

Multi-paths Routing with Load Balancing for Internet Access in Wireless Mesh Networks

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Abstract— Wireless Mesh Networks (WMN) have different characteristics compared with the mobile ad hoc networks (MANET). The issue of Internet access with wireless mesh connectivity is a very important issue in the design of WMNs. In this paper, we propose a novel multi-paths routing framework for the Internet access through WMNs by using multiple access routers (ARs) simultaneously. Within this framework, an efficient load balancing scheme has been proposed to further increase the network performance. This load balancing scheme is named Reactive Load Balancing (RLB). Extensive simulation experiments have been carried out to validate the proposed solutions. The simulation results show a reasonable improvement on network throughput, especially, in a small size mesh network. The proposal is verified to be able to produce a lot of benefits to WMNs such as effective soft-handoff, throughput improvement, load balancing among ARs, etc.

Keywords: WMNs, Internet Connectivity, Multi-path Routing, Hybrid Networks, Load balancing, Bandwidth Estimation, HMIPv6.

I. INTRODUCTION

Wireless Mesh Networks (WMNs) [1] recently received a lot of attention from researchers all over the world for its potential application in wireless communication. WMN has different characteristics compared with the Mobile Ad hoc Networks (MANET). In an MANET, all nodes in the network could communicate with each other without any existing infrastructure. Each node in an MANET can act as a router to forward data packets to the destination. While a WMN, on the other hand, evolved originally from the last mile extension of the existing infrastructure based wireless local networks. It becomes now to be able to allow mobile wireless nodes to communicate each other through multi-hops over mesh connections. If there's no connection to the existing networks (i.e. Internet), the WMNs work in the ad hoc mode. And the mobile wireless nodes communicate with each other only within the mesh networks. Their behaviors are same as those of the MANETs. In an MANET, there is only one type of nodes. While in a WMN, there're two types of nodes named as mesh routers and mesh clients. Mesh routers only provide the routing functionality for the mesh clients. It's expected that mesh routers do not move much and there's no restriction on their power consumption. Mesh clients, on the other hand, have restriction on their power consumption and expected to move about.

Mobile IP MANETs (MIPMANETs) in [2-3] are the first two proposals to provide Internet access to MANETs by extending Mobile IP (MIP) [4-5]. The Internet services to mobile nodes in an MANET can be provided through attachment points which are

called Internet gateways, Mobile Gateways (MG) or Access Routers (AR). A mobile node in an MANET requiring connection to the Internet has to go through the address auto-configuration [6-7], gateway discovery [8-9] and registration processes in order to register with ARs and obtains a global routable address. Depending on the types of ad hoc routing protocols used in MANETs, these processes could be manual, proactive or integrated with the routing protocols. When a mobile node in an MANET wants to send data, it will send its packets to the registered AR using the ad hoc routing protocol in the MANET. The AR will forward this packet to the destination through the Internet by routing protocols used in the wired network such as Routing Information Protocol (RIP) or Open Shortest Path First (OSPF). A packet sent to a mobile node in an MANET from the Internet will reach the AR first and the AR will forward the packet to this mobile node by the ad hoc routing protocol used in the MANET too. In MIPMANETs and alike, due to the dynamic nature of an MANET, mobile nodes could join and leave the network at any time resulting in the information delivery not easy in practice. It becomes even worse when more than one AR and/or large number of dynamic mobile nodes movement are involved. This will lead to the issues of ARs selection, connection maintenance, and handoff decision making, etc. Quite a number of solutions [8-10] have been proposed so far to tackle these problems. By current existing solutions, the preferable structure of the Internet access in an MANET is that a mobile node in the MANET registers with one AR, which has the least number of hops to the mobile, and sticks to that AR until the connection is over or a handoff happens.

The shortcoming of the existing solutions is that an AR is a bottleneck in the network. If the AR is down or disconnected, all the nodes in the MANET will lose the existing connections with the Internet. This shortcoming will become even worse when their solutions are applied to WMNs because WMNs have strong requirements on the robust connections with the Internet. To the best of our knowledge, there's no effective solution yet to provide stalwart connection between WMNs and the Internet.

Within WMNs alone, performance of the WMNs could be improved using multi-path routing. Some multi-path routing schemes have been proposed for the WMNs [11-13]. Multi-path routing schemes can take the advantage of rich mesh connections among mesh routers inside the WMNs. It can also balance the traffic load among routers in the network and provide higher degree of link disconnection tolerance. These existing multi-path routing schemes have also paved the way for the development of the routing protocols on the connectivity of the WMNs with the Internet in this paper.

