Heterogeneous Wireless Access in Large Mesh Networks

Haiping Liu, Xin Liu, Chen-Nee Chuah, Prasant Mohapatra
hpliu@ucdavis.edu, liu@cs.ucdavis.edu, chuah@ece.ucdavis.edu, mohapatra@cs.ucdavis.edu,
University of California, Davis

Abstract—**Wi-Fi-based mesh networks have been considered as a viable option to provide wireless coverage for a vast area, such as community-wide or city-wide. However, interference due to multihop transmissions and potential isolated (disconnected) nodes are the major obstacles to achieve high performance. In this paper, we propose a heterogeneous wireless network architecture, consisting of Wi-Fi and WiMAX, to overcome these limitations. We first construct an optimization problem to analyze the benefits of heterogeneous networks. Then, we design a practical protocol to efficiently combine the resources of Wi-Fi and WiMAX networks. The evaluations show that our new scheme greatly improves the system performance in terms of throughput and fairness.**

I. INTRODUCTION

[1] Originally developed for Local Area Networks, Wi-Fi technology has become a viable choice in a metro-scale mesh network. Using *portals* (A *portal* is a wireless node that also has a wired connection and acts as a gateway between the mesh networks and the wide-area Internet.) that are connected directly to the Internet, mesh networks of large size could forward customer traffic to the Internet and vice-versa through multihop transmissions (usually within four hops [1]). Mesh networks could provide universal wireless access to the Internet or peers in a reasonably large area in a cost-effective manner. In addition, many existing access points (APs) in big cities, such as New York and San Francisco, can further reduce the expense and facilitate the construction of city-wide mesh networks.

The major obstacles of large Wi-Fi mesh network include low capacity, limited system performance, and the uncertainty of mesh topologies and wireless link quality. Possible reasons for those problems inside large mesh networks are listed as follows. First, multihop transmission is one of the major reasons that limit the system performance. Since not all mesh nodes have direct connection to their final destinations, multihop transmissions are inevitable. However, the performance of multihop transmission decreases quickly as the number of hops increases. Packets that traverse through more hops either have little opportunity to reach the destination, or consume too much network resource, both of which decrease the system capacity and increase delay and congestion. Second, to take advantage of existing APs to construct a wide-area mesh network, the network topology is not always under control. Due to network topology and link or node failures, some mesh nodes (known as *island nodes*) may fail to find available paths to the portals. Depending on specific topologies and failure probabilities, the proportion of island nodes may not be negligible. Third, in large mesh networks, centralized MAC-layer schemes, global link transmission scheduling, or synchronization are not practical. Therefore, hidden terminals [23, 24] could cause collisions and further reduce the capacity. Fourth, because of the traffic dynamics, Wi-Fi mesh network is prone to network congestions and congested links negatively influence the performance of mesh networks.

All of these drawbacks come from the network architecture itself instead of specific protocols or algorithms. This motivates us to improve the network structure to alleviate the inherent limits of Wi-Fi mesh networks. In this paper we discuss a heterogeneous wireless network architecture consisting of Wi-Fi and WiMAX.

A. Motivation for Hybrid Wi-Fi/WiMAX Networks

WiMAX was originally designed for point-to-point broadband wireless transmission over long distance, and operated at 5 GHz, which requires line-of-sight transmission. Recently, with the quick development of WiMAX technology and additional spectrum availability (2.3, 2.5, 3.5, 3.7 and 5 GHz [2, 3]), it can support both outdoor and indoor, as well as both fixed and mobile scenarios.

However, large-scale wide-area meshes may not be efficient and cost-effective if we use only WiMAX. First and most importantly, although the large coverage of WiMAX reduces the number of wireless hops in the network, it cannot support good spatial-reuse of spectrum; while Wi-Fi has been proven to be a good solution. Second, WiMAX devices have much higher power consumption and are much more expensive than Wi-Fi devices. Third, from the economical aspect, Wi-Fi devices have been widely deployed, and therefore it is beneficial to integrate WiMAX networks with existing Wi-Fi networks.

Therefore, in this paper, we propose an integrated Wi-Fi/WiMAX architecture that exploits the advantages of both technologies. On one hand, the deep penetration of Wi-Fi networks provides good throughput and large (but not ubiquitous) coverage at low cost. On the other hand, the long range transmission of WiMAX can effectively solve the major problems in large Wi-Fi mesh networks. First, the presence of WiMAX networks alleviates the need to transmit over a large

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number of hops. Far-away nodes can forward traffic through WiMAX networks, while traffic generated by the nodes near portals still go through Wi-Fi. A good proportion of multihop wireless transmissions are replaced by one-hop wireless transmission through WiMAX. In addition, the hidden terminals would also become less severe with shorter paths. Second, island nodes with dual interfaces can connect to WiMAX, and thus network coverage is improved. In addition, WiMAX can provide reliable transmission in a large area. And thus, the heterogeneous network is robust and can provide ubiquitous wireless access in the presence of link/node failures. Third, the existence of WiMAX with large coverage area enables statistical multiplexing, which effectively reduces network congestion due to traffic dynamics and topology limitation of WiFi-Only mesh networks.

Another characteristic of WiMAX and Wi-Fi networks is that they can coexist without interference as long as they operate on different spectrums. In addition, the proposed architecture allows the independent operations of Wi-Fi/WiMAX networks, and any change of one network does not significantly influence the other network.

B. Architecture

In this paper, we propose a heterogeneous network infrastructure, as shown in Figure 1. There are three kinds of nodes, *customer terminals* such as laptops, PDAs and smart cellphones, *mesh nodes* such as APs and laptops with routing function, and *WiMAX base stations* (*WMBS*). These nodes cooperate to forward traffic from the individual customers to the Internet or peers inside the mesh network. *Customer terminals* have only Wi-Fi interfaces and send packets to the nearby *mesh nodes*; *mesh nodes* could either have only Wi-Fi devices and relay packets through multihop Wi-Fi mesh networks or have both Wi-Fi interfaces and WiMAX subscriber interfaces, and relay packets through two networks; *WMBS*s only have WiMAX interfaces, and can communicate with *mesh nodes* with WiMAX interfaces.

