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Interference aware resource allocation for hybrid hierarchical wireless networks ☆

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ABSTRACT

This paper addresses the problem of interference aware resource allocation for OFDMA based hybrid hierarchical wireless networks. We develop two resource allocation algorithms considering the impact of wireless interference constraints using a weighted SINR conflict graph to quantify the interference among the various nodes: (1) interference aware routing using maximum concurrent flow optimization; and (2) rate adaptive joint subcarrier and power allocation algorithm under interference and QoS constraints. We exploit spatial reuse to allocate subcarriers in the network and show that an intelligent reuse of resources can improve throughput while mitigating interference. We provide a sub-optimal heuristic to solve the rate adaptive resource allocation problem. We demonstrate that aggressive spatial reuse and fine tuned-interference modeling garner advantages in terms of throughput, end-to-end delay and power distribution.

1. Introduction

Broadband wireless access (BWA) networks are designed to provide cellular systems that support fixed and mobile users with heterogeneous and high traffic rate requirements. In such networks a single base station (BS) is deployed to cover a cellular area. In such a large area, users at the cell edge often experience bad channel conditions. Moreover, in urban regions, shadowing by various obstacles can degrade the signal quality in some areas. Increasing the number of base stations is an expensive solution and increasing the base station power only increases the intercell interference. Deploying relay stations (RS) is a feasible solution since typical relays are cheaper than base stations and they do not need their own wired backhaul, therefore they are easier to deploy. Relaying technology is increasingly applied to multihop communication in orthogonal frequency division multiple access (OFDMA) based BWA networks because of its ability to provide cost-effective enhancement of coverage, throughput, and system capacity [1,2]. In OFDMA networks, basic resources are subcarriers and power. Subcarriers experience frequency selective fading, which takes different values for different users and subcarriers. Therefore, optimal allocation of these resources is crucial in reaching various objectives such as improving throughput, reducing power consumption or maximizing fairness.

In multihop wireless networks, interference is seen as a major limiting factor in the performance of the network. Interference is quantified through the use of interference models. The two most prominent models are the protocol model and the physical model [3]. Graph based approaches for interference modeling using both of these models have been developed in [4,5]. An accurate modeling of interference is fundamental in order to obtain theoretical and/or simulation based results of some practical relevance.

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OFDMA networks pose an interesting set of resource allocation problems, particularly (1) routing: how to select paths that minimize interference and increase throughput? (2) subcarrier assignment: what is the set of subcarriers that each link should operate on? and (3) power allocation: what is the optimal power for the nodes transmitting on specific subcarriers? These problems are inter-related and form a challenging cross-layer problem across the network and MAC layers.

The contributions of this paper are twofold. First, we develop a routing approach based on maximum concurrent flow (MCF) that determines paths with least interference using the physical interference model (also known as the SINR interference model). The MCF approach has been a historically prevalent optimization approach to maximize throughput. It has typically been used in wired networks (i.e., traffic engineering). In order to extend the MCF approach in wireless networks, it must be tailored to consider interference constraints. We propose a novel algorithm to solve the traditional MCF problem under interference constraints of wireless networks. The optimization formulation for the MCF proposed in this paper, denoted as interference-based MCF (MCFI), uses a SINR derived interference quantification method to maximize the flow from a user and to determine the least interfering paths. We develop a novel weighted SINR based interference model using conflict graphs to quantify the interference between various nodes. In this model, the weighted conflict graph indicates which links will interfere and with what SINR level. The SINR value essentially provides the interference level on a link considering simultaneous transmissions exist. Given this information, it is possible to determine which flows interfere. By choosing the paths for the flows that have least weight, we are able to reduce the inter-flow interference. The interference constraints within the MCFI formulation are obtained from the weighted conflict graph. Second, we study the problem of rate adaptive subcarrier and power allocation with time and quality of service (QoS) constraints to maximize the overall rate while achieving proportional fairness amongst nodes under a total power constraint. The subcarriers are allocated using the concept of spatial reuse and interference constraints derived from the interference model are considered in the optimization formulation. In addition, in order to synchronize transmissions, time slots are also allocated. Specifically, time constraints (scheduling) have been considered in the optimization formulation. Solving such a problem is especially useful for rate constrained transmissions such as real time voice and video streaming sessions. The proposed rate adaptive resource allocation optimization framework captures the conflicting objectives of a network (maximizing throughput) and users (satisfying demands). The formulation is computationally demanding and therefore necessitates the use of a sub-optimal solution technique.

The remainder of this paper is organized as follows. The related work is given in Section 2. In Section 3, the system model is discussed. The MCFI routing is presented in Section 4. The rate adaptive joint subcarrier and power allocation formulation is discussed in Section 5. Our simulation results are given in Section 6. We conclude the paper in Section 7.

2. Related work

Research on subcarrier allocation in OFDMA networks focuses on assigning a subset of subcarriers to each link such that no subcarrier is assigned to more than one link [2,6,7]. These studies rely on the fact that inherently in OFDMA networks, the number of subcarriers is usually large enough so that each link can use a different subcarrier, guaranteeing no two links are transmitting on the same subcarrier, thereby eliminating inter-carrier interference. The focus of our work is to exploit the potential benefits of spatial reuse in subcarrier assignment and therefore is differentiated from existing research in the literature [8]. It has been shown that spatial reuse of resources provides gains in capacity and throughput [9,10]. The premise behind our work is that some subcarriers may be better for a specific node in terms of channel gain than others. It may be beneficial to have two nodes using the same subcarrier if that subcarrier provides a better transmission medium for both nodes.