The major contribution in this paper is that a novel multi-path routing solution to provide strong connections between WMNs and the Internet has been proposed namely Multi Access Routers (MARs) routing. Within the framework of MARs, an efficient load balancing scheme has also been proposed named as Reactive Load Balancing (RLB). By the MARs scheme, a mobile node in a WMN can register and use more than one AR simultaneously for the Internet access while the traffic load among ARs can be adjusted and balanced by the RLB algorithm.

The paper is organized as follows. The system background of the Internet connection with WMNs is presented in section II. The solution using multiple ARs for global connectivity with WMNs is proposed in section III. In section IV, the proposal of RLB using available bandwidth measurement is discussed. In section V, the results of performance evaluation and comparison on the proposed solutions are shown. Finally, section VI concludes the paper.

II. SYSTEM BACKGROUND

A. *Wireless Mesh Network - WMN*

There're three types of WMNs architectures named as the backbone, the mesh client and the hybrid architecture.

The backbone architecture is shown in the first circle of Figure 1. In this architecture, the mesh routers (or ARs) form a backbone and serve mesh clients to communicate with the Internet or with other mesh clients. Links between mesh routers are wireless and the mesh routers could use multi-radio interface to connect to each other. If a mesh client wants to send a data packet, it will send it to the mesh router in the range and the mesh router will forward this packet to the destination.

A structure consisting of mesh clients only is the second WMNs architecture as shown in the second circle of Figure 1. In this architecture, mesh clients communicate with each other in exactly the same way as in MANET. A packet coming from a mesh client will be forwarded to the next until it reaches the destination. There's no base station or existing infrastructure.

The hybrid architecture in Figure 1 is the backbone mixed with the mesh client architecture. In this hybrid structure, any mesh clients out of radio range of mesh routers still could access the Internet by the mesh routers multi-hop away through other mesh clients.

It's obvious that there're many mesh connections among mobile nodes. The multi-path routing could be applied to fully exploit these mesh connections. In order to fully take the advantages of the multi-path routing scheme, multiple ARs are possible to be used for the connection in a WMN to the Internet.

However, when a WMN client uses multiple ARs, it has to register with these ARs and obtain multiple IP addresses. Hierarchical MIP (HMIP) scheme has been taken to support multiple IP addresses so that a WMN client can use the Regional Care of Address (RCoA) of the HMIP for all of its connections.

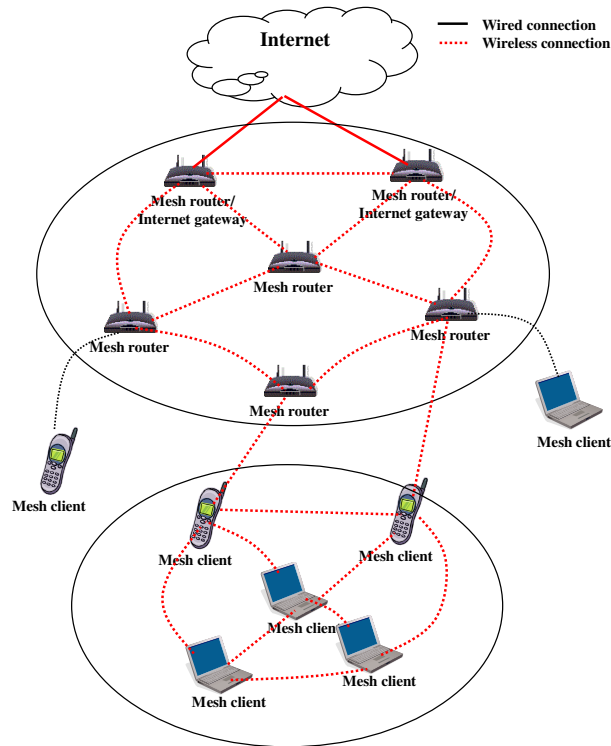


Figure 1: Hybrid architecture

B. MIPv6 & HMIP

MIP [4-5] allows mobile nodes (MN) being connected while moving in other networks through Home Agents (HA) and Foreign Agents (FA). A mobile node belonged to its home network can be represented by a HA because the mobile node has an IP address in its home network. Other hosts will access the mobile node by this IP address. When the mobile node moves into another network, it will obtain another IP address called IP care-of address (CoA) from the FA in that foreign network. The FA in turn will inform the MN's HA about the presence of its MN in the foreign network.

When a Correspondent Node (CN) wants to send data to a mobile node, it sends the packet to the mobile node home IP address. This packet will be routed to the home network and intercepted by the HA. The HA in turn encapsulates this entire datagram and sends it to the mobile node's CoA. This packet will eventually reach to the FA. The FA then strips the outer IP header and sends the original IP datagram to the mobile node.

