\text{h}_{\text{g},(\text{g}+1)}}{\text{noise}} \tag{5}$$
$$h_{g,(g+1)} = \frac{c}{4\pi f_{g,(g+1)} d_{g,(g+1)}}, \tag{6}$$

and $P_{g,(g+1)}$, $f_{g,(g+1)}$, $T_{g,(g+1)}$ are the chosen power, channel, data time span respectively. These are used to transmit the data packet from the $g^{th}$ RN to the next $(g+1)^{th}$ node. The constraint (2b) states that while using a particular $(P, f)$ pair, the buffer should not overflow, and this is checked against the $(g-1)^{th}$ RN's data rate $(\mathcal{D}_{(g-1)})$ and the $g^{th}$ RN's

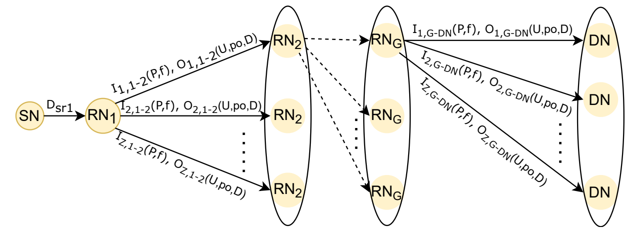


Fig. 2: Decision tree of proposed sequential game model for RNs.

available buffer size (buffsize). Constraint (2c) is defined as forcing the player to use the multi-channel/multiband opportunity in order to reduce latency. Constraint (2d) is the respective QoS constraint to maintain the data quality. Constraint (2e), however, is the power-limiting constraint of movable devices. $po$ is the payoff Boolean variable representing 1 for all constraints being met and 0 otherwise.

***Envisioned Game Theoretic Solution:*** Now, we propose following algorithm to progressively minimize the utility function (3) at the RNs. The steps of the algorithm are explained below.

1) The SN transmits data of size F (bits) to the $\text{RN}_1$.
2) The player $\text{RN}_1$ extracts the perfect information, including the incoming data size, F and rate, $\mathcal{D}$ from the header of the received packet.
3) The player $\text{RN}_1$ picks all the power value and channel $(P, f)$ pairs out of the $\mathcal{P}$ possible power values $P = [P_1, P_2, ..., P_{\mathcal{P}}]$ and $\mathcal{F}$ available channels $f = [f_1, f_2, ..., f_{\mathcal{F}}]$, and calculates the corresponding outcome of the utility function (U) as well as the payoff $(po)$ for each pair.
4) The utility function U is the corresponding time span, and T of each packet is to be forwarded on the basis of a particular $(P, f)$. The payoff, $po$ is a Boolean variable indicating 1 for the successful fulfillment of all constraints and 0 otherwise.
5) The player $\text{RN}_1$ then selects one pair out of all others, resulting in $po = 1$ and a minimum U among them. Therefore, it selects the pair with the minimum U, which fulfills all the constraints.
6) Since this is a sequential game, each player (RN) takes turns in a linear, progressive fashion. When the first RN finalizes its selection of $(P, f)$, it can forward packets to the next node, providing information about F and $\mathcal{D}$ in the header. Now, the next node is ready to play the game as was done by the $\text{RN}_1$.

The proposed algorithm is fast and simple for a limited number of branches. This approach makes decisions distributively and on the basis of current/updated local band/channel conditions, making its results more reliable. Moreover, all constraints can be handled by this approach, rendering our game theoretic algorithm suitable for instances with limited power and buffer size.

## IV. PERFORMANCE EVALUATION

In this section, we evaluate the performance of our game theoretic approach based on computer-based simulations. We then compare it with the two reference methods (i.e., centralized oracle and distributed greedy heuristic). MATLAB was used to construct simulations, using the same environmental parameters as in our earlier work [8] unless otherwise stated.