Subcarrier allocation in OFDMA networks cannot be investigated alone since various parameters such as power and time are all inter-related. Rate adaptive allocation without regards to interference has been studied in detail for traditional cellular networks in the literature. In [11] the authors formulate the capacity maximizing subcarrier and power allocation problem and propose a sub-optimal allocation algorithm that shows significant performance improvement with respect to static FDMA resource allocation. Similarly, in [12] the authors optimally solve the capacity maximization problem and show that allocating each carrier to the user with the best channel on that carrier and then distributing the power to the carriers by waterfilling maximizes the capacity. Optimal subcarrier and power allocation subject to rate with general objectives such as proportional fairness or QoS constraints have also been studied in [13–15]. However, resource allocation for cellular multiuser OFDMA systems with relay stations has not been studied sufficiently. In relay based networks such as our system model, rate adaptive resource allocation that deals with subcarrier and power allocation has generally focused on either (a) maximizing throughput subject to either only the base station power constraint or only the relay power constraint while proposing various optimization approaches [16–22]; or (b) solving the subcarrier and power allocation problems separately rather than jointly [11]. In addition, rate adaptive resource allocation based on subcarrier and power distribution has not taken into account the limitations of interference on the various optimization constraints. In this paper, we provide a comprehensive framework for rate adaptive resource allocation under interference, time and QoS constraints such that subcarrier and power allocation is performed effectively while exploiting the benefits of spatial reuse.

3. System model

We consider a multihop cellular network (MCN, also called hybrid network) consisting of a base station, $\mathscr{R}$ fixed relay stations and $\mathscr{N}$ mobile users where each user is

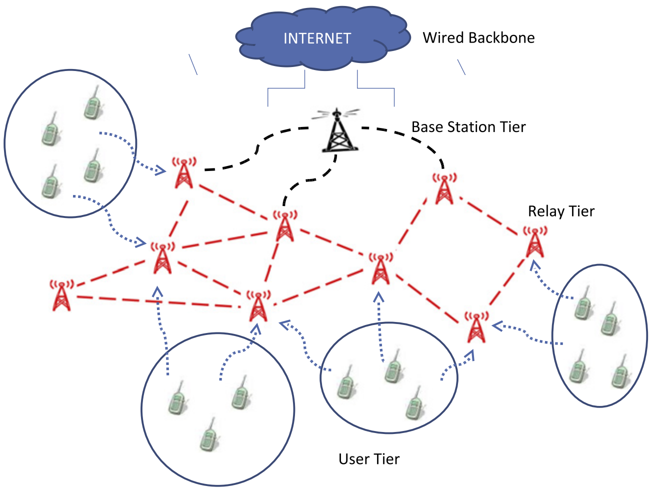


Fig. 1. Hybrid hierarchical wireless network.

assigned to either the base station or a relay station. Our network topology is based on the MCN model used in emerging BWA networks [23]. As shown in Fig. 1, the proposed network architecture is based on three tiers of wireless devices: (1) set $\mathscr{N}$ of user nodes which are the lowest tier have limited functionality (i.e., do not communicate with one another and have no routing capability); (2) set $\mathscr{R}$ of relay nodes that route packets between the user and BS is the second tier. They also communicate with one another; and (3) the base station is the highest tier and is connected to the wired infrastructure. We refer to this network as a hybrid hierarchical network (HHN). In order to avoid single points of failure (i.e., failure of a relay node which will disrupt traffic flow), the relays are connected in a mesh manner so that multiple paths are available between the user and BS thereby increasing service availability and fault tolerance. Mesh networking is a promising technology for numerous applications (i.e., broadband networking) and has garnered significant attention as a cost-effective way of deploying wireless broadband networks [24]. The combination of wireless mesh networks and relay networks has been discussed where the general structure of a mesh network has been incorporated with relaying aspects [25]. Our defined architecture uses a wireless relay network structure that is enhanced with mesh networking capabilities.

Each relay is equipped with a half-duplex transceiver. In this work we consider uplink traffic only where each user has some traffic to route. Note that relays do not inject traffic into the network. We assume that each user and relay node has a maximum power level, P_{max}, where the P_{max} value is different for the user and relay node.

The propagation effect is modeled by the radio propagation losses. The channel gain of a link will depend on the subcarrier used. Let $G_{n,k}$ be the channel gain of node n on subcarrier k. The OFDMA network under consideration has a total bandwidth of W which is divided in K subcarriers. We assume that the transmissions experience path loss, Rayleigh fading and log normal shadowing.[1] We consider frame by frame resource allocation. A frame is of duration T ms. Channel conditions and user population are assumed to be constant during a time frame. This assumption does not impose a serious restriction since the channel and user statistics are typically not available at a finer granularity than the frame durations. Rayleigh fading is assumed to be flat in each subcarrier and i.i.d for different users and subcarriers. We assume centralized scheduling and assume that the base station can perfectly obtain the channel conditions of all relay stations and user nodes. In addition, each node knows the geographic location of all the other nodes in the cell via location discovery schemes [26]. This information is necessary for the receivers to feedback SINR measurements to their respective transmitters.

[1] In the simulations we keep the users fixed but simulate the effects of mobility through Rayleigh fading and log normal shadowing.

4. Interference-based maximum concurrent flow (MCFI) routing

Given a HHN, $\mathscr{G}$, each user $n \in \mathscr{N}$ has a traffic demand that must be routed to the BS. In this section, we develop a network optimization formulation that determines the routes to forward traffic of each user to the BS under physical interference constraints such that the maximum possible traffic is routed. In other words, we determine the least interfering paths that each user can use to route the traffic demands such that the concurrent traffic flow is the maximum possible. The physical interference model states that a transmission between nodes i and j is successful if the SINR at j (the receiver) is above a certain threshold value. Therefore the SINR is contingent upon other simultaneous transmissions. The SINR for a transmission between i and j is given as follows

$$SINR_{ij} = \frac{P_j(i)}{N + \sum_{k \in V'} P_j(k)} \geqslant \beta \qquad (1)$$

where $P_j(i)$ is the received power at node j due to node i, N is the ambient noise power, V' is the subset of nodes in the network that are transmitting simultaneously, and β is the SINR threshold. In order to quantify interference using the

SINR model, we use a weighted conflict graph. In a conflict graph, a node is introduced for each link in the original network. An edge connects two nodes in the conflict graph if these two links interfere. An edge-based notion of the conflict graph for the physical interference model inserts a weighted edge between two nodes. Consider two links $e_1 = v_1w_1$ and $e_2 = v_2w_2$ (where e_1 and e_2 are the nodes in the conflict graph). We add a weighted edge between e_1 and e_2 if they potentially interfere with each other, where the weight of the link represents the fraction of the maximum permissible noise and interference level at the receiver node of e_2 that is contributed by activity on link e_1.

