Efficient Resource Allocation in Hybrid Wireless Networks

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Abstract— **In this paper, we study an emerging type of wireless network - Hybrid Wireless Networks (HWNs). A HWN consists of an infrastructure wireless network (e.g., a cellular network) and several ad hoc nodes (such as a Mobile ad hoc network). Forming a HWN is a very cost-effective way to improve wireless coverage and the available bandwidth to users. Specifically, in this work we investigate the issue of bandwidth allocation in multi-hop HWNs. We propose three efficient bandwidth allocation schemes for HWNs: top-down, bottom-up, and auction-based allocation schemes. In order to evaluate the bandwidth allocation schemes, we develop a simulated HWN environment. Our simulation results show that the proposed schemes achieve good performance: the schemes can achieve maximum revenue/utility in many cases, while also providing fairness. We also show that each of the schemes has merit in different application scenarios.**

Keywords- Hybrid wireless networks; resource allocation; fairness; profit maximizing allocation; bandwidth

I. INTRODUCTION

The combination of IEEE 802.11 Wi-Fi and 3G/4G cellular networks could significantly increase the coverage and/or bandwidth of mobile users while keeping additional costs low. Bandwidth requirements continue to increase due to new, bandwidth-hungry "apps" and the increasing computing resource requirements of today's mobile devices. These applications, including web browsing, VoIP, and streaming media, require larger and larger amounts of bandwidth and backbone infrastructure resource support, and therefore create new challenges for today's wireless networks. Previously, it was easy for network providers to allocate data channels for a few laptops in predictable high usage areas. These users had a distinct preference to hard line Internet connections, or local wireless networks, which generally have a surplus of bandwidth; so it was easy to predict the locations where the most intense mobile wireless usage would be – areas like airports and train stations where no (free) Wireless LANs (WLANs) exist. Coffee shops and libraries already had free WLANs (usually 802.11 Wi-Fi) connectivity; therefore urban areas that contained these types of places were not high priority for dedicated data channels. Now, modern wireless networks provide "last mile" broadband connectivity, and must provide multiple entry points into the wide area network, where there are no clear geographic constraints like those that laptop users faced.

Static wireless networks are necessarily constrained in their ability to support the requirements of its users because of a myriad of factors, including the mobile nature of those users, limitations in resources across segments of the network and routing inefficiencies between different devices [1]. Prioritizing an 802.11 connection over a 3G connection lowers the burden on traditional cellular networks somewhat, but not completely [2]. The emergence of a hybrid 802.11 and 802.16 network (e.g., Sprint 4G) to replace wired cable only means that bandwidth allocation issues are still a priority. Other services like Clear 802.16 4G for laptops (which also have 802.11 radios), show a trend that in the near future. The emergence of Hybrid Wireless Networks (HWNs) is necessary to accommodate the increasing wireless broadband demand, and not only provide cost reduction for better coverage but also to increase resource availability [3].

HWNs may achieve better performance by dynamic network construction rather than stand alone static infrastructure or ad hoc networking only. A HWN is a combination of an infrastructure network (such as a WiMAX, WLAN, or 3G Cellular networks) and ad hoc components (like Mobile ad hoc networks). HWNs could expand infrastructure coverage either horizontally (expanding coverage) [4] or vertically (expanding bandwidth) [5] at a low cost. HWNs provide mobile users the benefits of several types of networks-bandwidth, coverage, and mobility in a seamless fashion.

Most existing papers on HWNs did not study the resource allocation issue, but rather only discussed how hybridization could improve bandwidth availability [6]. A number of papers proposed resource allocation schemes for a non-hybrid context, for example, agent-based approaches as in [7]; micro-economic or game theoretic approaches as in [8], [9], and [10]; or via some min-max algorithms for certain network metric as in [11], [12], and [13]. In this work, we investigated the resource allocation issue specifically for HWNs.