Therefore there are three kinds of wireless connections, *customer terminals-mesh nodes*, *mesh nodes-mesh nodes*, and *mesh nodes-WMBS*s. For coexistence of the first two kinds of connections that share Wi-Fi interfaces, some solutions have been proposed, such as multiple-radio and multiple-channel [5–7], and partially overlapped channel transmission [8–10]. The primary objective of this paper is to facilitate a good cooperation of the last two kinds of connections, which share *mesh nodes*, to effectively alleviate the problems in WiFi-Only mesh networks and improve the overall system performance.

Besides the wireless connections, wired links in the system provide reliable connection to the Internet with high capacity. As shown in Figure 1, *portals* and *WMBS* are nodes with wired connections. They are usually traffic aggregation points if the destinations of packets are remote servers in the Internet. Note that first only some of *mesh nodes* are *portals*; second some portals may have both Wi-Fi/WiMAX devices, which helps when the packet destinations are other *mesh nodes* in the network.

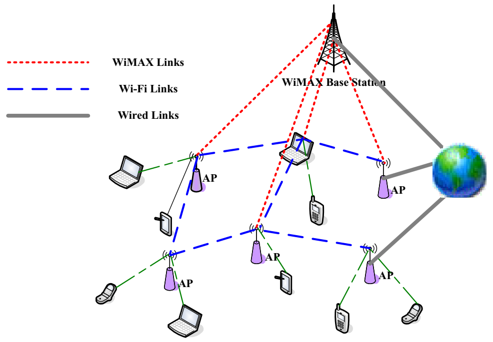

Figure 1. Heterogeneous network infrastructure.

C. Contribution

In this paper, we focus on the impact of the proposed heterogeneous network architecture. We first analyze the impact of the heterogeneous network and the amount of performance improvement through theoretical study assuming optimal routing and scheduling in Section II. We also study the impact of other factors, such as the topology, the number of portals, and the size of the network, on the performance of heterogeneous infrastructure to gain valuable insights on the design of practical schemes for the heterogeneous network infrastructure. Then, we design a new protocol for the heterogeneous network (Section III). In order to provide adequate network state information to the protocol, some network measures such as the link capacity, traffic demand and channel quality, are necessary. However, it is difficult to obtain these information in real-time and accurately with low overhead. So we adapt some heuristic-based solutions. The evaluations and comparisons of our results are presented in Section IV. Related works and the conclusions are discussed in Sections VI and VII, respectively.

II. THEORETICAL STUDY

In the theoretical analysis, the performance metric, γ, is defined as the maximum link utilization of the whole network. It indicates the worst link congestion in the network, taking into account of link interference. The objective is to minimize the maximum link utilization. We note that the maximum link utilization or worst-case link congestion has been extensively used in both wireless and wired networks as a metric for traffic engineering. Minimizing maximum utilization provides good load balancing solutions in the network that improve user experience, as well as system performance [12, 13].

In the theoretical study, we compare WiFi-Only mesh networks and heterogeneous networks assuming the *ideal* protocol and the complete global information. The *ideal* protocol implies there is no protocol overhead, and the complete global information implies that all the network conditions are accurately obtained in real-time. These assumptions do not hold in practical networks. However, they can be considered as the benchmark, where the system performance depends purely on the available resource provided by the network itself.

Table I
THE NOTATIONS IN THE FORMULATION.

Notations	*Meaning*
I	Wired Networks
W	*WMBS* set
N	Wi-Fi node set
P	Wi-Fi Portals
A	Wi-Fi nodes excluding P, and $A = N - P$
L_w	WiMAX link set, and $L_w = \{(a,b)\}$, a or $b \in W$
L_n	Wi-Fi link set, and $L_n = \{(a,b)\}$, $a, b \notin W$
$c_{a,b}$	Physical-layer capacity of link (a,b)
$f^s_{a,b}$	Flow from source s travelling through link (a,b)
t_s	Traffic generated from *mesh node* s
P_i	Independent Set i of the Wi-Fi network
α_i	Time associated to P_i
$\beta_{a,b}$	Time associated to WiMAX link (a,b)

A. Notation

Based on the ideal network assumptions, we formulate our problem as an optimization problem. Table I lists the notations used in this section. We consider the wired network outside the wireless network as a single network, which could be the Internet. Therefore the size of set I, ($|I|$), is equal to one. Nodes in P and W have wired connections to I. Since the capacities of wired links are usually much higher than those of wireless links, we set wired link capacity as $+\infty$, assuming they are not the bottleneck.

In order to simplify formulations in Section II-B, we assume the destination of all flows is I. Our objective of theoretical study is to compare the available resource supplied by different network architectures without concerning specific applications, so it is representative to consider only unidirectional traffic. This model can be easily extended to accommodate bi-directional traffic and peer-to-peer traffic among *mesh nodes*. Note that $f^s_{a,b}$ includes all routing possibilities, such as multi-path and single-path..

In wireless networks, packet routing and link scheduling are always intertwined. An efficient algorithm needs to determine possible sets of links that can transmit simultaneously. From the physical topology, we can construct the conflict graph [11], and subsequently find the independent sets [12]. Unfortunately it is an NP-hard problem, but in [12], Jain et al provide an efficient heuristic solution to search different independent sets. We follow their algorithm to derive the independent sets P_i in the Wi-Fi network. In our formulation, the more time (α_i) allocated to an independent set P_i, the more transmission opportunity Wi-Fi links in P_i can obtain. According to the current standard, WiMAX utilizes scheduled MAC scheme, so the *WMBS* can allocate orthogonal bandwidth or time slots, $\beta_{a,b}$, to different WiMAX links (a,b).