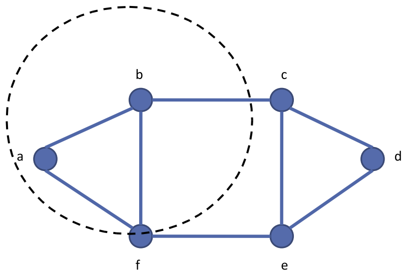
In order to determine the potentially interfering links, we use a method called a "reality check" that links the parameters of the physical model and the protocol model. The reality check method, introduced in [27], essentially sets a realistic interference range in which links are assumed to interfere. Let R_T^{max} (r_T^{max}) and $R_I^{max}(r_I^{max})$ represent the maximum transmission and interference ranges of each relay (user) node, respectively. The transmission range represents the maximum distance up to which a packet can be received, while the interference range represents the maximum distance up to which simultaneous transmissions interfere. In the literature, the interference range is usually chosen to be twice as large as the transmission range which is not necessarily a practical assumption [28]. The actual values of the transmission and interference ranges depend on the transmission power used by the nodes. Each wireless node has a transmission range which is a circle in a 2D plane, centered at the wireless node with radius $R_T^{max}(r_T^{max})$.

For the protocol model, there are two parameters, the maximum transmission and interference ranges, R_T^{max} and R_I^{max}, respectively. Since the underlying physical layer mechanism is the same, the parameter $R_T^{max}(r_T^{max})$ should be consistent with the β parameter in the physical model. Two nodes with distance $R_T^{max}(r_T^{max})$ should be able to communicate with each other under the maximum transmission power P_{max} and the SINR should be β. As a result, according to [27], $R_T^{max}(r_T^{max})$ is $\frac{P_{max}}{\beta}$, where P_{max} is the maximum power value for the relay node (user node).

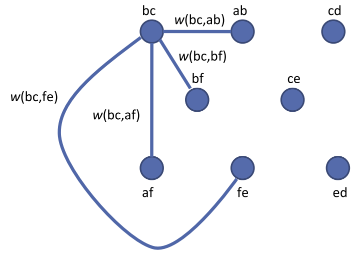
Note that the maximum interference range, $R_I^{max}(r_I^{max})$, is a parameter introduced by the protocol model and there is no corresponding parameter in the physical model. The only requirement on $R_I^{max}(r_I^{max})$ is $R_I^{max}(r_I^{max}) > R_T^{max}(r_T^{max})$, i.e., a lower bound for $R_I^{max}(r_I^{max})$ is $R_T^{max}(r_T^{max})$. Thus, if we set the interference range to be slightly higher than the transmission range, $R_T^{max}(r_T^{max}) = \frac{P_{max}}{\beta}$, then the solution is more realistic. Given the interference range, all links within that range will interfere and a weighted edge will exist between the interfering nodes in the conflict graph. We define a link weight $w(e_1, e_2)$ as follows

$$w(e_1,e_2) = \begin{cases} 0 & \text{if node } e_1 = e_2 \\ \frac{P_{w_1}(v_1)}{\frac{1}{\beta}P_{w_1}(v_2) - N}, & \text{otherwise} \end{cases} \quad (2)$$

Fig. 2 illustrates the mechanism of creating the weighted conflict graph (WCG) and determining the link weights



(a) Connectivity graph $\mathcal{G}$



(b) Composition of weighted conflict graph, WCG, for link (b, c)

Fig. 2. Illustration of the weighted conflict graph (WCG) construction from the original connectivity graph.

based on interference range. Fig. 2a shows the connectivity network $\mathcal{G}$ and the interference range of node *b*. The conflict graph composition for link (*b*, *c*) is given in Fig. 2b where the potentially interfering links are those within the interference range of node *b*. The network of Fig. 2b shows only a partial construction of the WCG.

In order to determine the individual routing paths and compute the maximum achievable throughput, we use the maximum concurrent flow approach (MCF) [29] with interference constraints. The MCF is a multicommodity flow problem in which each pair of nodes (user-destination pairs) can send and receive flow simultaneously. The ratio of the flow between the user and BS to the predefined demand for that pair is the throughput. The interference-based MCF (MCFI) is defined as follows. Let $\mathcal{G}(\mathcal{V}, \mathcal{E})$, be a HHN where $\mathcal{V}$ is the set of nodes and $\mathcal{E}$ is the set of links in the network. Note that $|\mathcal{V}| = |\mathcal{N}| + |\mathcal{R}|$. There is one base station in all networks considered in this paper. There are $\mathcal{N}$ user-BS pairs, where $\mathcal{N}$ is simply the number of users (i.e., there are a set of $\mathcal{N}$ commodities in the network). Each user is associated with a certain traffic demand that must be routed to the BS. We denote x_{ij}^n as the amount of flow from the *n*th commodity over link (i, j), normalized with respect to the capacity of the link. The link capacity is defined as

$$u_{ij} = Blog_2(1 + SINR_{ij}) \quad (3)$$

where *B* is the bandwidth of each subcarrier. The $SINR_{ij}$ is defined as in Eq. (1). We let f^n be the flow originating from user node *n*. We denote $Int(i,j)$ to be the set of links that interfere with link (i,j) according to the weighted conflict graph. The MCFI is formulated as follows

$$\text{maximize} \quad \sum_{n\in\mathcal{N}} f^n \tag{4}$$

$$\text{subject to} \quad \sum_{(i,j)\in\mathscr{E}} x_{ij}^n - \sum_{(j,i)\in\mathscr{E}} x_{ji}^n = \begin{cases} f^n & \text{if } i = n \\ -f^n & \text{if } i = BS \\ 0, & \text{otherwise} \end{cases}, \quad \forall n \in \mathcal{N} \tag{5}$$

$$\sum_{n\in\mathcal{N}} x_{ij}^n + \sum_{(p,q)\in Int(i,j)} \sum_{n\in\mathcal{N}} x_{pq}^n \leqslant 1, \quad \forall (i,j) \in \mathscr{E} \tag{6}$$

$$\sum_{n\in\mathcal{N}} \left[\sum_{(i,j)\in\mathscr{E}} x_{ij}^n + \sum_{(i,j)\in\mathscr{E}} x_{ji}^n \right] \leqslant 1 \tag{7}$$

$$x_{ij}^n \geqslant 0, \quad \forall (i,j) \in \mathscr{E}, \quad \forall n \in \mathcal{N} \tag{8}$$