MIP requires the mobile node to update its HA and all of its CNs about its new CoA whenever handoff occurs. If the

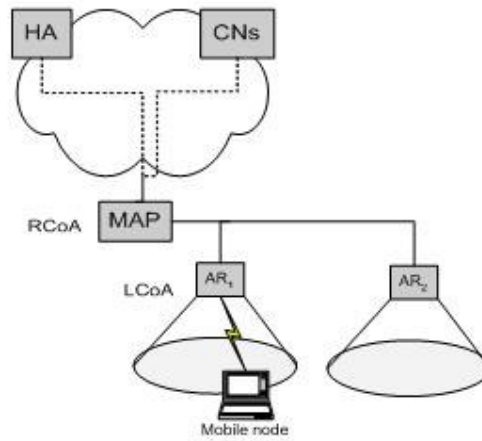


Figure 2: HMIP

HA and CNs are far away or handoff frequently happened, network performance will be severely reduced. HMIP [14-16] is proposed to solve this problem.

HMIP as shown in **Error! Reference source not found.** could be considered as the extension of MIP with a new functional node – Mobility Anchor Point (MAP). MAP locates in the foreign network at a higher level compared to ARs. Each MAP serves a domain consisting of several ARs. The main idea of HMIP is that when a mobile node visits an AR under MAP, it will register with this AR to obtain an on-link CoA (LCoA) and with MAP to obtain a regional CoA (RCoA). The mobile node then uses this RCoA for registration with HA and communication with CNs. When the mobile node moves to a new AR within MAP domain, it only has to register for a new LCoA and inform MAP about its new LCoA. HA and CNs don't need to know anything about this movement and still keep connected with the mobile node using the existing RCoA. When MAP receives a packet destined for a mobile node, it will look at its mapping table to find the correspondent LCoA and forward this packet to the correct AR and then to the mobile node. So MAP is actually a local HA which serves a lot of mobile nodes from different home networks. By using MAP, the overhead packets and registration time will be reduced and the performance of mobile IP could be enhanced in both signaling and handoff. HMIP will be applied in the proposed solution to solve the issue of multiple IP addresses the WMN should use for its connection.

C. Proposed MARs Architecture

The novel idea of this proposal is to use multiple ARs at the same time to connect to the Internet with support of multi-path routing. In short, MARs work as follow:

1. A WMN client needs to register with multiple ARs and obtains a LCoA for each registered AR.
2. To handle multiple LCoAs, we employ HMIP as shown in Figure 2. With the assistance of HMIP, the WMN client will firstly register with the ARs to obtain the corresponding LCoA. These ARs must be under the same MAP. It then registers with that MAP to obtain a RCoA address. And all the connections of the WMN clients will use this RCoA as the source address.
3. By doing so, a connection from the WMN client could use multiple ARs at the same time for its data transmission without any problem. Packets from CN sent to this RCoA source address will reach MAP. MAP will choose a AR to be the destination for the packet to be forwarded to and eventually this packet will reach the destination WMN client through the selected AR.
4. Data from a WMN client will be distributed among the multiple registered ARs based on the new proposed reactive load balancing algorithm presented in session IV.

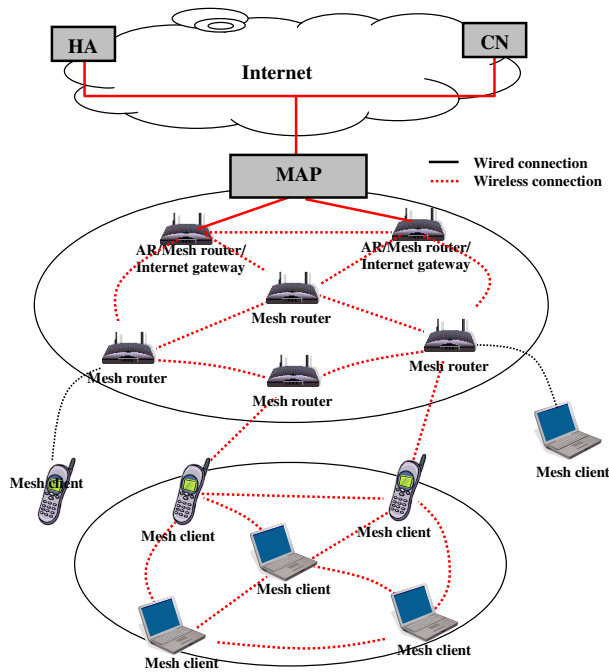


Figure 2: The proposed architecture

III. THE PROPOSED MULTIPLE ARs SOLUTION - MARS

The overall architecture of the proposed solution is shown in Figure 2. Under this architecture, all ARs/mesh router/Internet gateway will be managed by MAP. When a WMN client powers on, the first thing is to register itself with ARs and MAP to obtain its LCoAs and RCoA. Only when that WMN client has its own LCoAs and RCoA, it could use these addresses to communicate with other node in the Internet. With RCoA obtained from MAP, the WMN client could establish connections with nodes in the Internet and communicate without interruption even if it handovers from AR to AR. This entire procedure is described in details as follows.