According to our *ideal* assumptions above, the network topology, the link capacity, and traffic demand are known as the inputs. The decision variables are $f^s_{a,b}$, which shows the routing decision, and α_i and $\beta_{a,b}$, which show the link scheduling decision. We try to minimize γ by choosing the proper routing and scheduling schemes.

B. Formulation

$$\text{minimize}_{f^s_{(a,b)},\alpha_i,\beta_j} \quad \{\gamma\} \tag{1}$$

such that:

$$\sum_i \alpha_i \leq \gamma \tag{2}$$

$$\forall (a,b) \in L_n \quad \sum_s f^s_{a,b} \leq c_{a,b} * \sum_{(a,b)\in P_i} \alpha_i \tag{3}$$

$$\sum_{(a,b)} \beta_{a,b} \leq \gamma \tag{4}$$

$$\forall (a,b) \in L_w \quad \sum_s f^s_{a,b} \leq c_{a,b} * \beta_{a,b} \tag{5}$$

$$\forall s \notin I, \quad t_s = \sum_a f^s_{(s,a)} - \sum_b f^s_{(b,s)} \tag{6}$$

$$\forall \alpha_i \quad \alpha_i \geq 0 \tag{7}$$

$$\forall \beta_{a,b} \quad \beta_{a,b} \geq 0 \tag{8}$$

$$\forall f^s_{a,b} \quad f^s_{a,b} \geq 0. \tag{9}$$

Note that γ is the maximum link utilization, so all traffic would be forwarded to their destinations within γ, which introduces constraints (2) and (4). For any networks, the flow on a link cannot be larger than the *effective* capacity of that link, which is the product of the physical-layer capacity and the transmission time allocated to this link by MAC layer. This brings constraints (3) and (5). $\sum_{(a,b)\in P_i} \alpha_i$ in equation (3) shows the total transmission time obtained by link (a,b) if it is involved in multiple independent sets. In addition, each *mesh node* should serve the traffic t_s from the *customer terminals* connected to it (t_s may be zero if no customer connects to this node) besides forwarding flows from other *mesh nodes*, which introduces constraint (6). Note that generally it is not necessary for every *mesh node* to have dual interfaces, so for some *mesh nodes* there are no WiMAX links (in set L_w) connecting them.

C. Solution and Analysis

Given different sets of inputs to the optimization problem, one can numerically compare the performance of heterogeneous networks γ_h, WiFi-Only networks γ_f, and "WiMAX only" networks γ_w. The values of γ in the results are normalized by the time during which the traffic is generated. Therefore $\gamma > 1$ implies that at the worst link, the speed of forwarding traffic is lower than that of generating traffic, and the network is not stable.

Obviously γ_h is better, i.e. it is lower than γ_f or γ_w due to the additional bandwidth. However, the question is whether the gap is large enough to warrant the cost of introducing WiMAX networks. To answer the question, we compare the performance differences in various scenarios, considering the impact of topologies, the number of portals, and the network size.

Table II
NUMERICAL RESULT γ FROM OPTIMIZATION.

	t_s	1 M/s	2 M/s	3 M/s	4 M/s
Grid 16/3	γ_h	0.0887	0.1774	0.2661	0.3548
	γ_f	0.2098	0.4197	0.6296	0.8395
	γ_w	0.1857	0.3714	0.5571	0.7429
	t_s	1 M/s	2 M/s	3 M/s	4 M/s
Grid 16/1	γ_h	0.1320	0.2641	0.3962	0.5283
	γ_f	0.3888	0.7778	1.1667	1.5556
	γ_w	0.2142	0.4286	0.6429	0.8571
	t_s	1 M/s	2 M/s	3 M/s	4 M/s
Rand	γ_h	0.1186	0.2097	0.3258	0.4194
		0.1048	0.2127	0.3145	0.3478
16/3	γ_f	0.4259	0.4815	0.8889	1.1111
		0.3518	0.6297	1.0556	0.8849
	γ_w	0.1857	0.3714	0.5571	0.7429
		0.1857	0.3714	0.5571	0.7429
	t_s	0.2 M/s	0.4 M/s	0.6 M/s	0.8 M/s
Grid 100/10	γ_h	0.1763	0.3527	0.5290	0.7054
	γ_f	0.3518	0.7037	1.0555	1.4073
	γ_w	0.2571	0.5143	0.7714	1.0286

1) 16 Mesh Nodes*:* First we test the results on some small-scale topologies containing 16 Wi-Fi *mesh nodes* and one *WMBS*. All mesh nodes are supposed to be equipped with both Wi-Fi and WiMAX devices. The physical link capacities of Wi-Fi and WiMAX are fixed, 54 Mbps for Wi-Fi links and 70 Mbps for WiMAX links, and the transmission range of WiMAX is large enough to cover the whole network. Note that 54 Mbps is the PHY capacity between any two neighboring Wi-Fi nodes, while 70 Mbps is shared by all links between the *WMBS* and *mesh nodes*. We set the value t_s, the traffic demand of *mesh node* s, the same for all nodes for simplicity.

Grid topology: The first case is the *grid* topology, which results are shown in row 'Grid 16/3' (16 *mesh nodes* and 3 of them are portals) and 'Grid 16/1' in Table II. We find that γ increases linearly according to the traffic demand t_s because in our formulation all transmissions are scheduled and no collisions happen. The value of γ depends on the system capacity and user demand. Second, the ratio of γ of heterogeneous networks over γ with WiFi-Only networks is in the range of 2-3. The critical point where the traffic demand t_s makes the system unstable ($\gamma \geq 1$) in the heterogeneous network is much higher than that in the "Wi-Fi or WiMAX only" network. In addition, by comparing the different ratios between 'Grid 16/3' and 'Grid 16/1', it is also reasonable that the improvement is higher in more congested networks (such as '16/1'). Note that due to the scheduled MAC in WiMAX networks, γ_w actually keeps the same if the number of *mesh nodes* with traffic requirement does not change. However γ_w is different in 'Grid 16/3' and 'Grid 16/1' since *WMBS* only serves the traffic from the wireless *mesh nodes* that are not portals.