The first constraint (Eq. (5)) represents the flow conservation constraints at each node for each commodity. Eq. (6) is the link capacity constraint dictated by the interference model and the constraint in Eq. (7) is the node capacity constraint in which the sum of the ingoing and outgoing flows should be less than the channel capacity. The linear program described above leads to a multicommodity problem flow which uses multiple paths to route each commodity from source to destination. In many wireless network protocols, however, data are generally routed along a single path to avoid some side-effects that occur due to multi-path routing. In single path routing, each edge can either carry the full traffic for a given connection or none of it. This constraint is given in Eq. (9)

$$x_{ij}^n = f^n \cdot y_{ij}^n, \quad \forall n \in \mathcal{N}, \quad \forall (i,j) \in \mathscr{E} \tag{9}$$

The variable y_{ij}^n is a boolean variable which is set to 1 if the edge carries the traffic for the nth connection and 0 otherwise. The single path routing approach to route flows is based on the weighted conflict graph (i.e., the paths with least cost (least interference) are chosen for each user).

5. Joint subcarrier and power allocation under time and QoS constraints

5.1. Optimization formulation

In OFDMA networks, the BS controls how subcarriers are allocated and to which links they are assigned. In this paper we exploit spatial reuse and analyze the performance benefits of having such reuse. In order to ensure that links using the same subcarrier do not strongly interfere (spatial reuse), the subcarriers should be allocated to links which are far away from each other. Within the interference range of a node, $R_I^{max}(n)$, there are a set of nodes which we denote as the dominant interferers. Their proximity to n leads to a high probability that a transmission from any of them will result in interference at n. We denote the set of dominant interferers as $D_I(n)$. Note that $n \in D_I(n)$. The set of links emanating from each node within $D_I(n)$ is called the interference link set, $L_I(n)$. Also all links emanating from n will also be in $L_I(n)$. In addition, we define the spatial reuse factor as λ_c which is the number of times each subcarrier is used within a HHN cell (λ_c is different for each subcarrier). Furthermore, we define the value λ_{max} to be the maximum number of times a subcarrier is allowed to be reused within the cell (i.e., each λ_c cannot be greater than λ_{max}).

We aim to assign unique subcarriers to all links within the interference range of each node (i.e., links within $L_I(n)$ for all n). Outside of the interference range, reuse of subcarriers is allowed. The subcarrier assignment scheme is captured by the interference constraint given below.

5.1.1. Interference constraint

Let (u,v) and (i,j) be two distinct links and let $\Psi(\cdot)$ denote the subcarrier assignment of a link. We define the interference constraint for subcarrier allocation as follows: For a given node n

$$\Psi(u,v) \neq \Psi(i,j), \quad \forall (u,v) \in L_I(n) \text{ and } (i,j) \in L_I(n) \text{ and } (u,v) \neq (i,j) \tag{10}$$

The above constraint states that subcarriers assigned to links within the interference link set of each relay must be unique (each subcarrier is allocated only once within the interference link set). Fig. 3 shows an illustration of the interference constraint where links (u,v) and (i,j), both within $R_I(n)$, will be assigned different subcarriers.

Each link is allocated subcarriers from the subcarrier set C. To keep track of the available subcarriers in the interference link set of each node, we define the available subcarrier set for each link as follows. The available subcarrier set denoted as $\mathscr{A}(l)$ for link l at a particular time is the set of subcarriers which have not been allocated to any link in the interference link set of node n, $L_I(n)$.

We allocate subcarriers using the interference constraint above while jointly allocating power to the nodes according to time and QoS constraints. The rate adaptive resource allocation technique under consideration in this paper jointly solves both problems. The optimization problem can be formulated as follows

$$\text{maximize} \quad \sum_{t=1}^{T} \sum_{n=1}^{\mathcal{V}} \sum_{k\in A_n(l)} log_2(1 + P_{n,k}(t)\gamma_{n,k}) \tag{11}$$

$$\text{subject to} \quad \sum_{t=1}^{T} \sum_{n=1}^{\mathcal{V}} \sum_{k=1}^{K} P_{n,k}(t) \leqslant P_{total} \tag{12}$$

$$P_{n,k}(t) \geqslant 0 \tag{13}$$

$$\sum_{t=1}^{T} \sum_{n=1}^{\mathcal{V}} \sum_{k=1}^{K} y_{n,k}(t) + \sum_{t=1}^{T} \sum_{m=1}^{\mathcal{V}} \sum_{k=1}^{K} y_{m,k}(t) \leqslant 1 \tag{14}$$

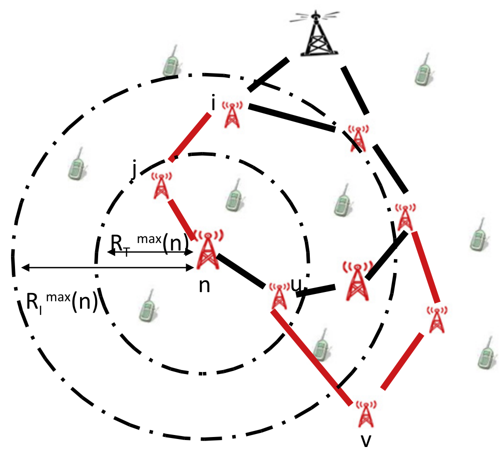


Fig. 3. Illustration of the subcarrier allocation interference constraint.