A. Address configuration & gateway discovery

Initial address configuration is quite straightforward and could follow [6]. If a WMN client does not have address when it joins WMN. It needs to create its MANET IP address as in [6].

The WMN client then has to discover the AR (Access Router - Internet gateway) to obtain the information such as global network prefixes, address lifetime, and MAP information for registration. And it will rout packets to the Internet. Basically, there're two ways for the WMN client to discover the ARs [8]. In both ways, ad hoc routing protocols or a modified Neighbor Discovery Protocol (NDP) could be used.

In the first way, the WMN client discovers the ARs by listening to the gateway advertisement messages (GWADV) periodically broadcasted by ARs as part of the ad hoc routing protocol or NDP. If a proactive ad hoc routing protocol is used, GWADV could be piggybacked to any broadcast routing message such as HELLO message. If a reactive ad hoc routing protocol is used, GWADV could be stored in the sent route reply/notify messages. If NDP is used, GWADV message could be sent in router advertisement message of NDP. In any case, the GWADV message could be broadcasted to all nodes in the WMN.

In the second way, the WMN client will explicitly ask for ARs to send the GWADV information. Again, both ad hoc routing protocols and NDP could be used. If a reactive routing protocol is used in WMN, WMN client could use the Route Request packet (RREQ) which is destined for all ARs as the Gateway solicitation message (GWSOL). Source address used in this RREQ message could be the above selected MANET address or the home address. ARs will reply by the route reply message (RREP) as the GWADV message. If NDP is used, MANET node could send the GWSOL message to Internet gateway multicast group (IGW_MCAST). ARs should belong to this group so they could be reached and reply with the GWADV message to the requesting WMN client.

With these GWADV messages, the WMN client will have enough information to process the next step – registration for data communication with outside networks.

B. Registration

To use multiple ARs, the WMN client has to register with multiple ARs. In this paper, the WMN client will register and use two ARs. However, more than two ARs could also be used by the same principle.

The WMN client, based on the information advertised by ARs in GWADV messages, will know the number of the available ARs, addresses of mobility anchor points (MAP), their IP prefixes and other metrics such as number of hops to reach ARs, etc. It then chooses the two best ARs, usually the shortest AR in term of hops, from the same MAP as its candidate ARs to register with.

Firstly, the WMN client creates two local on-link Care of Addresses (LCoA) and a regional CoA (RCoA) by appending its 64 bit EUI to the 64 bits IPv6 prefixes of the two candidate ARs and the MAP. It then sends a registration REG packet, which contain the information about the selected MAP, the newly created LCoA and the RCoA to all candidate ARs. These ARs will update their list of registered WMN clients and forward the REG packet to the selected MAP to update MAP's routing table and the list of registered nodes. Only registered nodes could use ARs, MAP for communication with external networks. The WMN client is now ready to receive and send data from and to the Internet.

C. Routing & data delivering

A WMN client should create a default route in its routing table so that connection to global CNs could be made. The default route is similar to the Table I depending on the type of ad hoc routing protocol used.

TABLE I. ROUTING TABLE

Destination/prefix length	Next hop gateway
Default Route/0	<AR address>
<AR address>/128	<next-hop address>

Note that the AR address in Table I could be either the first registered AR or the second registered AR depending on the load balancing algorithm at the WMN client. So this address will change from time to time, from the first AR to the second AR and back to the first AR and so on.

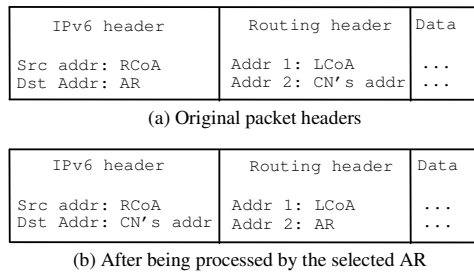


Figure 3: Packet's headers

Routing inside WMNs is quite straight forward using the ad hoc routing protocol. Routing outside WMN can be performed through registered ARs and MAP. When the WMN client wants to send a packet to the Internet, it will choose one of the two registered ARs to send this packet to, based on the WMN client load balancing function. Detail of this load balancing function is presented in session V.