In this paper, we consider a hybrid network made up of base stations (BS) that connects to relay stations (RS). A mobile device may connect to either a BS or a RS (then to a BS). The BS has a fixed amount of bandwidth that it can provide to each RS, and each RS has a set amount of demands based on the number and requirements of each of its mobile nodes. When user bandwidth demand exceeds the available bandwidth, the BS has to allocate its resources in an efficient, fair, and profit maximizing manner. Although the resource allocation problem has been well studied in traditional cellular networks, few works have studied the issue in the specific context of a Hybrid Wireless Network.

The rest of the paper is organized as follows. In Section II, we discuss the impacts of hybridization and adding relay stations. In Section III, we describe our simulated network environment. In Section IV, we present our resource allocation schemes and their performance. In Section V, we conclude this paper.

II. IMPACTS OF HYBRIDIZATION AND RELAY STATION

Generally, the deployment of infrastructure resources is limited by geographic coverage and resource availability, which are inversely related.

There are two typical ways to build/improve backbone networks. The first type of network uses a high bandwidth backbone that adds more expensive BS to the network to provide more bandwidth to users, but at the cost of less geographic coverage. This type of network is referred to as the bandwidth-maximization network, as illustrated in Figure 1. The second type of network seeks to maximize geographic coverage, and as a result cannot provide as much bandwidth per user as the first type. The second type of network is referred to as the coverage-maximization network, as illustrated in Figure 2. Bandwidth allocation itself is made difficult because not all mobile devices are the same: some devices demand significantly more bandwidth for applications that go beyond simple voice and data; and secondly, not all networks are created equally. This is especially apparent in the current customer war between AT&T and Verizon. During mobile network development, there is typically a trade-off between performance (bandwidth) and coverage.

Certainly this affects device choice across those networks. For instance, AT&T was the ideal network provider and partner for Apple during the release of their 3G iPhone. Simply put, no other network was capable of providing extensive data coverage for these new, bandwidth-expensive devices. The joke is now that iPhone users have great applications on their phone, but they can't make a call! The high bandwidth backbone network contains fewer, more bandwidth intensive devices provisioned via BS that provide a higher amount of bandwidth. Devices that require low amounts of bandwidth are typically not provided with service in favor of the more expensive, bandwidth hogging devices.

Coverage-maximization networks on the other hand use slightly different topography. Overlapping coverage regions mean that bandwidth is provided more frequently to lower usage devices. Bandwidth allocation is a tougher issue, simply because there are more devices requesting bandwidth. These networks value more connections/coverage at a lower bandwidth, and thus high usage mobile devices are at a distinct disadvantage. This type of network provides larger geographical coverage, sacrificing the amount of available bandwidth per network region.

These two very different types of network designs produce different challenges in resource allocation, where one type of network may favor certain means of allocation schemes over others. Simply adding infrastructure would require a lot of investments from wireless service providers, and it may not solve the problem because user bandwidth requirements change over time. Hybrid wireless networks not only could extend geographical coverage and increase available bandwidth for users, but also may alleviate the fairness problem among users.