Random topology: In the second case, nodes are *randomly* located in a square area, whose results are shown in row 'Rand 16/3' in Table II. We collect data from different random topologies, which makes γ not monotonically increase according to different t_s and have some fluctuation with the same t_s. However, in terms of the average γ, the ratio still lies in the range of 2-3 (the values of γ with "WiMAX only" keep the same as in 'Grid 16/3'). The improvement in the random topology indicates the potential utilization of heterogeneous networks in the practical system. In addition, we find some random topologies are *partitioned* (*island* nodes) and some *mesh nodes* cannot find paths to the Internet or other parts without WiMAX networks. In 'Rand 16/3' we eliminate those topologies since the value of γ becomes $+\infty$ in the WiFi-Only networks. In other words, the total average improvement of heterogeneous networks is even higher than that shown in 'Rand 16/3' if we consider all possible random topologies.

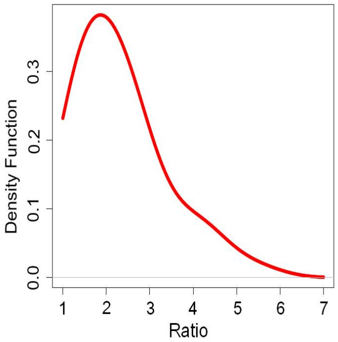

Figure 2. PDF of γ_f/γ_h in random topologies.

2) 100 Mesh Nodes*:* We continue our comparison on large-scale networks, with 100 *mesh nodes*. In large wireless networks, one significant characteristic is that the wireless link capacities are quite different depending on the locations of transmitters and receivers. Therefore, we vary the link capacities based on a distance model. The Wi-Fi physical-layer link capacity is $C_1 \times d^{-\alpha} \times$ 54 Mbps, and that of WiMAX links is $C_2 \times d^{-\alpha} \times$ 70 Mbps, where d is the distance between the transmitter and the receiver and $\alpha = 4$ as the normal configuration. In 'Grid 100/10' of Table II, the average capacity of Wi-Fi links is 22.48 Mbps, and that of WiMAX links is 27.55 Mbps.

Grid Topology: The data in 'Grid 100/10' are also based on the grid topology but with 100 *mesh nodes* and 10 portals. The large ratio of γ_h and γ_f or γ_w indicates that even in a large wireless network with variable link capacities, the improvement remains significant.

Random Topology: Since γ_f/γ_h changes according to different topologies, we evaluate the performance in 100 random topologies and plot the histogram of the ratio in Figure 2. From this figure, we can see the improvement ratio is still obvious. The density function has a long tail due to *bad* WiFi-Only topologies, where much traffic contends one or a few links. Note that we also eliminate the *partitioned* topologies in Figure 2.

D. Insights from Theoretical Study

The theoretical study shows the significant performance improvement of the hybrid WiMAX/Wi-Fi network with the optimal routing and scheduling. The optimal scheme presents insight for the practical protocol and algorithm design. Although we assume that all *mesh nodes* have dual interfaces, only the following subsets of nodes prefer to forward packets to WiMAX networks: (a) the nodes far from portals, (b) the nodes with congested traffic, and (c) the nodes with better WiMAX link qualities than their Wi-Fi links. The first kind of nodes consume too much network resource due to multiple hops and introduces interference to neighbor nodes or links if the packets from them travel though Wi-Fi networks. The second category of nodes need help from WiMAX networks since the Wi-Fi links cannot provide enough transmission capacity when some *mesh nodes* are badly congested. The third kind consumes less WiMAX resource to transmit the same amount of traffic due to their better WiMAX link quality. Therefore, we need to consider the number of hops, traffic congestion level at a *mesh node*, and the link quality as important parameters in the practical protocol design.

III. PROTOCOL AND ALGORITHM DESIGN

Although it is shown that a heterogeneous network is a good solution through the theoretical study, it is necessary to design a protocol that can achieve the gain in practice and deal with challenges that are not captured by the idealized model. In a practical system, the protocol needs to allocate resources based on the information of the dynamic network conditions, such as link capacity and traffic demand. Unfortunately, accurate real-time information is hard to obtain, so the protocols need to perform under network information with delay and inaccuracy. In addition, complicated protocols with high overhead are not suitable for wireless networks since the wireless transmission resource, time or bandwidth, is very precious. Therefore, we propose a threshold-based protocol and an optimization algorithm, which answer two basic questions: (1) which *mesh nodes* connect to the WiMAX network, and (2) the amount of traffic *mesh nodes* forward to the WiMAX network.

A. Assumptions and Objective

Before discussing the protocol in detail, we first clarify the assumptions and state our objective. We make the following assumptions.

1) WiMAX utilizes the scheduled MAC scheme.
2) In Wi-Fi networks, nodes utilize IEEE 802.11 MAC instead of the scheduled MAC as in theoretical study.
3) The *WMBS*s do not try to control the routing or scheduling inside the Wi-Fi network.

The last assumption preserves the basic properties of Wi-Fi mesh networks: the easy extension and independent routing. Our objective is to minimize the maximum utilization inside the whole network. Since it is too complicated to synchronize link scheduling in practical networks, our only decision variable is the routing variable, which determines the amount of traffic going through the Wi-Fi or WiMAX networks.

B. Protocol Design

We do not design any new routing protocols for the Wi-Fi mesh network. Inside the Wi-Fi mesh network, mesh nodes can find paths according to any existed protocols, such as *AODV* or *DSR*. Instead, we focus on the cooperation between the Wi-Fi and the WiMAX networks, and introduce load balancing protocol in the heterogeneous network (*LABHW*). *LABHW* is shown in Figure 3 and the details are explained below.