When the WMN client knows which AR it should sent the packet to, it sends the packet to the chosen AR using the routing header option as in the Figure 3. The source address and the destination address in this packet's IPv6 header are RCoA and the chosen AR address respectively. The next header field in the IPv6 header has the value of 63 which will force the AR to examine the next header – the routing header [17]. The routing type field in the routing header is 0 and the fields next to reserved field are the 128 bits LCoA and 128 bits CN destination address respectively. This routing header will inform AR that this packet is come from LCoA and to the destination CN address. AR could check to determine whether this packet is come from a registered WMN client or not based on this LCoA. Because the routing type in the packet routing header is 0, the AR will then exchange the AR address in the IPv6 header with the CN address in the routing header. It means that the packet is sent from RCoA node to the CN node through the LCoA node and the AR. The destination of the packet is now the CN address.

The AR now will check the destination CN address in the packet header. If this destination is inside the WMN, an ICMP error packet is sent back to the source to force it to use route within WMN for data communication. If the destination is a host in the Internet, AR will forward the packet normally using the internet routing protocol. All nodes outside WMN will only know the RCoA of the WMN client. Packets sent by CNs/HA to this RCoA will eventually reach MAP. Based on the load balancing function, MAP will choose which AR it should use to forward the packet to the WMN client. AR then route the packet to the destination WMN client using the ad hoc routing protocol.

D. Handoff

Within MAP, handoff to a new AR could follow [2]. It means, if the WMN client finds a new AR (under the same MAP) which is two hops nearer one of its registered ARs, it will perform handoff to this new AR. The WMN client send a REG packet to the new AR containing WMN client's new LCoA. The new AR will update and insert a new entry for the newly registered WMN client. This REG packet is then forwarded to MAP so MAP could also update its registered tables. During this time, WMN client still maintains normal operation with CNs/HA using the remaining AR. MAP then sends an acknowledgement packet to the WMN client through the new registered AR. The WMN client sends the De_REG packet to the old AR to remove it from the registered node at the old AR. The handoff is completed. The new AR could be used for data transfer normally as described in previous session.

When a WMN client finds two new ARs of a new MAP, both of these two ARs are two hops nearer than its current registered ARs, handoff to a new MAP – also a new MAP domain will be carried out.

The handoff process between MAP domains is as follow: the WMN client sends the REG packet to the two new ARs and in turn to the new MAP. The new MAP will liaise with the old MAP for buffered packets to be forwarded to the new MAP and then to WMN client through two new ARs. After the handoff is over, WMN client will inform HA/CNs about its new RCoA. The new RCoA will be used for all subsequent packets.

The WMN client can perform handoffs to the new MAP only when both ARs of the new MAP are two hops nearer than its current registered ARs. It ensures that handoff between MAP is minimized and hence reduces the effect of handoff over the existing connections.

By the proposed MARS solution, the WMN client could use multiple ARs to route its packets to the Internet. Data will be distributed among these multiple registered ARs based on our proposed load balancing algorithm to maximize connection throughput.

IV. REACTIVE LOAD BALANCING

The reactive load balancing (RLB) can measure the available bandwidth in two paths from the WMN client to its two registered ARs and find out which path is busier and which path is not using probe packets. It then performs the load balancing among these paths. If the first path (path to the first AR) has more bandwidth, the default route in the routing table will be the first AR and vice versa.

The main difference between RLB and other load balancing methods is who will send probe packets. By the existing load balancing schemes, the source node will send probe packets to the destination and wait for the packets to be returned by the destination. By measuring the time gaps between the returned probe packets, the source node could estimate the bandwidth on the paths and determined which path will be used. By doing so, the probe packets have to travel a round trip between the source and the destination, consuming more network resource and producing more overhead. On the contrary, by the RLB scheme, the probe packets will be sent by the destination only. The source node could correctly estimate the bandwidth by the gaps between probe packets. However, the overhead and consumed network resources will be reduced to half.

A. Available bandwidth measurement

The source node initiates the available bandwidth measurement by sending a probe packet to the destination node to start the measurement process. After a timeout period, if no probe packet is received at the source node, implying that the probe packet could be lost, it sends the probe packet to the destination node again. When the destination receives the probe packet sent by the source, it will reply by sending a series of piggybacked probe packets on all paths to the source. From now on, the available bandwidth measurement of reactive load balancing has been activated. These packets travel along paths from the destination to the source to produce time gaps, which can be measured at the source.

Some probe packets may be never received by the source node due to the packets lose to make the time gaps between probe packets vary from packet to packet. By sending more probe packets in a sequence, the chance to have more probe packets received by the source node will be higher. The number of lost probe packets can be estimated because each probe packet has a unique sequence number. The received probe packets at the source node and the number of lost probe packets will be used to produce raw time gaps for further estimating bandwidth.

A filtering scheme has been designed to estimate the bandwidth by only evaluating the time gaps between the probe packets with adjacent packet sequence numbers. The time gap of each a pair of available packets will be calculated. $Gap_{measured}$ is calculated as the mean value of the raw time gaps. The ratio of lost probe packets will be used to estimate $Gap_{measured}$ as a factor. Based on $Gap_{measured}$, the available bandwidth estimation will be obtained.