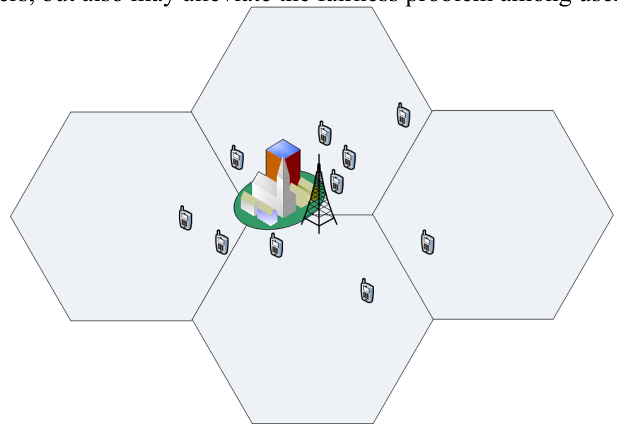

Figure 1. The bandwidth-maximization style network

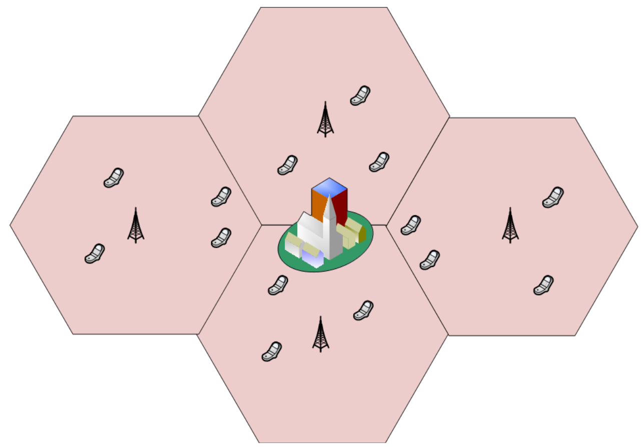

Figure 2. The coverage-maximization style network

As usage requirements change, both types of networks described above must be bolstered in order to meet new requirements. Instead of expanding a backbone network at great expense, we consider a cost-effective solution - the installation of RSs (which may be mobile in order to be brought in for temporary spikes in usage at conferences or major events like the Super Bowl), and the hybridization of the network to allow multi-hop ad hoc routing to provide connectivity to the BS.

The addition of RSs and ad hoc nodes has different effects for the two types of networks described above. In fact, because of the nature of the backbone network, addition of RSs and ad hoc nodes accomplishes two very different goals in terms of network extension.

The geographically distributed BS of the geography-maximizing network do not require RSs to extend coverage: the areas are already well covered by BS. Instead, the addition of RSs and ad hoc nodes in this network type attempts to increase the amount of bandwidth available to mobile nodes. Additional RSs will have the effect of adding a routing layer on top of the existing coverage, meaning that bandwidth throughput can be distributed evenly across the BS, so one BS by itself is not overloaded with bandwidth requests. Ad hoc connectivity means that mobile nodes can choose the best route with the highest available bandwidth, even if that route doesn't terminate in the closest BS.

In the bandwidth-maximizing network, however, fewer BS provide more bandwidth to its mobile nodes. Obviously, the addition of RSs and using multi-hop of mobile nodes in this type of network is meant to extend coverage, without the expense of additional, high cost BS. Ad hoc nodes in this network extend coverage by allowing multi-hop relay (by mobile nodes) from outside the coverage of BS and RSs.

III. SIMULATED NETWORK ENVIRONMENT

In order to test the various resource allocation schemes, we developed a simulated hybrid wireless network that contained various aforementioned network components. The simulated network (illustrated in Figure 3) was designed to evaluate the effects of different allocation schemes on various types of wireless saturation. Although small, this sample network can be thought of as a scale model, with different regions of different requirements, including:

- Low density of low-cost devices
- Low density of high-cost devices
- Average density of low and high cost devices
- High density of average cost devices

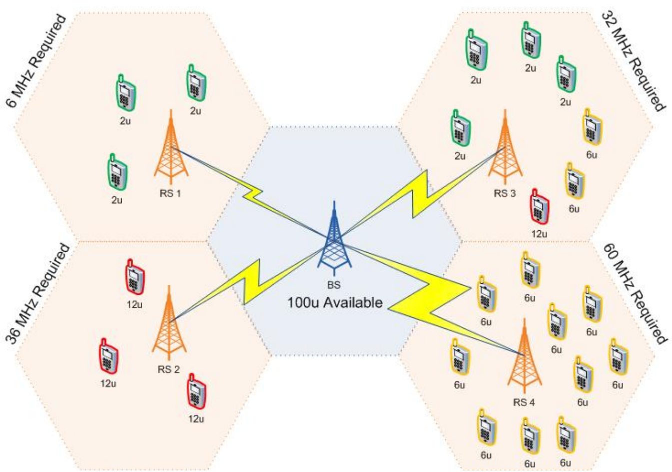

Figure 3. The simulated network environment

The net effect is that of a balance of the two previously described network styles: high resource/low dispersion vs. low resource/high dispersion networks. Importantly, this network has a fixed amount of available bandwidth that is less than the total bandwidth requested by all mobile nodes.