$$\frac{G_{n,k}P_{n,k}(t) + (1 - y_{n,k}(t))}{\xi} \geqslant \beta, \quad \forall n \in \mathscr{V}, \quad \forall t \in T, \quad \forall k \in K \tag{15}$$

$$y_{n,k}(t) \leqslant \frac{P_{n,k}(t)G_{n,k}}{NB}, \quad \forall n \in \mathscr{V}, \quad \forall t \in T, \quad \forall k \in K \tag{16}$$

$$A_1(l) \cup A_2(l) \cup \ldots \cup A_{\mathscr{V}}(l) = \{1, 2, \ldots, K\} \tag{17}$$

$$y_{n,k}(t) \in \{0, 1\} \tag{18}$$

$$R_1 : R_2 : \ldots : R_{\mathscr{V}} = \alpha_1 : \alpha_2 : \ldots : \alpha_{\mathscr{V}} \tag{19}$$

where $\mathscr{V}$ is the total number of nodes (users and relays), K is the total number of subcarriers, P_{total} is the overall available power and $P_{n,k}(t)$ is the power allocated to the nth node on the kth subcarrier. This signal power is split across the different subcarriers that node n uses. $\gamma_{n,k} = \frac{|G_{n,k}|^2}{\frac{NW}{K}}$ is the channel gain to noise power ratio for the nth node on the kth subcarrier. $G_{n,k}$ is the channel gain for the nth node on the kth subcarrier, N is the noise power, and W is the overall available bandwidth. $A_n(l)$ is the set of all subcarriers allocated to the nth node. The rate of the nth node, R_n, is defined as $\sum_{k \in A_n(l)} log_2(1 + P_{n,k}(t)\gamma_{n,k})$ (as given in the objective function of Eq. (11)). $\{\alpha_1, \alpha_2, \ldots, \alpha_{\mathscr{V}}\}$ is the set of predetermined constants to ensure proportional fairness amongst nodes.

Constraints in Eqs. (14)–(16) reflect the scheduling constraints [30]. Because we use spatial reuse when assigning subcarriers, we must ensure that the transmissions on the same subcarrier do not interfere if scheduled in the same time slot. Therefore, we check if these transmissions contribute to the SINR and if so, schedule these transmissions in different time slots. We modify the SINR equation given in Eq. (1) to incorporate the effect of transmissions on the same subcarriers

$$SINR^t_{n,k} = \frac{G_{n,k}P_{n,k}(t)}{N + \sum\limits_{m \neq n} X_m G_{m,k} P_{m,k}(t) \chi_{m,k}} \geqslant \beta \tag{20}$$

X_m is a binary variable which denotes whether node m is transmitting or not. $\chi_{m,k}$, also a binary variable, denotes whether node m is transmitting on the same subcarrier k as node n. The constraint in Eq. (14) states that two adjacent links must be assigned different time slots while Eq. (15) expresses the required SINR threshold that should be satisfied to have a successful transmission. The term $1 - y_{n,k}(t)$ ensures that the SINR inequality is satisfied when node n does not transmit in time slot t. ξ denotes the denominator of Eq. (20). Eq. (16) is based on the assumption that all links in the network satisfy the SINR constraint when there are no concurrent transmissions.

5.2. Proposed sub-optimal solution

To solve the rate adaptive joint subcarrier and power allocation optimization problem presented in Section 5.1 we propose a sub-optimal solution. Each of the K subcarriers is to be allocated to at least one of the $\mathscr{V}$ nodes and the power allocated to each of the $\mathscr{V}$ nodes is to be optimized. This means that $\mathscr{V} + K$ parameters need to be optimized to achieve the optimal solution. Power allocation amongst subcarriers belonging to a particular node is achieved through waterfilling. According to [11], the optimization problem given in Eq. (11) can be simplified into one that has K optimization parameters by assuming equal power allocation to all subcarriers, i.e.,

$$P_{n,k} = \begin{cases} \frac{P_{total}}{K} & \text{if } k \in A_n(l) \\ 0 & \text{otherwise} \end{cases} \tag{21}$$

for all $k = 1, 2, \ldots, K$ and $n = 1, 2, \ldots, \mathscr{V}$. Since the power allocated to each subcarrier is fixed, optimization now involves assigning the K subcarriers to $\mathscr{V}$ nodes. In our proposed solution, optimization of the $K + \mathscr{V}$ parameters is carried out by alternating between subcarrier and power allocation. We use waterfilling for each node. When a subcarrier is allocated to a node, the power allocated to the node is incremented by $\frac{P_{total}}{K}$, i.e., the power allocated to each node is proportional to the number of subcarriers currently allocated to that node. The node's rate is also updated assuming that waterfilling is used. This updated rate information is used in the allocation of the remaining subcarriers. Thus, the gain from the waterfilling is seen in the subcarrier allocation stage by all the nodes resulting in higher rates. Let T be the number of time slots and let T_n be the number of time slots assigned to the nth node. Let $t(i,j)$ be the time slot of subcarrier k of time index j.

The joint subcarrier and power allocation strategy is as follows.