B. Available bandwidth measurement using RLB in WMN

1) RLB in general WMN

The source mesh client initiates the available bandwidth measurement by sending a probe packet to the registered ARs to start the measurement process. When the AR receives the probe packet sent by the mesh client. It will reply by sending a series of

piggybacked probe packets to the mesh client. From this moment, the AR will periodically send a series of probe packets to the mesh client. These probe packets travel along the path from the AR to the mesh client and produce raw time gaps between them. These raw gaps will be measured at the mesh client by the filtering scheme.

2) *Bandwidth estimation*

In the MANETs, the wireless medium is shared by using four ways handshake RTS/CTS/DATA/ACK mechanism to combat the hidden and exposed terminal problems. By four ways handshaking, a node wishes to send data has to wait until the medium is idle and sends a control packet called Request To Send (RTS) which contains information such as data length, source, destination address, etc to inform other nodes that it has data to send. In other words, RTS is used to reserve the medium for the duration stated in RTS. The destination node once receives the RTS will reply with the Clear To Send (CTS) message to inform the source node that it's ready to receive the data for the duration stated in the RTS. Other nodes once heard the RTS and/or CTS will cease to access the medium during the duration stated in the RTS/CTS messages because they know that a transmission is on the way. The source node will then send the Data packet and the destination node will send the ACK to acknowledge that the data has been received successfully.

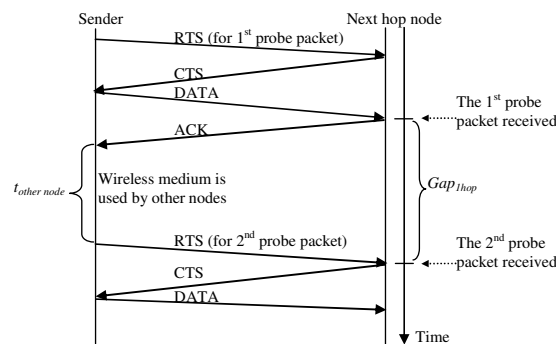


Figure 4: Transmission of probe packets in 802.11 MANET

If the medium is busy, the mobile node has to follow the backoff algorithm by initializing its *backoff timer* for a randomly selected *backoff interval*. This timer will decrease when the medium is idle. When the *backoff timer* reaches zero, the node is allowed to transmit its RTS. This algorithm prevents the phenomenon that once the channel is idle many nodes will access the channel at the same time resulting in collisions.

When a node uses the reactive load balancing, it will send the probe packets to the destination to activate the bandwidth measurement process and the destination will send a series of probe packets to the source in a regular interval. These probe

packets sent by the destination to the source node can be illustrated in Figure 4. The sender is the destination node. The next hop node is the next node on the way to source node.

To send the first successful probe packet, the sender needs to send the RTS to the next hop node, after that the CTS, DATA and ACK packet will follow as in Figure 4. The second probe packet may be sent following the first probe packet immediately. In general, there will be a delay between these two probe packets when the medium is used by other nodes or there's a contention in the medium. Let's call this delay time the $t_{other\ node}$.

Total time to transmit a probe packet from the sender node to the next hop node consists of the transmission time of RTS (t_{RTS}) and CTS (t_{CTS}), the transmission time of the probe packet itself (t_{DATA}), the transmission time of the ACK (t_{ACK}) for the probe packets and the processing time as depicted in Figure 4. So the time gap between the 1st and the 2nd probe packet at the next hop node is:

$$Gap_{1\ hop} = t_{ACK} + t_{other\ node} + t_{RTS} + t_{CTS} + t_{DATA} + t_{processing\ time} \quad (2)$$

t_{RTS} , t_{CTS} , t_{DATA} , t_{ACK} are the time used to transmit the RTS, CTS, the probe packet and ACK, respectively. $t_{other\ nodes}$ is the duration in which the wireless medium is used by the sender's neighboring nodes. In the best case, $t_{other\ nodes}$ is zero. In this case, the time gap between the 1st and the 2nd probe packets in the next hop node can be expected as:

$$Gap_{best} = t_{ACK} + t_{RTS} + t_{CTS} + t_{DATA} + t_{processing\ time} \quad (3)$$

$t_{other\ nodes}$ implies the amount of traffic over the wireless medium. If $t_{other\ nodes}$ is larger, then the available bandwidth for the sender node is smaller and vice versa.

If the next hop node is not the destination of the probe packets, the next hop node will forward these packets again until they reach the destination. The $t_{other\ nodes}$ is accumulated during this process. A time gap between the two probe packets will be eventually measured at receiver node. This gap is called the $Gap_{measured}$.

