Joint Power-Frequency-Time Resource Allocation in Clustered Wireless Mesh Networks

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Abstract

Wireless mesh networking is an emerging technology for future broadband wireless access. Future wireless networking can benefit from a robust and reliable wireless mesh backbone rendered by mesh routers, providing an all-wireless ambience. Due to the requisite multichannel communications for high-speed data transmissions, power allocation for opportunistically exploiting fading wireless channels, and packet scheduling for QoS provisioning, joint power-frequency-time resource allocation is indispensable. In this article we propose a low-complexity intracluster resource allocation algorithm, taking power allocation, subcarrier allocation, and packet scheduling into consideration. Numerical results demonstrate that our scheme is near optimal, and that our optimality-driven resource allocation approach outperforms a greedy algorithm, working out a better performance compromise among throughput, packet dropping rate, and packet delay.

Wireless mesh networking has emerged as a promising technology for future broadband wireless access, supporting ubiquitous communications and mobile computing. Generally, wireless mesh networks (WMNs) consist of wireline gateways, mesh routers, and mesh clients, organized in a multitier hierarchical architecture [1], as shown in Fig. 1. Recently, wireless mesh networking has been attracting a plethora of attention from academia and industry, for example, Mesh@Purdue, MIT Roofnet, Microsoft, Nokia last mile access (LMA), BelAir Networks, and MeshDynamics. Specifically, wireless mesh networking is of great interest and has several advantages for suburban residential areas [1, 2]. Under this networking paradigm, mesh routers can be set up at premises in the neighborhood, rendering a robust and reliable mesh backbone, and providing an *all-wireless* ambience to the suburban area of interest.

In the literature, pure random medium access is shown to perform poorly in multihop networks. Concerning the capacity of a wireless network with random access, the throughput of a node decreases with the number of wireless nodes [3]. The implication behind these dispiriting results is that a node should only communicate with nearby nodes, thereby favoring *clustering*. Besides, resource allocation should not be random but governed in an orderly manner to improve system performance. In a *multichannel* environment, efficient channel allocation is required to facilitate quality of service (QoS) provisioning and maximize *frequency reuse*. With the help of clustering, channel negotiation can be performed among clusters instead of individual nodes, thereby facilitating efficient channel assignment for satisfying QoS requirements and elevating the system capacity. Within a cluster, collision-free scheduling is feasible with the aid of a clusterhead that collects the requests of and allocates corresponding resources (i.e., power, timeslots, and frequency channels) to its cluster members, satisfying various QoS demands. The resource allocation can be carried out in a hybrid centralized-distributed fashion (i.e., centralized intracluster and distributed intercluster resource allocation). In this article we focus on resource allocation within a cluster for the mesh backbone.

The problem of subcarrier-bit-and-power allocation for orthogonal frequency-division multiplexing (OFDM) systems has been investigated with respect to the physical layer. In [4] a Lagrangian-based approach is employed to solve the total transmit power minimization problem, achieving better power efficiency. However, the high complexity of the proposed algorithm impedes its practical implementation. To reduce the computational complexity, the NP-hard joint optimization problem is decoupled into two smaller problems, suggested in [5, 6]. In [5] the objective function is to maximize the total achievable rate. With a Hungarian approach, the complexity is at least on the order of $O(N^3)$, where N is the number of subcarriers. In [6] a greedy approach based on the signal-to-noise ratio (SNR) is employed to solve the total transmit power minimization problem. QoS demands and fairness constraints are taken into consideration in [7], where heuristic schemes are proposed for convex optimization problems (e.g., the SNR maximization and system throughput maximization problems). Utility-based resource allocation is also studied in OFDM-based wireless networks [8]. In the preceding works time scheduling is not addressed properly, which is vital in a practical medium access control (MAC) scheme for QoS provisioning. Regarding packet scheduling, most of the proposed