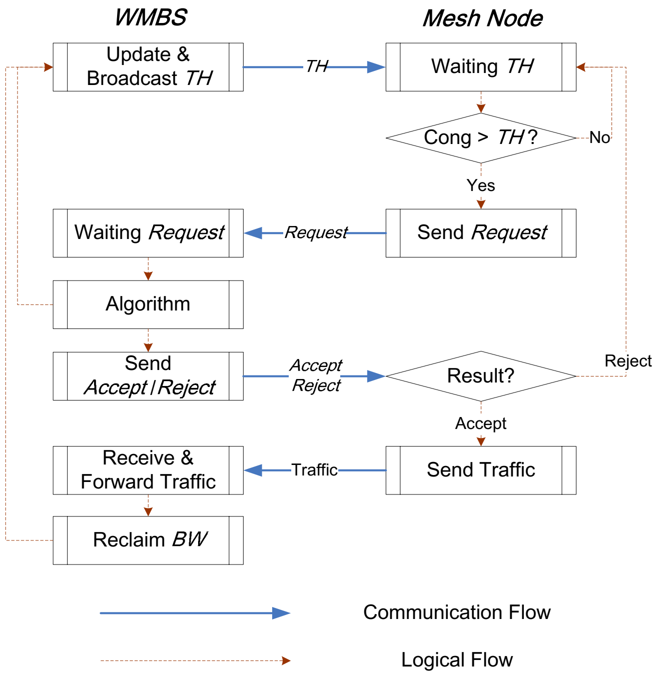

Figure 3. Flow chart of the proposed protocol.

The *WMBS* broadcasts ’Threshold’ (TH) to all Wi-Fi nodes when TH gets updated. TH is the reference for all mesh nodes to compare their local congestion situations with the global one.

When a mesh node, say node a, receives a new TH from the *WMBS*, it updates its local TH_a. Node a compares its current local utilization $Cong_a$ with the latest TH it has received from *WMBS*. If $Cong_a$ exceeds TH_a, node a sends a *Request* to the *WMBS*.

WMBS keeps receiving *Requests* from *mesh nodes*. Once a new *Request* from node a arrives, the *WMBS* decides whether node a can send traffic to the WiMAX network and the amount of the WiMAX bandwidth assigned to it, WBW_a, based on the algorithm that will be introduced in Section III-C. If there is not enough WiMAX bandwidth, or node a sends a *faulty Request* due to non-latest TH_a, the *WMBS* sends *Reject* to node a; otherwise, the *WMBS* sends *Accept*. No matter whether it sends *Accept* or *Reject*, the *WMBS* updates and broadcasts the TH based on the new network condition since it received the updated information from node a. However, it is not guaranteed that all *mesh nodes* successfully receive THs, in order to avoid multiple *ACK*s.

Once node a acquires *Accept*, it sends the traffic to the *WMBS* with the transmission rate limit WBW_a; while the *WMBS* receives and forwards the traffic to the destination. When the *WMBS* finishes forwarding flows from node a, it reclaims the WiMAX bandwidth, and updates and broadcasts

Table III
THE NOTATIONS IN PRACTICAL ALGORITHM DESIGN.

Notations	*Meaning*
W	Set of nodes that send request packets to *WMBS*
V	Set of nodes that do not send request packets to *WMBS*
I	Measurement Interval
s_i	Number of bytes sent by the Wi-Fi interface of node i
q_i	Number of bytes queued in node i
c_i	Wi-Fi capacity of node i
t_i	Idle time of the Wi-Fi interface of node i
x_i	WiMAX bandwidth to allocate to node $i \in W$
θ_i	WiMAX link quality factor of node i
h_i	Hop-number from node i to a portal through Wi-Fi Mesh
Z	WiMAX bandwidth that has been allocated to $W \cup V$
B	Total WiMAX bandwidth

the new TH.

Based on this protocol, the *WMBS* can dynamically adjust the TH based on the utilization conditions of the heterogeneous network. Any *mesh nodes* that incur high congestion can request additional resource from the WiMAX network.

C. Algorithm Design

In addition to the protocol to schedule the interactions between *WMBS* and *mesh nodes*, we also develop an algorithm for *WMBS* to decide the amount of WiMAX bandwidth to allocate to *mesh nodes* with *Request*s. As in Section III-A, our objective is to minimize the maximum utilization in the heterogeneous network. Therefore first we need to find proper definition of *utilization* for practical Wi-Fi networks and WiMAX networks. As we mentioned before, it is very challenging to obtain all network information in real-time accurately. Therefore our metric only relies on some network conditions that are easy to measure. In a given measurement interval, we collect the following data: number of packets sent, queue length, transmission rate and idle time of Wi-Fi interfaces, and channel factor for WiMAX links (all notations are shown in Table III).

By counting *ACK*s from the MAC-layer and queue length, we can measure the number of bytes sent through the Wi-Fi interface, s_i, and number of bytes queued, q_i, by node i. Checking the modulation rates of interface cards gives us the Wi-Fi PHY rates. Note that they are not the capacities in the network or application-layer, at which our protocol is operating. Therefore we need to consider some factors, such as headers from different layers and preamble in the physical-layer, to derive the corresponding transmission rates on the network-layer or application-layer, c_i. Idle time, t_i, can be estimated by periodically checking the status of interface cards. The WiMAX link capacities depend on many parameters. Some factors such as channel bandwidth and *FFT* size are under control; while others such as transmission distance and channel condition, can only be measured in practice. Therefore we estimate the actual WiMAX link capacity by the ideal WiMAX bandwidth allocated to node i, x_i, and the WiMAX link quality factor θ_i that is obtained from network measurement. The actual WiMAX link capacity is $x_i \times \theta_i$. From the study of the optimal scheme in Section II-D, we find the nodes with poor WiMAX link qualities seldom route packets to the WiMAX networks because they waste WiMAX resource. Therefore we introduce the factor θ_i to indicate the impact of different link qualities.