The network consists of a central BS with four attached RSs in a hexagonal cell configuration (allowing for overlap and transference as mobile users move between cells). Two of the regions provided by the BS are not covered by any RS, and could be either ad hoc zones, or with indirect connectivity to the BS. We set the BS resource availability as 100 units (for simplicity, we may refer to the BS as having 100 MHz of bandwidth). Each of the four RSs has a varying amount of bandwidth required by their mobile users from 6 to 60 units (MHz).

Mobile users in the network have different resource requirements, from low bandwidth users (in green) that only use 2MHz of bandwidth, to the high bandwidth users (in red) that use 12MHz. Every cell has a mixture of different user types. It is clear that a simple division of bandwidth in equal parts is insufficient because then only one cell would have its requirements met, and have extra resources that be wasted. In addition, a fix allocation per user is insufficient, because of the varying requirements of users.

Next, we discuss how to calculate profit for a wireless service provider. The utility of each resource allocation scheme is calculated via a profit formula. Each resource allocation scheme seeks to maximize the profit, and there is a profit ceiling based on the total available bandwidth. Each allocation scheme is compared to the others by means of percent profit achieved. In this paper, we use a heuristic, weighted profit scheme that allows for two different profit calculations.

Suppose that each node has a bandwidth requirement (b_r) that if fulfilled provides a certain value/utility to the BS (p_i), then we can calculate the total profit of the BS by summing the profits of those nodes times the percentage their requirements are met. Denote b_i as the bandwidth assigned to user i. We have the total profit P:

$$P = \sum_{i=1}^{n} p_i \times \frac{b_i}{b_r}$$

This approach is a weight-based approach. If one wished to value some nodes higher than others, we can assign those nodes a higher weight. We have the following two methods of assigning weights:

- Equality-based approach: $p_i = 1$ for all nodes. Hence, the maximum P - $P_{max} = n$. In this approach all nodes are treated equally.
- High-cost maximization: p_i is assigned via an increasing function related to bandwidth; fulfilling the requirements of higher-cost nodes will allow higher profit.

In this paper, we adopt an approach that assigns weights by using a heuristic step function, where we have assigned a weight of 2 to low-cost nodes, 4 to medium-cost nodes, and 8 to high-cost nodes.

IV. EFFICIENT RESOURCE ALLOCATION

In this section, we present several resource allocation schemes for HWNs. We also present the simulation results for the schemes obtained by the simulated network environment.

A. Top-Down Allocation

The top-down approach is presented in Figure 4. In the top-down approach for resource allocation, the BS is given the requirements of each RS and then decides how to allocate resources. It has no knowledge of the number of mobile nodes that each RS is provisioning; it only knows the load request from RSs. Once resources are allocated to each RS, the RS performs a similar allocation to its requesting nodes based on the bandwidth provided by the BS.

Table I shows the simulation results of using the top-down fairness-based scheme. For this particular test, the available bandwidth is set to be only 74.6% of the total requested bandwidth. The results in Table I show that the top-down scheme achieves very good performance. The scheme actually has a slightly higher profit (77.29%) than the percentage of the available resources (74.6%). Table I also shows that step-weights perform slightly better than equal-weights. Note that in the simulations there is no penalty for not meeting a node's full bandwidth requirement. The scheme allocates partial resource to some nodes. Also note that the number of low-cost (high-cost) nodes would affect the profit of the scheme.

```
begin
    set B = available bandwidth, set Nodes = X, set N = Nodes.length
    sort Nodes ascending by b_r
    for each node in Nodes:
        if node b_r < B/N:
            allocate b_r
        else:
            allocate B/N
        B – allocation, decrement N
    end for each
end
```