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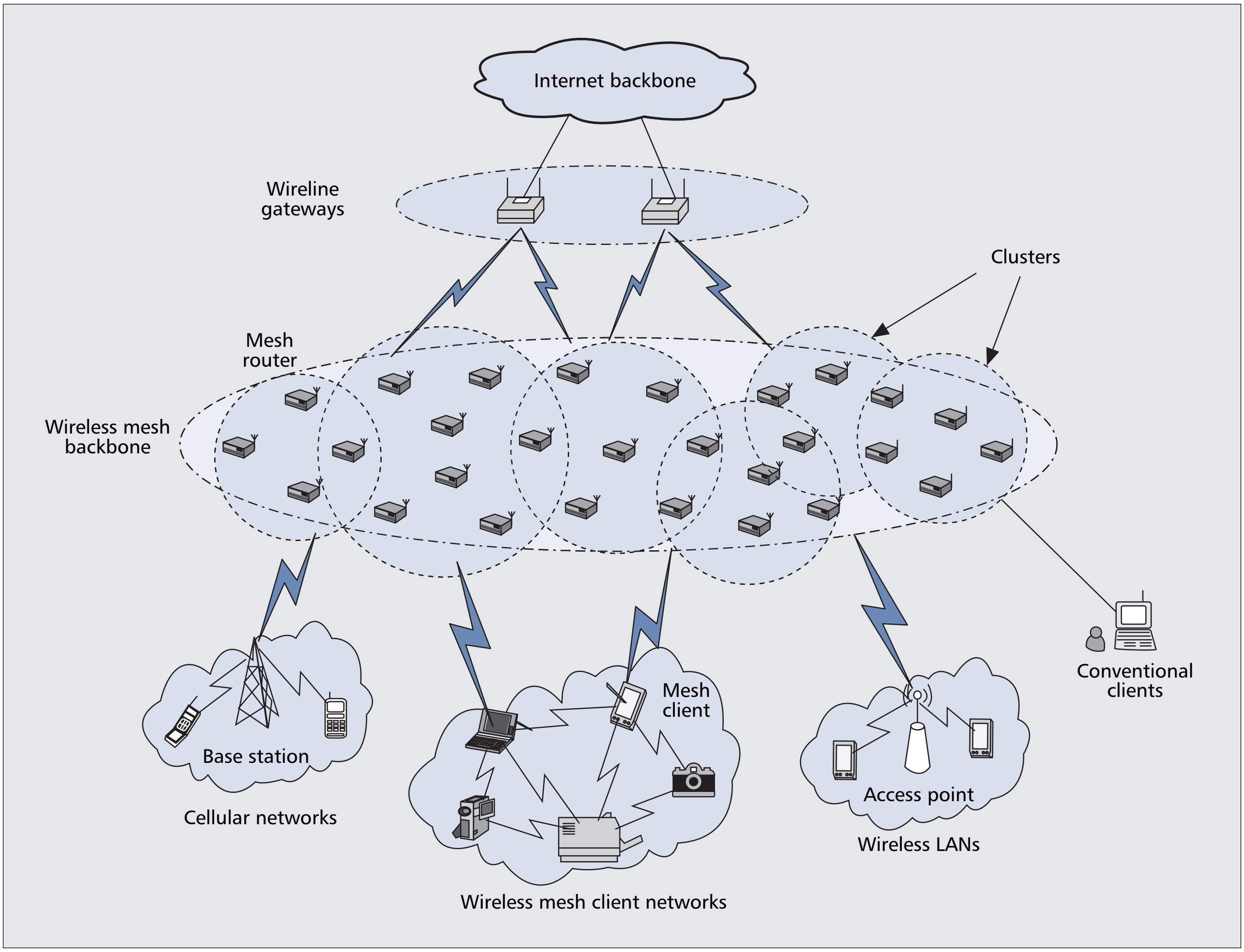


■ Figure 1. *An illustration of a wireless mesh network.*

work either envisages the MAC layer only without taking the wireless channel characteristics into account or does not fully utilize the channel information for resource allocation.

In general, for practical implementation, simple heuristic algorithms are necessary. The cost is system performance degradation, however, which can be far from optimal. A price-based approach is also commonly used by considering the dual optimization problem. Distributed algorithms can be deduced by decomposing a network optimization problem into several user optimization problems. However, finding a suitable pricing scheme may be problematic where the dual problem is not separable. Other work attempts to propose lower-complexity schemes using the theory of convex optimization. Nonetheless, those schemes may not be efficient or applicable to non-convex optimization problems. In this article we propose a low-complexity intracluster resource allocation algorithm for a utility maximization problem, taking power allocation, subcarrier allocation, and packet scheduling into consideration. The time complexity of our proposed scheme is on the order of $O(LMN)$, where L is the number of time slots in a frame, M is the number of active links, and N is the number of subcarriers. The result obtained from our scheme is close to optimal, verified through numerical analysis. Furthermore, computer simulations show that our optimality-driven resource allocation approach outperforms the greedy algorithm by providing a better performance compromise among throughput, packet dropping rate, and packet delay.