With the inputs, the reasonable definition of *utilization* in Wi-Fi networks is the traffic demand over the efficiency capacity, which is $(s_i+q_i-x_i*\theta_i*I)/(s_i+c_i*t_i)$, where $(s_i+c_i*t_i)$ is the maximum capacity node i could obtain. In WiMAX networks, we follow the similar idea but have a more compact format, $(\sum_i x_i+Z)/B$. The definition about Wi-Fi utilization above is fair but does not take into account of the number of hops within Wi-Fi networks. Considering the insight in Section II-D, under the same network conditions, it is more efficient for *WMBS* to help the nodes far from portals other than the nodes nearby. Therefore we adjust the utilization definition for Wi-Fi networks to $(s_i+q_i-x_i*\theta_i*I)*h_i/(s_i+c_i*t_i)$, where h_i is the number of hops from node i to the portal. Actually the amount of resource for multihop transmission depends on both the number of hops and the interference range. We only use h_i because it is too difficult to obtain the exact network topology and to derive the interference relationship among all *mesh nodes*; and if the *mesh nodes* and portals distribute evenly in the area, any link (transmission) interferes with almost the same number of other links in the topology. The objective here is to minimize the maximum utilization by effectively allocating WiMAX resource to mesh nodes. Formally, we have

$$\text{minimize}_{x_i, i\in W} \qquad \{\gamma\}, \tag{10}$$

such that:

$$\frac{\sum_{i\in W} x_i + Z}{B} \leq \gamma, \tag{11}$$

$$\forall i \in W \quad \frac{s_i + q_i - x_i * \theta_i * I}{(s_i + c_i * t_i)/h_i} \leq \gamma, \tag{12}$$

$$\sum_{i\in W} x_i + Z \leq B, \tag{13}$$

$$\forall i \in W \quad x_i \geq 0. \tag{14}$$

Note that γ is the maximum utilization in the heterogeneous network. Constraints (11) and (12) are the *utilizations* in Wi-Fi and WiMAX networks, respectively. By solving this optimization, the *WMBS* determines the WiMAX bandwidth x_i to allocate to *mesh node* i, and γ as threshold to broadcast in Figure 3.

IV. EVALUATION

We compare heterogeneous networks with ”Wi-Fi and WiMAX only” networks, and evaluate our protocol and algorithm by *Qualnet 4.0* [20]. In the following scenarios, all wireless *mesh nodes* except portals generate CBR traffic with the same rate, which simulates the aggregate traffic from *customer terminals*, and the sole destination is the Internet. In the result figures, the x-axis is the CBR rate of one *mesh node*, while the *system throughput* C is total throughput to the Internet.

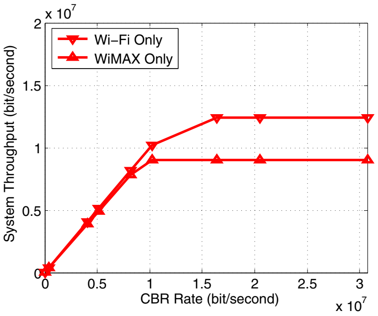

Figure 4. System throughput of one *mesh node* in a chain.

Table IV
LINK CAPACITIES ON DIFFERENT LAYERS.

	Physical-Layer	Application-Layer
Wi-Fi	54 Mbps	12.388 Mbps
WiMAX(7MHz)	22.5 Mbps	9.003 Mbps

A. System Throughput

We begin our analysis from the simplest case, the *chain* topology, where *mesh nodes* locate in a chain and the portal is at one end. We test the chain containing one or four (non-portal) *mesh nodes*. For the first case, we get the system throughput of the WiFi-Only C_f and "WiMAX only" C_w, which are shown in Figure 4.

In Figure 4, the throughput C linearly increases with the CBR rates before it reaches the system capacity limit. After that, C keeps constant no matter how large the CBR rate is. The maximum capacity values on different layers are also shown in Table IV. Since there is no contention or interference in one-hop wireless transmission, the values shown here are the maximum capacities by a Wi-Fi link and the WiMAX network. Note that due to scheduled MAC in WiMAX, C_w will almost keep the same in Table IV in different topologies discussed later on, but it is impossible for Wi-Fi links with IEEE 802.11 MAC. The values in the table provide the bounds for the next comparisons.

The results of the chain topology with four *mesh nodes* are shown in Figure 5. We compare four scenarios: WiFi-Only, "WiMAX only", simple-sum, and then heterogeneous architecture. The simple-sum is the sum of C_f and C_w, which network uses the same amount of resource, but does not intelligently integrate the advantages of the two networks. In the heterogenous case, C_h comes from two parts, one from Wi-Fi networks $\bar{C_f}$ and the other from WiMAX networks $\bar{C_w}$. After analyzing the results, we find two major reasons of the significant throughput improvement compared to normal WiFi-Only mesh networks. First is the additional WiMAX bandwidth. Second, the throughput from the Wi-Fi network $\bar{C_f}$ also increases compared to C_f. Since the WiMAX network helps the nodes that are far from the portals or have poor Wi-Fi link quality, the Wi-Fi network only supports the nodes that are nearby the portals. Therefore $\bar{C_f} > C_f$; and since $\bar{C_w} \approx C_w$, $C_h = \bar{C_f} + \bar{C_w} > C_f + C_w$, which means the cooperation of the heterogeneous networks is better than the simple-sum of two separated networks. The analysis is validated in the Figure 5. The improvement ratio of the throughput from the Wi-Fi network, $\frac{\bar{C_f} - C_f}{C_f}$, is up to 63.1%.