Figure 4. The top-down approach

TABLE I. RESULTS OF TOP DOWN, FAIRNESS-FIRST ALLOCATION

	Equal Weights		Heuristic Step Weights:	
	P	Pmax	P	Pmax
RS 1	3	3	3	3
RS 2	2.611	3	20.889	24
RS 3	6.944	7	15.555	16
RS 4	5.222	10	10.444	20
Total	17.777	23	49.888	63
%Pmax	*77.29%*		*79.19%*	

No. of Fully Allocated Nodes: 9
No. of Partially Allocated Nodes: 14

1) *Highest-Cost-First Top-Down Allocation*

A variant to the top-down allocation is to change the algorithm to sort descending and to allocate to the highest cost nodes their requested bandwidth first in an attempt to maximize profit. The result of this scheme is presented in Table II. Obviously when trying to maximize the number of nodes that are supported, this scheme falls short considerably. However, for maximization of high-cost nodes, this scheme actually comes pretty close to the equality-based method, and would likely exceed it if there were more high cost nodes.

TABLE II. RESULTS OF TOP DOWN, HIGHEST-FIRST ALLOCATION

	Equal Weights		Heuristic Step Weights:	
	P	Pmax	P	Pmax
RS 1	0	3	0	3
RS 2	3	3	24	24
RS 3	0.666	7	5.333	16
RS 4	10	10	20	20
Total	13.666	23	49.333	63
%Pmax	*59.42%*		*78.31%*	

No. of Fully Allocated Nodes: 13
No. of Partially Allocated Nodes: 1
No. of Unallocated Nodes: 9

2) *Lowest-Cost-First Top-Down Allocation*

In the second variation to the top-down allocation, resource is still allocated to low-cost nodes first; however, the allocation is not bound by an equal distribution to the remaining nodes. This scenario hopes to completely fulfill requests for more nodes, rather than splitting bandwidth and only partially fulfilling nodes. The result of the lowest-cost-first top-down scheme is presented in Table III.

Unsurprisingly, this method fairs better than the highest-cost first method in terms of number of nodes receiving full bandwidth required. This method actually gives us a higher weighted profit than both the previous two methods, but that is by virtue of our red (high cost) nodes being in the two moderate requirement RS zones.

TABLE III. RESULTS OF TOP DOWN LOWEST-FIRST ALLOCATION

	Equal Weights		Heuristic Step Weights:	
	P	Pmax	P	Pmax
RS 1	3	3	3	3
RS 2	3	3	24	24
RS 3	7	7	16	16
RS 4	4	10	8	20
Total	17	23	51	63
%Pmax	*73.91%*		*80.95%*	

No. of Fully Allocated Nodes: 17
No. of Partially Allocated Nodes: 0
No. of Unallocated Nodes: 6

B. *Bottom-up Allocation*

Top-down allocation at first glance is a natural method, because the asset holder parcels out assets to asset requesters in a controlled manner. Bottom-up allocation in a similar manner is not applicable because assets aren't distributed from the bottom towards the top. However, in order to achieve dynamic allocation the lowest level of the allocation tree must be aware of what resources are available to it, and therefore will allocate itself the best available resources for a specific application. When all levels of the allocation tree perform this analysis, we achieve bottom-up allocation. Therefore, what is meant by bottom-up allocation is in fact a reporting and feedback mechanism from the lower levels to the top level to report the success or failure of an allocation scheme. The bottom-up allocation scheme is given in Figure 5.

```
function getProfitMetric(node):
    return sum(node.getProfit()) / Nodes.length

function acceptAllocation(amt, node):
    if amt > node.threshold: return true
    else: return false

begin
    set B = available bandwidth, set Nodes = X
    profitMetric = sum(for node in Nodes: getProfitMetric(node)
    for node in Nodes:
        ratio = getProfitMetric(node) / profitMetric
        if acceptAllocation(B * ratio, node):
            allocate B * ratio
            B -= allocation
    if B > 0:
        return B
end
```

Figure 5. The bottom-up allocation scheme

In our example, the mobile nodes signal their requirements to the RS. In turn, each RS calculates the potential profit to its nodes then reports to the BS how much profit it will receive if its full bandwidth requirements are met. The BS is therefore aware of the number of nodes that each RS is hosting, and allocates its resources so as to maximize the ratio of profit to number of nodes, by allocating resources to the highest profit/node ratio zones first. When the RSs become aware of the available bandwidth allocated from the BS, they signal the nodes how much bandwidth they are willing to provide in a similar profit-maximization manner as the BS. The nodes then select the service, or reject the allocation if it is below a minimum threshold, and RSs report the actual allocation back up to the top of the allocation tree. Note that in this scheme, an equality based weight function becomes irrelevant because the number of nodes is accounted in for the profit to node ratio.