System Model

We consider a WMN for suburban residential areas. The underdeveloped terrain in some suburban areas discourages the setup of base stations, giving rise to a preference for distributed control for network operation. In addition, the austere environment thwarts line-of-sight direct communications (i.e., one-hop transmissions). Even if the maximum transmit power constraint is relaxed, successful transmission over a poor link requires very high transmit power, generating more interference, deterring frequency reuse, and hence resulting in inefficient use of network resources. On the other hand, multihop transmissions provide ease of deployment and offer greater coverage of wireless access. In multihop networks the links are relatively shorter, and their quality is usually better. Thus, higher data rates can be attained with lower symbol error rates.

In order to support future wireless broadband applications targeting high-data-rate transmissions, OFDM has been demonstrated as a promising modulation technology with resistance to delay dispersion due to multipath propagation, realizing the notion of multichannel communications. The efficiency of such a high-speed mesh backbone is the key element to success in providing an all-wireless ambience. In fact, the concept of frequency reuse can be exploited to utilize resources more efficiently and ameliorate system capacity. Two transmissions can use the same channel(s) if they are far away enough that the co-channel interference level is below a desired threshold.

We envisage a WMN divided into several clusters (Fig. 1). The network topology can be static or varying, depending on the mobility of mesh routers. Here, we assume the mesh routers are stationary, and the channel gains can be estimated accurately. The cluster structure and hence the clusters can be changed at times for the sake of traffic load distribution. Within a cluster, one node is selected as a clusterhead. The main responsibility of the clusterhead is to provide timing information and perform resource allocation for the active connections in the cluster. Time is partitioned into frames, each of which is further divided into a beacon slot, a control slot, and a number of DATA slots. The beacon is used to provide timing and cluster information, and broadcast scheduling decisions for the DATA slots. In the control slot the clusterhead collects the requests from its cluster members and announces the resource allocation in the subsequent beacon. Each mesh router is equipped with one omnidirectional transceiver so that it cannot transmit and receive at the same time. A mesh router can be a transmitter, relay, or receiver at different times. Some mesh routers are directly connected to a gateway, whereas others are scattered around, rendering a multihop network. With multichannel OFDM technology, each router can choose a set of subcarriers for DATA transmissions and/or receptions, allowing simultaneous transmissions over different subcarriers. In order to focus on intracluster resource allocation, we make the following assumptions for presentation clarity:

- There is a clustering algorithm in place so that frequency reuse can be facilitated and a set of channels allocated in the cluster of interest can be determined.
- Co-channel interference follows a Gaussian distribution. Despite frequency reuse whereby two clusters far away from each other can reuse the same set of subcarriers, dynamic traffic load can cause different interference levels to be experienced by the cluster of interest.
- Effective call admission control is in place such that the QoS requirements of the admitted calls can be satisfied.

Joint Power-Frequency-Time Resource Allocation

With the OFDM physical layer, to support multimedia applications (e.g., voice, video, and data), subcarrier allocation over the frequency domain is necessary to grant diverse transmission rates. By assigning different subcarriers to different nodes, simultaneous transmissions are fostered in a cooperative manner, potentially increasing system capacity. Since different frequency bands experience different channel fading characteristics, power allocation with respect to channel conditions is proven to be crucial for QoS provisioning on multichannel communications. In order to effectively and efficiently support multimedia services with QoS assurance in the MAC layer, bandwidth reservation and hence packet scheduling over the time domain is imperative. Consequently, joint power-frequency-time resource allocation is vital.

There are various constraints associated with resource allocation. At each node, the sum of the transmit power on the allocated subcarriers is bounded by a maximum power level. In subcarrier allocation, similar to the concept of the exclusive region, applying time-division multiple access (TDMA) over a subcarrier is more advantageous than all-at-once transmissions [9]. As a result, each subcarrier can only be allocated to one transmission link in a cluster. Different traffic types require different packet transmission rates. For example, voice packets require a constant rate; video traffic has minimum, mean, and maximum rate requirements; while data traffic is usually treated as background traffic whose source rate is dynamic. In our problem formulation, we only take the minimum rate requirement of these three traffic types, if any, into account. Variable-rate packet transmissions are to be handled by MAC-layer packet scheduling. For simplicity, given the allocation of transmit power, subcarriers, and time slots, the achievable transmission rate is computed using the Shannon capacity formula. With the above constraints, the objective of our joint power-frequency-time resource allocation is to optimize system performance, which can be system throughput, fairness, or trade-offs among several system performance metrics (e.g., a trade-off between throughput and fairness with QoS support [10]). Here, we employ the well-known utility maximization framework to abstract the objective.