B. Fairness Issue

The system throughput is not the only metric improved by employing the heterogeneous architecture and our protocol. In this section, we consider the fairness metric. We test the grid topology with 16 *mesh nodes* as in Section II-C. We compare the performance of our *LABHW* protocol with that of the popular *AODV* protocol.

In *AODV*, *mesh nodes* with dual-device consider the *WMBS* as a wireless node only one-hop away. These nodes broadcast *RREQ* (route request) to both Wi-Fi and WiMAX interfaces, and forward packets to the interface that first receives *RREP* (route reply). However not all *mesh nodes* forward packets to *WMBS* although their *RREQ*/*RREP* travel one-hop wireless transmission through WiMAX. Severe competition and limited WiMAX bandwidth force some *mesh nodes* to forward packets to the Wi-Fi network; in addition, *mesh nodes* close to portals can easily transmit their *RREQ* and data packets to portals through Wi-Fi links. Note that the conclusions in this section still keep for other routing protocols, such as *DSR*. However since it is not our focus to compare different existed routing protocols, we only show comparison results based on *AODV*.

The system throughput and fairness results of the grid topology are shown in Figures 6 and 7. In Figures 6, the throughput performance is compared. When the network is highly congested, using standard AODV, *mesh nodes* that are on-hop away from portals use the Wi-Fi network while other nodes transmit through the WiMAX network. In this case, the standard AODV provides high overall throughput. The throughput of *LABHW* is comparable and even a little better than that of AODV, which shows its efficiency.

Our protocol shows unique advantages on the fairness issue. We count the packets successfully received by the final destination from different wireless nodes (end-to-end traffic), and derive Jain's fairness index, $\frac{(\sum p_i)^2}{(n*\sum p_i^2)}$, where p_i is the number of successfully received packets from node i. In Figure 7, we compare the fairness index of WiFi-Only, AODV, and LABHW. Our scheme achieves significant better fairness among users. When the CBR rate is very high, almost only one-hop *mesh nodes* forward packets to the destination in WiFi-Only mesh networks. The probabilities of contention due to interference, and packet dropping due to buffer overflow in the multihop transmissions are so high that packets from remote nodes have little opportunity to reach the final destination. Therefore, its fairness performance is poor. When we use AODV for heterogeneous networks, some remote nodes get the opportunity to forward packets through WiMAX networks. However the randomness of delays of multiple paths may change the path selection of AODV. In addition, some lightly congested nodes may contend the precious WiMAX bandwidth with other highly contested nodes; or some nearby nodes may contend with remote nodes. The ideal case is that the badly congested or remote nodes choose WiMAX while lightly

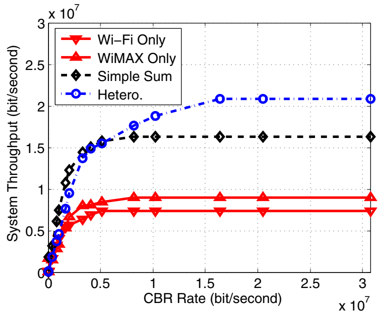

Figure 5. System throughput of four *mesh nodes* in the chain.

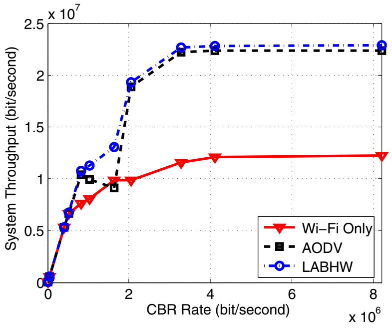

Figure 6. System throughput of the grid topology.

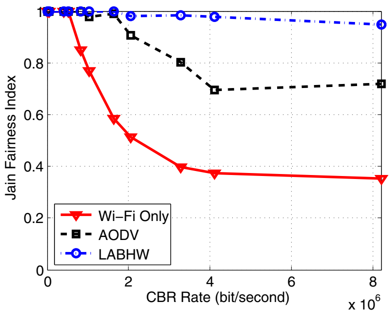

Figure 7. Fairness of the grid topology.

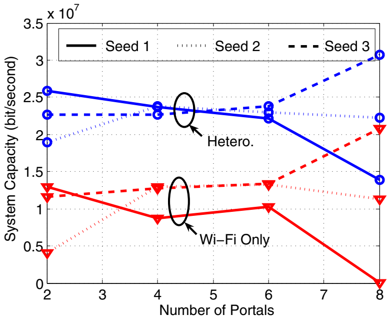

Figure 8. Numbers and locations of portals.

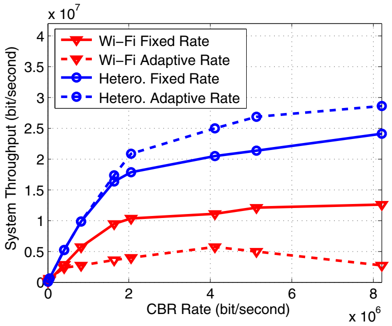

Figure 9. Fixed and adaptive rates.

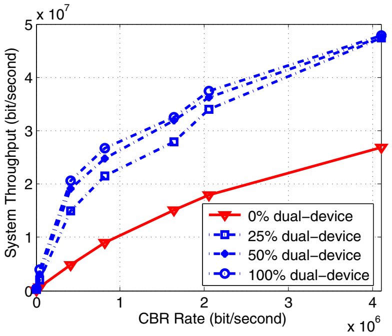

Figure 10. A subset of nodes have dual interfaces.

congested or nearby nodes forward packets to both Wi-Fi and WiMAX, which is implemented exactly in LABHW.

C. Other Factors

In this section, we study the impact of various factors on the system performance.