(1) Initialize $A(l) = \{1, 2, 3, \ldots, K\}, T_n = \emptyset, \lambda_c = \emptyset$
(2) $\forall n = 1$ to $\mathscr{V}, A_n(l) = \emptyset, P_n(t) = 0$
(3) $\forall n = 1$ to $\mathscr{V}$,
  (a) $\gamma_n = max_k \gamma_{n,k}, \forall k \in A(l)$
  (b) $A_n(l) = A_n(l) \cup \{k\}, P_n(t) = P_n(t) + \frac{P_{total}}{K}$
  (c) $R_n = log_2(1 + P_n(t)\gamma(n))$
  (d) $A(l) = A(l) - \{k\}$
  (e) $\lambda_c + +$
  (f) Find a slot $t(i,j) \in T$ so that the SINR is satisfied according to Eq. (20)
  (g) $T_n \leftarrow T_n \cup \{t(i,j)\}$
(4) While $A(l) \neq \emptyset$,
  (a) Find i such that $\frac{R_i}{\alpha_i} \leqslant \frac{R_n}{\alpha_n}$
  (b) For the above i, find k such that $\gamma_{i,k} \geqslant \gamma_{i,j}, \forall (k,j) \in A(l)$
  (c) $A_i(l) = A_i(l) \cup \{k\}, P_i(t) = P_i(t) + \frac{P_{total}}{K}$
  (d) $A(l) = A(l) - \{k\}$
  (e) $\lambda_c + +$
  (f) Find a slot $t(i,j) \in T$ so that the SINR is satisfied according to Eq. (20)
  (g) $T_n \leftarrow T_n \cup \{t(i,j)\}$
  (h) $R_i = \sum_{k \in A_i(l)} log_2(1 + P_{i,k}(t)\gamma_{i,k})$ where $P_{i,k}(t) = \left(\gamma - \frac{1}{\gamma_{i,k}}\right)^+$ and $\sum_{n \in A_i(l)} P_{i,k}(t) = P_i(t)$.

The $f(x) = (x)^+$ operator indicates that $f(x) = 0$ when $x < 0$ and $f(x) = x$ when $x \geqslant 0$. The algorithm described above uses the equation in 4(h) for the rate updates. The proposed algorithm requires waterfilling to be performed $K - \mathscr{V}$ times. In the simulations, given in Section 6, we use waterfilling in Step 4(h) after a subcarrier is allocated to a node. This is for the purpose of evaluating the performance of our proposed algorithm against existing algorithms.

6. Performance evaluation

6.1. Simulation model and performance metrics

We consider a multihop cellular network, $\mathscr{G}$, in a 900 m × 900 m region. Each user generates traffic and the flows are routed towards the base station. There is no downlink traffic generated. We use NS-2 to simulate the networks. The base station is located in the center of the network. Locations for the set of relay nodes that form the mesh network are randomly generated. Locations for the user nodes are also randomly generated. We assume that the BS and relays have an infinite buffer, thus eliminating complications due to buffer overflow. The following numerical parameters are used in the simulations: System Bandwidth (W) = 1 MHz, Number of subcarriers = 256 and 512, AWGN Noise = −90 bBW/Hz, Pathloss exponent (LOS/NLOS) = 2.35/3.76, $P_{total} = 39$ dBm, Frame length = 4 ms, Time slot length = 0.1 ms. As mentioned in Section 3, we use Rayleigh fading for the subcarriers. The maximum transmit power of each relay is 35 dBm and the maximum transmit power of each user is 24 dBm. Packets are scheduled using a first in first out (FIFO) priority scheme. We let $\alpha_1 : \alpha_2 : \ldots : \alpha_{\mathscr{V}} = 1 : 1 : \ldots$ so that the overall rate is maximized while trying to achieve equal rate for all nodes.

To evaluate the performance of our algorithms, we study the following performance metrics: (1) throughput generated by the MCFI; (2) end-to-end delay of the MCFI routing procedure; (3) affect of λ_{max} on subcarrier allocation; (4) throughput generated by the joint subcarrier and power allocation algorithm; and (5) power distribution versus varying number of nodes.

As benchmarks, we compare the MCFI algorithm with two interference aware routing procedures in the literature. First, the algorithm in [31] develops a routing metric where a node calculates the SINR to its neighboring links based on a 2-hop interference Estimation AlgoRithm (2-HEAR). Second, the algorithm given in [32] uses a multicommodity flow approach to routing and uses the protocol model to capture the interference constraints. We denote this algorithm as MCF-Protocol in the simulation graphs. In addition, as benchmarks for comparison of our proposed rate adaptive joint subcarrier and power allocation algorithm, we compare with the two prominent rate adaptive allocation techniques given in [11,33]. In [11], power is allocated uniformly across all subcarriers used by a node. In [33] power and subcarrier allocation is solved separately as individual problems rather than jointly as in this paper.

6.2. Simulation results and discussion

We first evaluate the routing procedure of our MCFI formulation in terms of throughput. The throughput obtained by the MCFI is the overall normalized system throughput obtained under SINR interference constraints. We run simulations on networks with 47 nodes (40 users, 6 relays, 85 links), 25 nodes (20 users, 4 relays nodes, 62 links) and 13 nodes (10 users, 2 relays, 44 links). Each network has 1 base station. The results are shown in Fig. 4 and are averaged over 20 simulations per network. The proposed MCFI algorithm achieves the highest possible throughput compared to the other algorithms. We can justify the better performance of our algorithm as follows: In both the 2-HEAR and MCF-Protocol algorithms, the routing paths are formed using incomplete interference information. In 2-HEAR the SINR calculated by each node only includes those nodes within a 2-hop range which means that even if interference beyond this range occurs, it is not captured in the routing metric. In the MCF-Protocol algorithm, interference is gauged using a distance based method (random interference range is used) which restricts the possibility that transmissions can occur even if they are close to each other as long as the signal strengths do not interfere. In our case, the MCFI algorithm quantifies the interference using a more refined interference range which may be less or more than the 2-hop range.

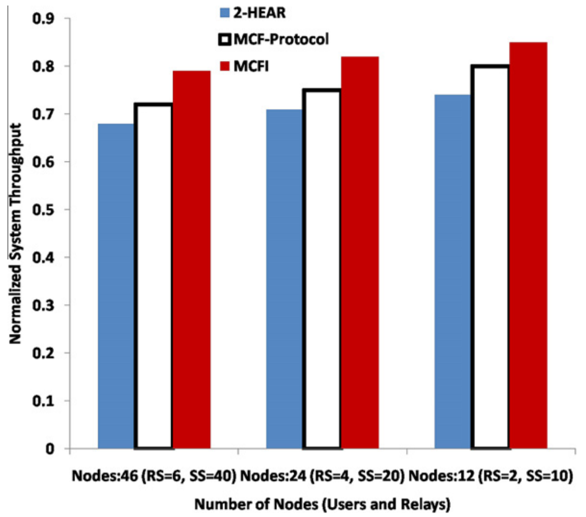


Fig. 4. Throughput results of the MCFI algorithm compared to 2-HEAR [31] and MCF-Protocol [32] algorithms.