Problem Formulation: Consider the following resource allocation optimization problem:

$$\max_{\mathbf{a},\mathbf{p}} \left\{ \sum_{m=1}^{M} U_m(R_m(\mathbf{a},\mathbf{p})) \right\} \tag{1}$$

$$\text{subject to } R_m\ (\mathbf{a},\ \mathbf{p}) \ge R_m^d,\ \forall m \tag{2}$$

$$p_{m,n}^l \ge 0,\ \forall_{m,n,l} \tag{3}$$

$$\sum_{n=1}^{N} p_{m,n}^l = p_m^{\max}, \forall_{m,l} \tag{4}$$

$$\sum_{m=1}^{M} a_{m,n}^l = 1, \forall_{n,l} \tag{5}$$

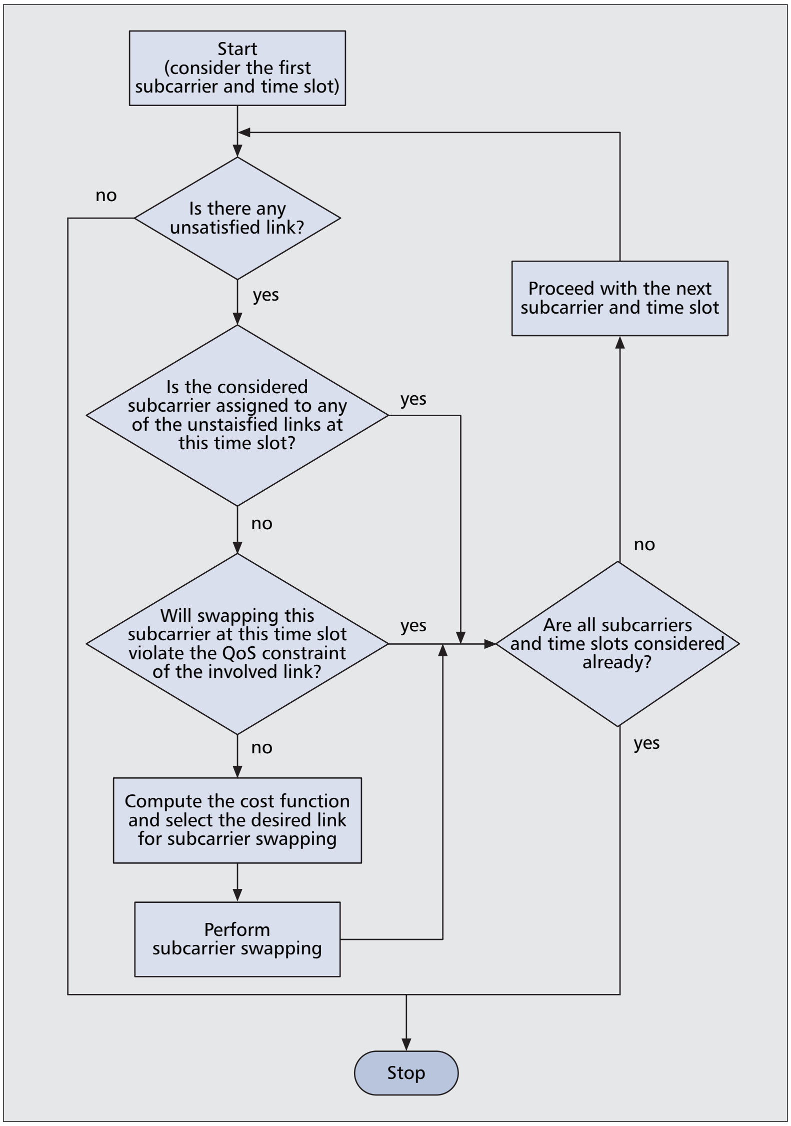
$$a_{m,n}^l \in \{0,1\},\ \forall_{m,n,l} \tag{6}$$

where $U_m(.)$ is the utility function of the mth link,

$$R_m(\mathbf{a},\mathbf{p}) = \sum\nolimits_{l=1}^{L} \sum\nolimits_{n=1}^{N} a_{m,n}^l \ln\left(1 + \frac{G_{mm,n}^l p_{m,n}^l}{I_n + \eta}\right)$$