The resource allocation occurs at each level of the allocation tree via two way communications between child and parent, where child reports its profit metric, and its acceptance when requested, and thus a two way signaling from the leaves of the tree to the root and back again occurs. The actual amount of bandwidth allocated is the percentage of the total profit to node ratio, calculated by the parents of each node. A leaf node simply provides its cost, but if it is hosting an ad hoc route, then it would also have a profit.

Interestingly, this method results in waste; 1.86 units go unallocated because the most saturated zone covered by RS4 does not have mobile nodes that accept the threshold from the ad hoc zone. However, even with this waste, more nodes are fully accommodated than the average of the top down approach, and every node receives some bandwidth. In fact, the zone that suffers the most is the most saturated zone, and would not benefit from more bandwidth, but from some form of load balancing. Even more interestingly, in RS3's zone, several of the nodes found better QoS from the ad hoc zone, rather than receive partial fulfillment of their requirements from their RS, which has an updating effect on the entire network. Previously the ad hoc zones were not a factor in top-down allocation, because there was no allocation above the requirements to any one zone.

Comparing the results in Table III and IV, we can see that the performance is marginally better than the top down, lowest-cost first results, with one key difference. In top-down, 6 nodes were unallocated, but in this approach, all nodes receive some (may be partial) allocation. Clearly some signaling and feedback mechanism increases the opportunity for profit maximization in a HWN that can support dynamic or application-based allocations.

TABLE IV. RESULTS OF BOTTOM UP PROFIT TO NODES

	Equal Weights			Heuristic Step Weights:	
	P/N	P	Pmax	P	Pmax
RS 1	1	3	3	3	3
RS 2	3	3	3	24	24
RS 3	2.286	7	7	16	16
RS 4	2	4.023	10	8.0466	20
Total	8.286	17.023	23	51.0466	63
%Pmax		*74.01%*		*81.03%*	

No. of Fully Alllocated Nodes: 13
No. of Partially Allocated Nodes: 10
No. of Unallocated Nodes: 0

Profit-Cost Variant. The profit-node ratio takes in account the total number of nodes in the service zone for a particular allocator. However, in order to reduce bandwidth waste that was created by a pure profit-to-node consideration, an alternative metric can be used, profit-cost. Profit-cost feedback in a dynamic HWN simply uses a different *getProfitMetric*(node) function, where the calculated profit is divided by b_r rather than the *Nodes.length*. Since cost is calculated by bandwidth saturation instead of node saturation, allocation comparisons for QoS thresholds tend to be higher on a per node basis, this means that more acceptance of offered resources, which in turn leads to less bandwidth waste.

C. Auction-Based Allocation

Our last approach to resource allocation moves away from the metric maximization algorithms, and instead takes a more game theoretic approach to resource allocation. Because every resource requestor has a utility function constructed by the direct relationship between profit and percentage of maximum requested allocation, and all mobile nodes are competing for scarce resources, a game theoretic approach seems to fit well. Top down and bottom up allocation forced a profit calculation and maximization choice to be made at a specific branch of the network, and forced the decision-making node (either the RS or the BS) to maximize profit at that network level (without knowledge of other levels). In auction-based allocation, the RS bids to the BS for a specific amount of bandwidth for a certain amount of profit. Each RS also receives information concerning the bids of other RS and adjusts its bid in an effort to win the maximum amount of bandwidth possible.