We next evaluate the ability of the our MCFI routing approach to decrease end-to-end delay (amount of time it takes to deliver packets from user to the BS). Based on the calculation of SINR at each receiver, the arrived packets are determined to be successfully accepted or dropped. For a given SINR value, two error modeling approaches are most commonly used in network simulations [34]: the SINR threshold (SINRT) based method and packet error ratio (PER) based method. With the SINRT based method, packet error is determined by directly comparing the received SINR with the SINRT. With PER based method, the packet error decision is made probabilistically based on the PER, which can be yielded from the theoretical calculation, link layer simulation or experimental measurement. Generally, it is considered that the PER based method is simpler and more accurate than the SINRT method in a simulation setting; it is also readily available in NS-2. Thus, in our simulations we use the PER model to quantify the packet losses. Because of the fact that the MCFI algorithm captures interference more accurately than the other two algorithms, dropping of packets due to interference is

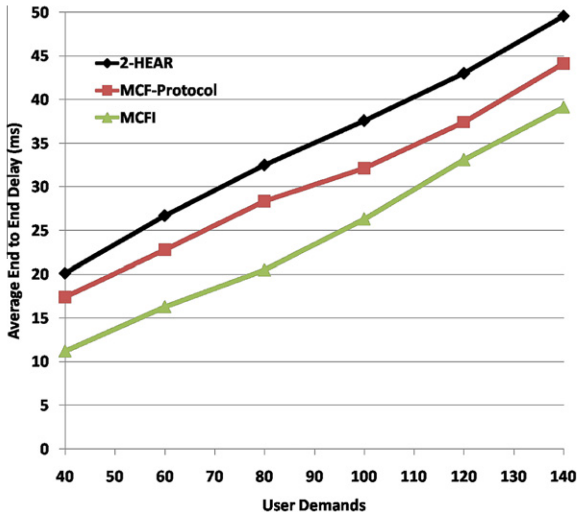


Fig. 5. End-to-end delay comparison for networks with 47 nodes (1 BS, 6 relays and 40 users).

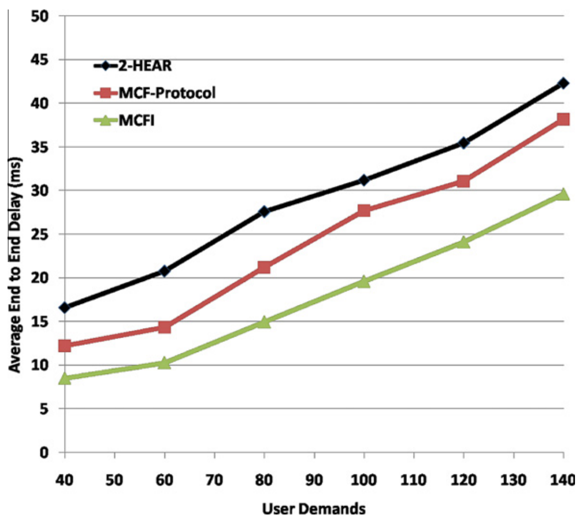


Fig. 6. End-to-end delay comparison for networks with 25 nodes (1 BS, 4 relays and 20 users).

limited. Therefore retransmission time is decreased, thereby improving end-to-end delay. The results are shown in Figs. 5 and 6 for networks with 47 nodes (40 users, 6 relays, 85 links) and 25 nodes (20 users, 4 relays nodes, 62 links), respectively. The results are averaged over 20 simulations. As expected, when traffic load decreases, the delay decreases for all three algorithms. However, the MCFI algorithm has the lowest end-to-end delay when compared to 2-HEAR and MCF-Protocol. We can conclude that the MCFI algorithm effectively incorporates interference constraints into the maximum multicommodity flow approach and thereby provides least interfering paths while maintaining a high throughput.

Finally, we evaluate the effectiveness of the spatial reuse factor in the subcarrier allocation. Specifically, we evaluate the effect of the spatial reuse factor λ_{max} (maximum

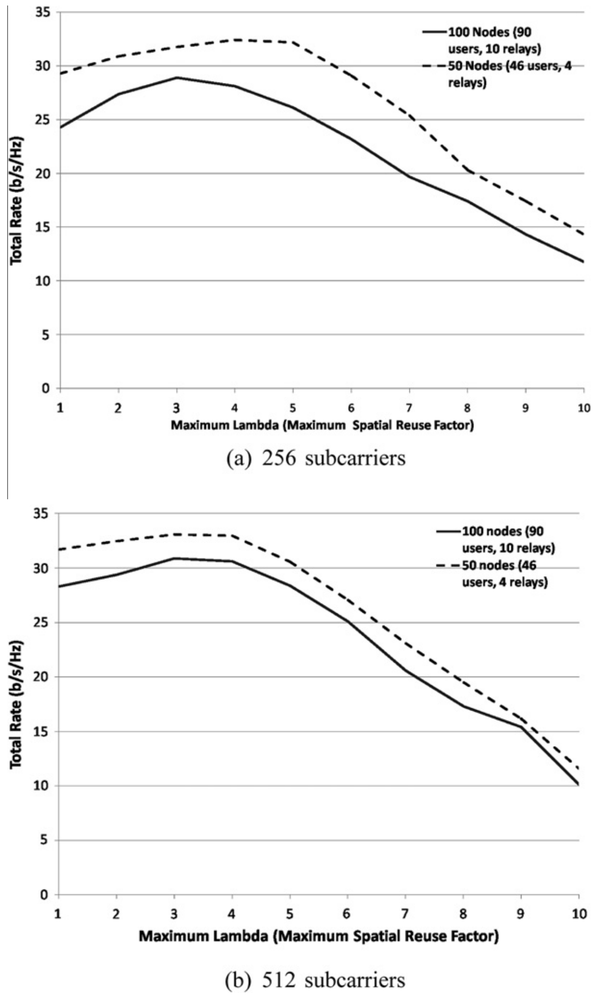


Fig. 7. Effect of spatial reuse of the subcarrier allocation on the total rate.