representing the actual aggregate transmission rate of the mth link over a frame with $\mathbf{a} = [a_{m,n}^l]_{M\times N\times L}$ and $\mathbf{p} = [p_{m,n}^l]_{M\times N\times L}$, $a_{m,n}^l$ is the indicator of allocating the nth subcarrier to the mth link on the lth time slot, $p_{m,n}^l$ is the transmit power over the nth subcarrier of the mth link's transmitter on the lth time slot, $G_{mk,n}^l$ is the channel gain from the kth link's transmitter to the mth link's receiver over the nth subcarrier on the lth time slot, I_n is the interference power at the nth subcarrier, η is the background noise power, R_m^d is the minimum required rate of the mth link, $P_m^{\max}$ is the maximum power constraint of the mth link's transmitter, M is the number of active links in a cluster, N is the number of subcarriers available in a cluster, and L is the number of time slots (i.e., DATA slots) in a frame. The objective function given by Eq. 1 is to maximize all the utility functions. Here, we assume that $U_m(R_m\ (\mathbf{a},\ \mathbf{p}))$ is an increasing function of $R_m\ (\mathbf{a},\ \mathbf{p})$ for all m. QoS constraints in terms of transmission rates are given by Eq. 2. The transmit power is non-negative, given by Eq. 3. Since increasing power can always increase the rate on a subcarrier and hence the utility, the sum of the transmit power over all the subcarriers should equal the maximum transmit power, which is given by Eq. 4. Constraints for subcarrier allocation are given by Eqs. 5 and 6, for a subcarrier can only be allocated to one transmission link.

By interpreting the Karush-Kuhn-Tucker (KKT) conditions, the criterion of subcarrier allocation can be deduced as follows: For each timeslot l and each subcarrier n, choose m^* such that



■ Figure 2. *Subcarrier swapping.*

$$m^* = \arg\max_{m} \left\{ U'_m(R_m(\mathbf{a},\mathbf{p})) \ln\left(1 + G^l_{mm,n} p^l_{m,n} / I_n + \eta\right) \right. \tag{7}$$

and set $a^l_{m^*,n} = 1$. For a given subcarrier assignment, the optimal power allocation can be obtained via *utility-based water-filling*. However, the criteria of optimal subcarrier and power allocation are coupled. To reduce computational complexity, our resource allocation first fixes the power allocation, invokes subcarrier allocation based on the criterion given in Eq. 7, reallocates the subcarriers until all the system constraints are met, and performs utility-based water-filling for power allocation. The detailed procedure is given below.

Step 1: For each user m, equally distribute the transmit power over all N subcarriers on each time slot l.

Step 2: For each time slot l and each subcarrier n, allocate the nth subcarrier according to Eq. 7. Repeat until all subcarriers are allocated over all time slots in the next frame.

Step 3: Since the initial obtained resource allocation may not satisfy all the constraints in Eq. 2, subcarrier reallocation is needed. Subcarrier reallocation should result in only a small decrease in total utility while satisfying all QoS constraints. Let M_u be the set of unsatisfied links. Consider the following cost function of reallocating a subcarrier to the jth link instead of the originally assigned ith link:

$$e_{j,n} = \left(\frac{1}{U_i(R_i(\mathbf{a},\mathbf{p})) - U_j(R_j(\mathbf{a},\mathbf{p}))} \cdot \right) \left(\frac{a^l_{j,n} \ln\left(1 + G^l_{jj,n} p^l_{j,n} / (I_n + \eta)\right) \cdot}{R^d_j - R_j(\mathbf{a},\mathbf{p})} \right), \forall j \in M_u. \tag{8}$$

The cost represents the *likelihood* of reallocating the nth subcarrier to the jth link instead of the originally assigned ith link. The first term in Eq. 8 measures the decrease in the total utility for subcarrier swapping. The smaller the change in total utility, the larger the value of the first term, maintaining the objective function as large as possible. The second term indicates the tendency of satisfying the QoS requirement of the jth link if the nth subcarrier is reallocated to it. The larger the second term, the more likely the QoS requirement of the jth link can be met. Therefore, we should choose the subcarrier with the maximum cost (i.e., $j^* = \arg\max_{j \in M_u} e_{j,n}$). If the QoS constraints in Eq. 2 for the ith link are not violated, perform subcarrier swapping by setting $a^l_{j^*,n} = 1$ and $a^l_{i,n} = 0$. Repeat this step until all the subcarriers and the timeslots have been searched. The flowchart of the subcarrier swapping is depicted in Fig. 2.

Step 4: For each timeslot l, perform utility-based water-filling for power allocation on each link.