In Fig. 3, it can be seen that packet transmission latency increases with the number of interconnected RNs/players. Even so, the light-weight greedy and game approaches manage to demonstrate much less latency than the centralized approach. However, since game theory provides a proper framework for understanding choices in situations involving

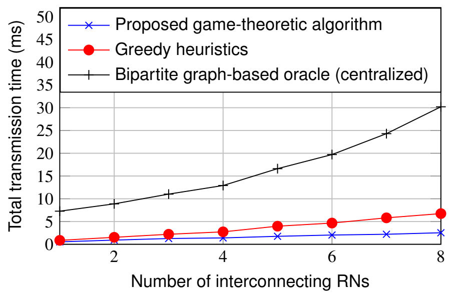


Fig. 3: Comparison for the total transmission time.

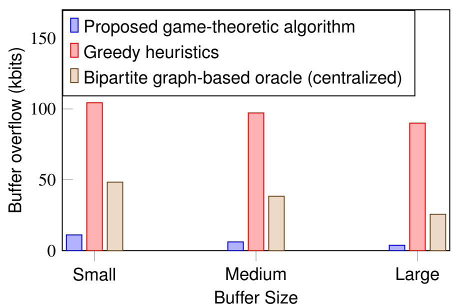


Fig. 4: Buffer overflow comparison with different buffer sizes for 8 RNs.

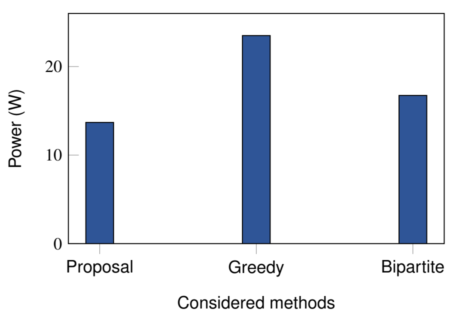


Fig. 5: Power usage comparison for 8 RNs.

competing players, the game approach performs more efficiently than the greedy heuristic.

Next, in Fig. 4, we consider three different buffer sizes and present the results. It can be seen from the figure that as the available buffer size increases, the number of overflown bits decreases and vice versa. Moreover, in the worst-case scenario, the greedy approach results in maximum buffer overflow. The game-theoretic approach, on the other hand, manages the buffer constraint more effectively than the other two methods. Furthermore, it is can be seen from Fig. 5 that, because the greedy approach ignores the power usage consideration for packet transmission, it ends up depleting all the power available for that particular transmission. However, when the problem is solved centrally, the oracle-based approach considers the buffer size to be the maximum. The distributed approach, though, remains tightly constrained by the buffer overflow condition.

Thus, our proposed method uses the least amount of power among all the methods. The effective throughput is defined as the number of successful packets received during the total time of relaying. It can be seen from Fig. 6 that the effective throughput of the proposed game theoretic method is the highest, yielding both the most time-efficient performance and the least occurrences of buffer overflow. On the other hand, the oracle-based method has the least effective throughput, demonstrating an exponential rise in the packet latency.

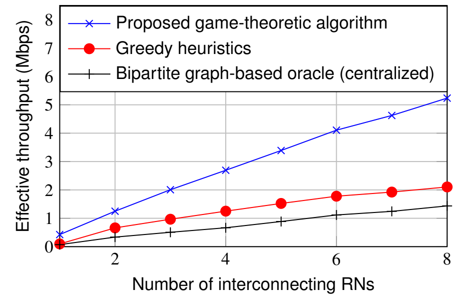


Fig. 6: Effective throughput comparison with different number of RNs.

## V. CONCLUSION AND FUTURE WORK

In this letter, we addressed the need to optimally assign channels from heterogeneous frequency bands to RNs to improve the overall transmission time, effective throughput, and RN efficiency. Due to the practical limitations of a centralized oracle, we developed a sequential game algorithm. Simulation results demonstrated that our proposed model outperforms the traditionally used approaches (i.e., centralized oracle, a greedy heuristic-based distributed). In the future, we envision working on a detailed performance analysis of the proposed game theoretic model. We want to focus on analyzing the Nash equilibrium specific to proposed sequential game model. To be precise, for sequential games, the Nash equilibrium can be achieved using the perfect equilibrium of the sub-games. We do this using backward induction. We intend to discuss the topic using simulations along with detailed numerical examples.

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