1) Number and Locations of Portals: In mesh networks, both the number and the locations of portals impact the system performance. We test their influence in a square area, where 16 *mesh nodes* are uniformly located and the portals (2, 4, 6, 8 portals) distribute randomly. The system capacity is shown in Figure 8. In the unplanned topologies, the improvement of system performance does not linearly increase with the number of portals. Instead, if the locations of the portals are far from the group of wireless *mesh nodes*, the throughput is ever worse with more portals, such as the scenarios of WiFi-Only with 8 portals from random generation seed 1. However with the WiMAX network, the instantaneous perturbation of the performance is much less than that of WiFi-Only network.

2) Adaptive Rate: In the previous comparisons, the modulation rate of Wi-Fi is 54 Mbps. However in the practical networks, most of the Wi-Fi cards utilize adaptive rate fallback based on link quality(ARF in [21]). With the adaptive rate mechanism, the transmission ranges of *mesh nodes* can increase with lower modulation rates. In Figure 9, when the CBR rate is low, the system throughput with adaptive rates is higher since more nodes could connect to portals directly. However when the CBR rate is high, the traffic through links of low qualities or low modulation rates consumes most of the transmission time [22], so the throughput is lower. In the heterogeneous networks, remote nodes are most likely to route packets through WiMAX networks, which avoids the low qualities links to consume too much time. Near nodes choose adaptive rates according to different link qualities, which avoids unnecessary retransmissions. Therefore the total system throughput with adaptive rates is better than that with fixed rate. This further confirms the benefit of the heterogeneous architecture in practical networks.

3) Dual-interface Nodes: We propose our solution for a metro-scale mesh network, so we need to verify the influence of the heterogeneous architecture and our protocol in a mesh network of large size, which contains 100 wireless *mesh nodes* and 10 portals. In addition in practical networks, not all *mesh nodes* have dual devices to connect to the *WMBS*. Therefore we also discuss the influence of the percentage of nodes with dual devices. Figure 10 shows that these three curves of the heterogeneous network are comparable, which means our system and protocol work well with different percentage of dual-interface nodes. In Figure 10 when the CBR rate is low, the network with more dual-interface nodes has more choices in routing and consequently gains more throughput; however when the CBR rate is high, only a few dual-interface nodes can exhaust all WiMAX bandwidth, and then all curves of heterogeneous networks converge.

V. RELATED WORK

Most solutions to load balancing belong to two categories, traffic engineering in wired networks and admission control in wireless networks. Most solutions by traffic engineering [25–27] reroute the packets according to the statistic information about congestion in the routers, or the estimated *RTT* information in the sender or receiver. The rerouting schemes usually need complicated interaction among nodes, and the full knowledge of the network topology for multiple possible paths from sources to destinations, which brings a large amount of protocol overhead in wireless networks. In addition, the interference between neighbor nodes makes the load-balancing much more complicated. For example, in wired networks, one congested node is usually independent to others in the view of transmission opportunity; nevertheless in wireless networks, a congested node also blocks the transmission of its neighbors as well. For the admission control solutions, the prevalent solution is that all nodes would contact the remote admission controller [16–19] if new customers arrive, and the latter determines whether to accept or reject the new requirements according to the current network conditions. However the mechanism introduces a long delay in multihop mesh networks, the pre-determined bandwidth by the remote controller is not flexible for many applications greatly influenced by customers, and the out-of-band control is high protocol overhead.

Earlier studies on heterogeneous wireless networks are mostly concerned with Wi-Fi and Bluetooth [14, 15] in local area networks. Some studies apply WiMAX to mesh networks [28, 29]. [28] adopts an interference-aware cross-layer design for multihop routing and scheduling to increase the utilization of WiMAX mesh networks. Company *Cygnus* [29] improves WiMAX devices by combining 802.16e and MIMO to fit mesh requirements. However WiMAX-only mesh cannot fully reuse bandwidth and disregards the widely deployed Wi-Fi devices. A number of technique reports, such as [30], mention the combination of Wi-Fi and WiMAX for mesh networks; some companies, such as *Redline Communications* [31], announced to unveil Wi-Fi/WiMAX mesh network solutions. However few of them analyze the major drawbacks of Wi-Fi or WiMAX-only mesh networks, offer theoretical proof of the heterogeneous architecture and publish corresponding solutions. Authors of [32] propose an interesting pricing model for heterogeneous networks, however they focus on efficiently sharing bandwidth between Wi-Fi and WiMAX, which does not discuss the network structure. Therefore it is valuable to provide a thorough performance evaluation, derive guidelines for protocol design and propose a mechanism to achieve benefits of the heterogeneous architecture.

VI. CONCLUSION AND FUTURE WORK

This paper proposes a heterogeneous network architecture, consisting of Wi-Fi and WiMAX, to solve the major problems and improve the performance of multihop Wi-Fi mesh networks of large size. The large coverage of WiMAX networks avoids long multihop transmissions, connects isolated nodes in uncontrolled topologies, and provides alternatives to mesh nodes that suffer Wi-Fi links of low qualities. Our theoretical study indicates significant improvement of the heterogeneous architectures. The solutions also provide us a good estimation of the system performance in practical networks, which is important in the network design. Based on the insights from the theoretical study, we design a practical protocol, which is more suitable for the heterogeneous architecture in practice. Simulations show significant improvement of our scheme over heterogeneous networks, WiFi-Only networks and ”WiMAX only” networks in terms of system throughput and fairness. In addition, we also choose good metrics of utilization for both Wi-Fi and WiMAX networks with some parameters easily captured, which efficiently indicates conditions of large mesh networks.

Although we have discussed the improvement of heterogeneous network architectures, there are some interesting directions to extend the current work. First, in this paper we suppose the Wi-Fi mesh nodes or customers are fixed, however most of the time a large number of consumers are moving around inside mesh networks. The mobility of customers causes high traffic density and congestion in some areas, which may influence the efficiency of our protocol. Second, different from the normal expectation that increase in number of mesh nodes may result in increase in number of portals, the simulation shows the importance of locations of portals. Therefore it is significative to study ideal number and locations of portals in heterogeneous networks for different topologies and number of mesh nodes.

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