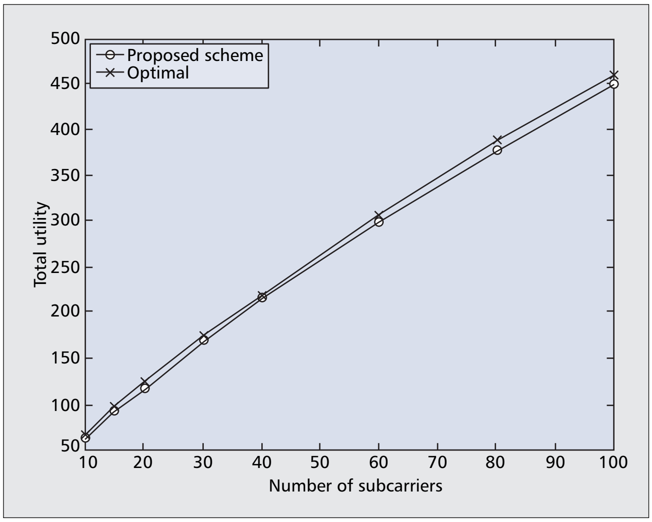
The time complexity of our proposed algorithm is on the order of $O(LMN)$ only, leading to low computational cost and hence facilitating practical implementation.

In terms of medium access, we consider a simple MAC protocol to illustrate the notion of packet scheduling. Each node estimates the traffic load by averaging the rate requirement over the fixed estimation window (e.g., 100 ms) on a regular basis. In the control slot the clusterhead collects the traffic demand from its cluster members by polling them periodically. Then the clusterhead runs the proposed algorithm and announces the resource allocation decision in the next beacon slot. The time slots and subcarriers allocated to a particular node (or link) are reserved for packet transmissions in the DATA slots until the next polling. To streamline QoS provisioning, service differentiation is essential, which can be achieved through packet prioritization, meaning that a higher-priority packet is served before a lower-priority one. We conceive that priority of voice packets and video packets is related to the performance of their packet dropping rates. The higher the packet dropping rate a traffic flow experiences, the higher the priority of the packets associated with that flow. After gathering the transmission requests, the clusterhead grants the requests of those higher-priority packets first, facilitating QoS provisioning.

Performance Evaluation

Numerical Analysis

First, we compare our proposed resource allocation scheme with the optimal solution. The optimal solution is acquired by an exhaustive search, where complexity is at least on the order of $O(M^{NL})$. In the numerical analysis, the objective function given in Eq. 1 is chosen to maximize system throughput (i.e., $U'_m(.) = 1$). We consider $M = 3$, $L = 1$, $R^d_1 = 9$ kb/s, $R^d_2 = 0$



■ Figure 3. *Comparison of the results obtained from our proposed resource allocation algorithm and the optimal solution acquired via an exhaustive search (system parameters:* $M = 3$, $L = 1$, *and* $R^d = [9, 0, 3]$ *kb/s; channel model parameters:* $d_0 = 100$ *m,* $l \approx 0.1579$ *m,* $a = 4.6$, $b = 0.0075\ m^{-1}$, $c = 12.6$ *m,* $h_b = 10$ *m, and* $\sigma_s = 10.6$ *dB).*

kb/s, and $R_3^d = 3$ kb/s. The bandwidth occupied by each subcarrier is assumed to be 1 MHz. We adopt the channel model suggested in [11]. Figure 3 shows the total utility as a function of the subcarrier number. It is observed that the performance of our proposed resource allocation scheme is close to the optimal solution. Due to the low complexity and near-optimal performance, our resource allocation algorithm can be a good candidate for implementation in practice.

Simulation

We consider a cluster with several wireless nodes randomly located in a 1 km × 1 km coverage area. We assume that the routing is predetermined, so the transmission source and destination pair of an incoming packet is known in advance. Simulation parameters are chosen as follows: $\eta \sim N(0,10^{-12}\text{ W})$, $I_n \sim N(0,10^{-10}\text{ W})$, $\forall_n$, $P_m^{\max} = 8$ mW, $\forall_m$, $U_m(R_m(\mathbf{a}, \mathbf{p})) = R_m(\mathbf{a}, \mathbf{p})$, $\forall_m$, $N = 100$, and $L = 4$. The operating frequency band is assumed to be 1.9 – 2.0 GHz. The bandwidth and maximum transmission rate of each subcarrier are set to be 1 MHz and 1 Mb/s, respectively. There are one beacon slot, one control slot, and four DATA slots in a frame. The duration of a time slot is 5 ms; hence, the duration of a frame is 30 ms. The polling is done every 100 ms. Both the polling and beacon packet transmission are assumed to be error-free. We perform the simulations for 1000 runs and average the results, where each simulation run sustains 10,000 frames.