There are several styles of bid/auction methods available to consider: for instance, the type of auction where all bids result in a particular price, either the highest price or some calculation of all bids received. All bidders are offered the percentage of the resources they bid for at the price calculated, and if it is below a threshold as defined by the node's utility function, the bid is accepted and the resources are allocated appropriately. The bidding process is given as follows:

- Send bid (cost in terms of units of resources per node)
- Assess quality (profit for the bid)
- Calculate rank (profit x cost)
- Allocate resource per node, based on next higher bidder: $b_2 = (b_1 \times p_1) / p_2$

TABLE V. RESULTS OF AUCTION ALLOCATION

	Equal Weights				Heuristic Step Weights:		
	Bid	Quality (P)	Rank	Allocation	Quality (P)	Rank	Allocation
RS 1	2	3	6	2	3	6	2
RS 2	12	3	36	10.6666667	24	288	5
RS 3	4.571	7	32	0.85714286	16	73.1428571	0.375
RS 4	6	10	60	3.6	20	120	3.65714286
Total	24.57	23	134	17.1238095	63	487.142857	11.0321429

No. of Fully Alllocated Nodes: 3
No. of Partially Allocated Nodes: 20
No. of Unallocated Nodes: 0*
* Threshold refusal unaccounted

Because the allocated resource is based on a runner-up's bid, there is built-in feedback to the system that allows knowledge of the entire problem space before allocation. This feedback system therefore prevents high cost nodes from overpowering lower cost nodes through very high bids, but also allows lower cost bids to bid slightly more than their actual profit in attempt to achieve their threshold values. In addition, nodes can easily bid on a per-application basis rather than on a total amount, in order to ensure that high priority traffic is bid at a higher rate. Finally, the auction method is carried out at every level of the allocation tree like top-down and bottom-up, and therefore still has the same time requirements, and still allows for dynamic allocation. In fact, the auction method attempts to combine the fairness-based top-down allocation, with the fairness-based bottom-up allocation, and then adds a feedback mechanism similar to the bottom-up allocation methodology. Table V lists the allocation map and results.

One criticism of the results in this particular network topology is that the bids of all zones are not necessarily close together as perhaps bidding in real network topologies would be. Because our topology had two edge cases, the results were severely skewed, especially for RS 3, who had the misfortune of being tied to the lowest edge case, and therefore was allocated hardly any resources. Network topologies with similar node saturations would probably fair better from an auction based allocation scheme.

D. *Selecting an Allocation Mechanism*

The criteria for selecting an allocation mechanism in the deployment of a HWN is based on node saturation and the magnitude of bandwidth requests on a per node basis. The various allocation mechanisms are differently suited for different combinations of saturation and request magnitude. Table VI shows the best allocation mechanism for different network attributes.

TABLE VI. RECOMMENDED SCHEME PER NETWORK ATTRIBUTES

		Node request volume		
		High Bandwidth	*Low-Bandwidth*	*Average Bandwidth*
Saturation	*High Nodes*	Bottom-up Profit to Nodes	Top-Down Lowest First	Bottom-up, Profit to Cost
	Few Nodes	Bottom-up Profit to Cost	Top-Down Fairness First	Top-Down Highest First
	Static Nodes	Auction Method	Dynamic Allocation not required	Auction Method

V. CONCLUSION

In this paper, we studied bandwidth allocation in multi-hop Hybrid Wireless Networks (HWNs). We proposed three efficient bandwidth allocation schemes for HWNs. All of these approaches have merits in different contexts. The bottom-up allocation scheme achieves the best total profit, especially when dealing with high-cost nodes. In general, it gives more full allocations, again favoring high-cost nodes. The top-down allocation scheme, on the other hand, favors a low-cost first maximization and is better at node fairness. The top-down scheme is also lightweight and the least computation-intensive of the three schemes. The auction method is probably the most fair one of the three methods, but its performance degrades when there are outlier nodes (nodes bidding far less or far more than the others). we developed a simulated HWN environment to evaluate the performance of the schemes. Our simulation results showed that the schemes achieve good performance.

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