number of times a subcarrier can be used within a cell). To show how λ_{max} impacts the system performance, we show the total transmission rate for the flows in the network versus varying λ_{max} values. We run simulations using 256 and 512 subcarriers in networks with 50 nodes (46 user nodes, 4 relay nodes) and 100 nodes (90 user nodes, 10 relays). Note each network has 1 base station. We use a 64-QAM modulation strategy. The results are shown in Fig. 7a and b. The λ_{max} value ranges from 1 (no spatial reuse; all subcarriers used only once) to 10. From the results we see that moderate spatial reuse of subcarriers can considerably enhance the performance compared to the case where no spatial reuse is used. In Fig. 7a we see that from $\lambda_{max} = 1$ and $\lfloor \lambda_{max} \rfloor = 4$, there is a 6.32% increase in performance for the 50 node case. Note that $\lfloor \lambda_{max} \rfloor = 4$ is the maximum spatial reuse factor at which performance begins to decrease. In Fig. 7b there is a similar increase of 10% in performance for the 50 node case. The 50 node cases can handle more spatial reuse (i.e., the λ_{max} for the 50 node cases before performance deteriorates is higher than for the 100 node cases) because the number of nodes and links is less, thus inherently they are less susceptible to the same level of interference as the 100 node networks. This is an

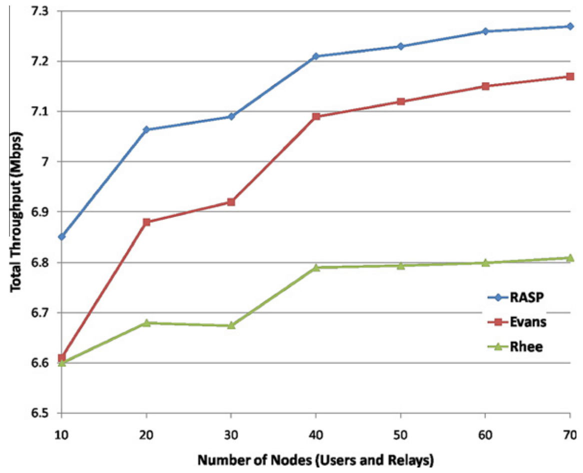


Fig. 8. Total throughput versus the number of nodes.

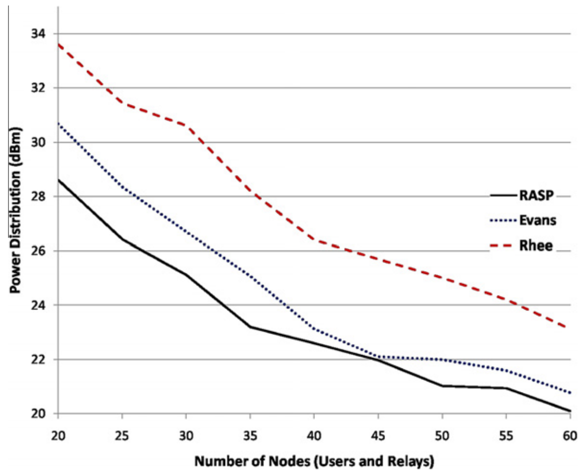


Fig. 9. Comparison of power distribution over varying number of nodes.

indication that our subcarrier allocation strategy does mitigate interference while improving throughput by reusing subcarriers. On the other hand, once the λ_{max} value reaches a certain level, it becomes evident that there is drop in system performance indicating that spatial reuse is no longer a benefit (links begin to strongly interfere). Thus, an appropriate amount of spatial reuse in subcarrier assignment is tolerable.

We next evaluate the effectiveness of our joint subcarrier and power allocation algorithm in terms of throughput versus varying number of nodes. We compare our results (referred to as rate adaptive joint allocation of subcarriers and power (RASP) in the simulation graphs) with the algorithms in [11,33], denoted as Rhee and Evans, respectively, in the simulation graphs. The results are shown in Fig. 8. We see that our algorithm performs better than that of other two approaches for the following reasons: In [11], though proportional fairness is achieved, the frequency selective nature of a node's channel is ignored by allocating power uniformly across all subcarriers belonging to a particular node. The algorithm in [33] takes a two step approach to solve the subcarrier and power allocation problem rather than solve it jointly.

Finally, we evaluate the power distributions for the case of varying nodes. We compare our proposed approach with those in [11,33]. The results are shown in Fig. 9 and are an average over 20 simulations. It can be seen that the performance of our approach and Evans are closer than that of Rhee particularly because with Rhee's approach, the power is uniformly allocated.

7. Conclusion

In this paper, we have developed a framework for interference aware resource allocation for hybrid hierarchical wireless networks. We have shown that our novel approach to solve the interference-based MCF (MCFI) routing algorithm appropriately discovers the least interfering paths while producing the maximum achievable throughput in comparison to other interference based routing protocols. In addition, we have shown that the our subcarrier allocation technique performs better than that of assigning subcarriers with no spatial reuse. However, there is a tradeoff of too much reuse, which is detrimental to network performance. Furthermore, we have shown using a heuristic solution that our proposed rate adaptive joint subcarrier and power allocation algorithm garners better overall throughput than the two well-known joint resource allocation schemes. In addition, our proposed joint allocation algorithm considers the influence of interference on the system performance which is neglected by other schemes. We conclude that our approach, given the proper interference model and algorithmic measures, can mitigate the effects of wireless interference in dense wireless multihop networks thereby providing effective resource distribution.

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