In the simulations voice traffic is generated according to a two-state ON-OFF model. In the ON state a fixed-size packet arrives at a constant rate, whereas in the OFF state no packet is generated. The duration of an ON period and that of an OFF period both follow an exponential distribution. For simplicity, video traffic is characterized by a two-state ON-OFF model [12], where different incoming packets have different packet sizes, generating variable-rate traffic in the ON state. Data traffic is the background traffic and available anytime, without any rate requirement.

In our simulations data packets, assigned the lowest priority, can be transmitted whenever there are excess resources left in the system. The parameters of the voice and video traffic models are summarized in Table 1. To mimic mixed traffic types in the mesh backbone, we assume that there are a voice source, a video source, and a data source residing at every node. Higher-priority packets are to be served first. If the packets are of the same priority, they are served in a first-come-first-serve manner.

We carry out simulations to compare the proposed scheme with a greedy resource allocation scheme. In the greedy resource allocation scheme each node selects a number of subcarriers to meet its current traffic demand. Subcarrier selection is considered to be random. Transmit power is uniformly distributed over the selected subcarriers. If a subcarrier is chosen by more than one node, a collision occurs, and the subcarrier is wasted and does not contribute to the actual packet transmission rate. Packet scheduling with resource reservation is not taken into account in this greedy algorithm. Since every node behaves independently, the complexity of this greedy algorithm is on the order of $O(N)$.

We evaluate system performance in terms of throughput, packet delay, and packet dropping rate. We study the impact of the number of links on system performance for both schemes. For a fair comparison, we employ the same call admission control for both the proposed scheme and the greedy scheme: we acquire the maximum number of voice and video calls that can be admitted into the system without violating their QoS constraints by carrying out offline simulations based on our proposed resource allocation approach. Here, serving as a benchmark, we set the maximum number of admitted voice calls and that of admitted video calls to be 13 and 12, respectively. Figure 4 shows the throughput performance for background data traffic vs. the number of links. The standard deviations of the results are also plotted for

Parameter	Definition	Value
$\bar{T}^{ON}_{voice}$	Mean ON period for voice traffic	1.00 s
$\bar{T}^{OFF}_{voice}$	Mean OFF period for voice traffic	1.35 s
t_{voice}	Packet interarrival time for voice traffic	20 ms
R_{voice}	Constant data rate for voice traffic	32 kb/s
D_{voice}	Delay bound for voice traffic	20 ms
PLR_{voice}	Packet loss rate for voice traffic	1 percent
$\bar{T}^{ON}_{video}$	Mean ON period for video traffic	1.47 s
$\bar{T}^{OFF}_{video}$	Mean OFF period for video traffic	1.92 s
t_{video}	Packet interarrival time for video traffic	5 ms
R_{video}	Minimum data rate for video traffic	256 kb/s
D_{video}	Delay bound for video traffic	75 ms
PLR_{video}	Packet (frame) loss rate for video traffic	1 percent

■ Table 1. *Summary of simulation parameters and the values used for them.*

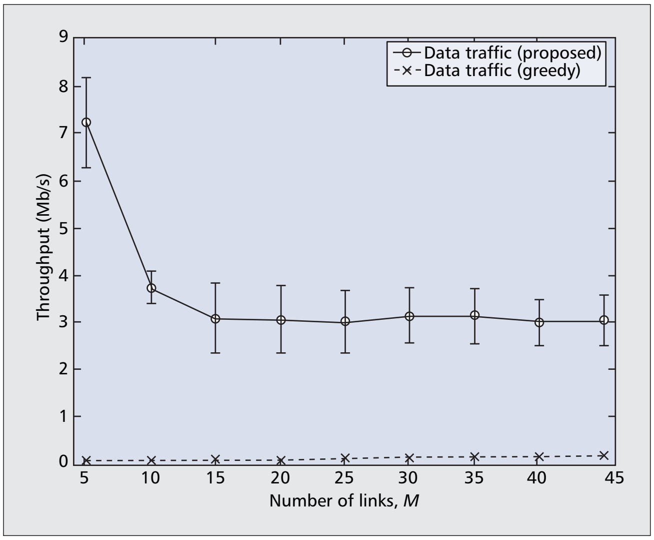


Figure 4. *Comparison of the throughput performance of the proposed algorithm and that of the greedy scheme vs. the number of links.*