Based on the $t_{other\ nodes}$ expressed in $Gap_{measured}$, the available bandwidth for the path could be calculated as follow:

$$Available\ bandwidth = \frac{Gap_{best}}{Gap_{measured}} \times B \quad (4)$$

B is the currently maximum available bandwidth. Gap_{best} is the smallest time gap, calculated according to (3). For the sake of simplicity, $t_{processing\ time}$ could be assumed as 0.

By measuring the time gap between the two probe packets, the available bandwidth on the path could be estimated by equation (4).

V. SIMULATION EVALUATION

Simulation experiments have been conducted to evaluate the effectiveness of the proposed MARs solution with reactive load balancing. Three sets of simulation have been taken. The first set of simulation is to evaluate the MARs solution without load balancing. The second set is to evaluate the reactive load balancing scheme, and the last set is to evaluate the effectiveness of the MARs solution with reactive load balancing. To achieve a fair evaluation, both proactive and reactive ad hoc routing protocols have been used in different node density and movement schemes. The simulations have been conducted with the NS2 simulator [18]. Destination Sequence Distance Vector (DSDV[19]) and Ad hoc on-demand Distance Vector (AODV [20]) have been selected as the proactive and reactive ad hoc routing protocol, respectively.

Two metrics have been used for performance comparisons in the first set of simulation. The first one is throughput, which is defined as the number of packet received at the destination over the simulation duration. The other is routing overhead defined as the total number of ad hoc routing messages transmitted during the simulation. If the routing packet is forwarded by a node it will also be counted as one transmission. The higher overhead, the less efficiency of the routing protocol.

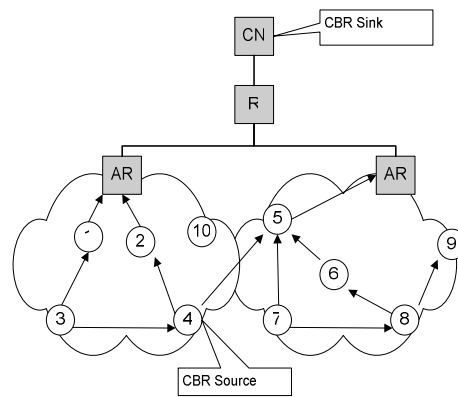


Figure 5: Network simulation scenario

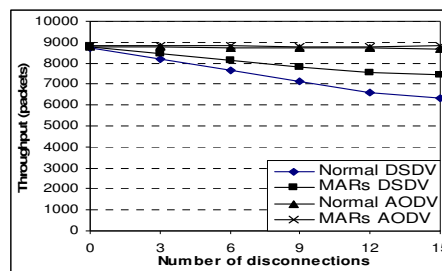
In the first group of simulation, a hybrid network consisting of a fixed network and a wireless network as in the Figure 5 will be evaluated in various scenarios. The fixed network consists of 4 nodes including one CN, one Router and two ARs. The wireless network consists of 10 nodes in the small network simulation scenario or 50 nodes in the large network simulation scenario. If DSDV is used in the wireless network, information about the ARs is piggybacked in the standard DSDV routing packet by adding a new flag. The flag is one byte long. If AODV is used, WMN clients use RREQ & RREP packets to discover the ARs.

To simplify the simulation, the whole wireless network is belonged to one MAP. Therefore, there's no handoff between MAPs. We also assume that as long as WMN clients receive the advertisement from an AR, it will learn all the information needed to route

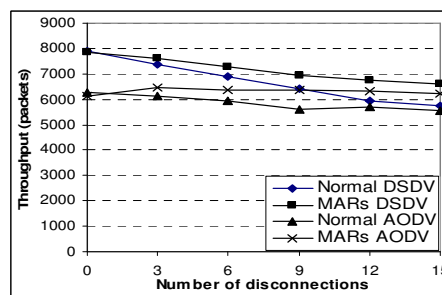
packets to the AR. MIP and HMIP operations have not been considered in the simulation. The simulations are used only for evaluating the effectiveness of using more than one AR at the same time in different scenarios.

In the small network scenario with 10 WMN clients, there're three CBR traffic sources among WMN clients, one more CBR source from a WMN client to the router and one more CBR source from a WMN client to the CN. So totally, there're five CBR traffic sources. A CBR source sends 10 packets per second, each has 512 bytes. WMN clients move in a 450m x 450m area. In the large network scenario with 50 WMN clients, there're four more CBR traffic connections among the WMN clients and the area of the WMN clients' movement has been increased to 1000m x 1000m.