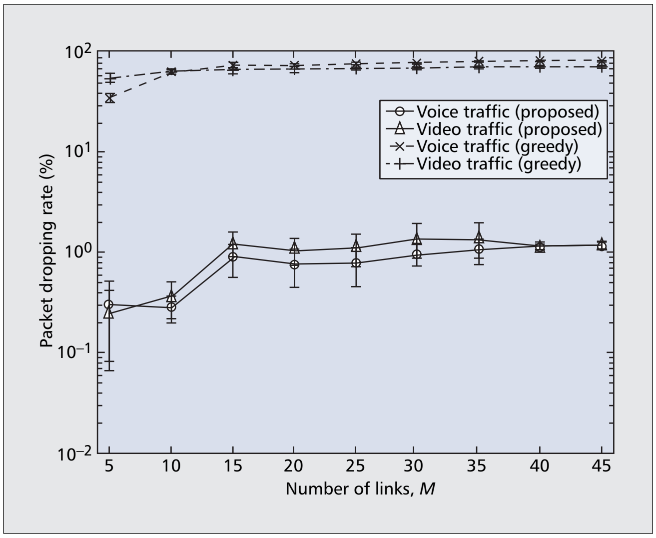


Figure 5. *Comparison of the packet dropping rate of the proposed algorithm and that of the greedy scheme vs. the number of links.*

reference. Clearly, our optimality-driven resource allocation approach achieves significantly higher total throughput than the greedy one, and our scheme is more robust against the increase in the number of active links. The total throughput of background data traffic in our proposed approach drops when the number of links increases, due to the fact that more network resources (i.e., bandwidth) are to be reserved for the real-time traffic and more nodes compete for the reduced amount of resources left for background data traffic. Thus, the total throughput for data traffic decreases. On the other hand, due to the call admission control in place, no more than 13 voice sources and 12 video sources can be admitted into the system. From $M = 15$ onward, the amount of resources left for data traffic is more or less the same, and hence the total throughput levels off. The slight fluctuation of the curves is partly because of the random arrival of voice and video packets. Regarding system throughput contributed by all three traffic sources, it can be observed that the system throughput drops from about 8.5 Mb/s to about 6.5 Mb/s when the number of links increases from $M = 5$ to 15 in our proposed scheme. The reduction in system throughput is ascribed to the bandwidth reservation for the real-time traffic. The simulation results illustrate the fact that QoS provisioning and system throughput increment are two conflicting performance metrics [10]. In Fig. 5 the voice/video packet dropping rates are depicted. The packet dropping rates for both voice and video traffic are capped (by the level of 1 percent) in the proposed scheme, whereas in the greedy approach the packet dropping rates for both voice and video traffic increase from $M = 5$ to 15 and then roughly level off afterward (due to the call admission control). It is observed that the greedy scheme has poor packet dropping performance and basically cannot provide the same level of QoS assurance as our optimality-driven approach. Under the same call admission control criterion, both voice and video packet dropping rates are far lower in our proposed scheme, for QoS provisioning and packet scheduling with bandwidth reservation are taken into consideration. Concerning packet delay performance for both voice and video traffic, we observe that the packet delays of voice and video traffic in our proposed scheme are about 8 ms and 9.5 ms, respectively, more or less independent of the link number. Both packet delays using the greedy approach are around 2.5 ms. Apparently, the greedy scheme has better delay performance for real-time traffic. The fact, however, is that the successful packet transmission rate in the greedy scheme is so low that the dispersion of the delay experienced by those packets is small. On the contrary, the proposed scheme works out a good performance compromise among throughput, packet dropping rate, and packet delay. Our simulation results reinforce the idea that greedy (or random) resource allocation cannot efficiently provision QoS, leading to poor resource utilization and system performance. To acquire higher resource efficiency, the methodology of the optimality-driven resource allocation approach is demonstrated as promising, thereby facilitating QoS provisioning and improving system capacity.

Conclusion and Further Work

Effective and efficient resource allocation is essential for meliorating system performance in WMNs with heterogeneous traffic. In this article we have addressed and proposed a low-complexity algorithm for the joint power-frequency-time intracluster resource allocation problem. Via numerical analysis, our proposed scheme is shown to be close to optimal. Simulation results demonstrate that our optimality-driven resource allocation approach performs better than the greedy approach, providing a better performance trade-off among throughput, packet delay, and packet dropping rate.

For further research, node clustering specifically tailored for WMNs is needed to bring about a stable and scalable networking architecture. Due to unique networking characteristics, novel intercluster scheduling and communications targeted for WMNs are imperative. In addition, accurate traffic modeling is necessary to evaluate and validate system performance.

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