All WMN clients are randomly in the movement following the random waypoint mobility model [21] except one node, since we want to study the multi-hops connection from this node to ARs. The maximum speed of the WMN client movement is 20m/s. A WMN client uses the proposed MARs scheme only for packets originating from itself. If it has to forward packets for other nodes, it will forward the packet to the nearest AR. All the simulations are lasted for 900 seconds. Links between CN, Router and ARs are 5Mbps with 2ms delay.



(a) Throughputs in small WMN simulations



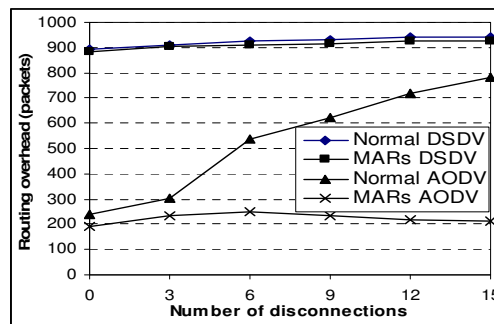
(b) Throughputs in large WMN simulations

Figure 6: Throughputs in small and large WMNs

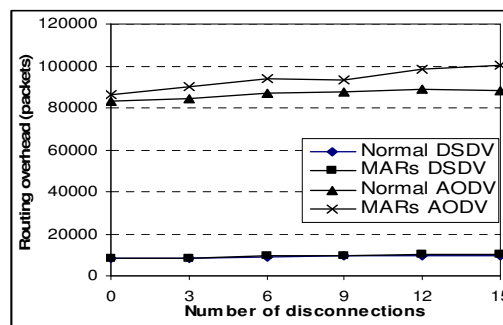
Number of disconnection is the number of times the WMN client is disconnected from its registered AR. Figure 7(a) shows the throughputs of the client using normal DSDV, MARs DSDV, AODV and MARs AODV schemes in the small WMN scenario.

When a connection with current AR is lost, it takes a longer period for a normal WMN client to react to the change. A client with MARs during one connection lost still can use other remaining AR for transmission so the disconnection has less impact on the client with MARs. That's reason when the number of disconnection increases, the throughput of both the client with MARs and the client with other schemes decreases but the latter decreases faster.

Figure 7(b) shows the simulation results of the large scale network with 50 WMN clients. It's obvious from Figure 7(a) and Figure 7(b) that when the number of WMN client increases the network performance will be decreased. However, the simulation results in Figure 7(b) prove that client with MARs still outperform the client with other schemes in the large network environment in term of throughput.



(a) Routing overhead in small WMN simulations



(b) Routing overhead in large WMN simulations

Figure 7: Routing overhead in small and large WMNs

Routing overhead of the MARs DSDV (Figure 8(a)) is slightly less than normal DSDV in the small network scenario due to the fact that network is a little bit more stable using MARs so there are less triggered updates compared to network using normal DSDV. In the case of AODV, when the link is disconnected, the WMN client has to perform the discovery process again. During the period of the discovery process, packets have to be stored in the buffer and RREQ packets are sent, which will increase the

routing overhead (Figure 8(a)). A client with MARs AODV doesn't have to buffer packet when the link is lost because it could use another AR. So the routing overhead is less than that of normal AODV.

In the large scale network, routing overhead of the client using DSDV with or without MARs is almost identical (Figure 8(b)). However, the routing overhead of MARs AODV is higher than that of normal AODV due to the overhead for maintaining the connections with both ARs. In the small size network, this overhead is neglected. But in the large network, there're more RREQ and RREP packets being sent, received and forwarded so that the cost for maintaining one more connection is higher resulted in higher routing overhead.

The next two sets of the simulation are taken to validate the proposed reactive bandwidth measurement. And the final set of simulation is to be used to evaluate the effectiveness of the proposed load balancing solution applied in MARs.

The system setting of the second set of simulation is shown in Figure 8. It consists of just two mobile nodes running the 802.11 in the ad hoc mode (1Mbps ~ 125KB/s). The routing protocol used in the ad hoc network is the proactive routing protocol - Destination Sequence Distant Vector - DSDV [19]. DSDV regularly exchanges routing packets to all nodes in the network. Moreover, there's a constant bit rate - CBR connection from MN2 to MN1 at the rate of 60pkt/s. Each packet is 512bytes in size. It implies that the CBR connection takes the bandwidth of around 42KB/s including the RTS/CTS/ACK packets. There're two types of traffic on the network: the DSDV routing traffic and the CBR traffic. All simulation lasts for 900 seconds.

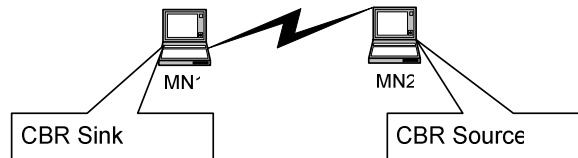


Figure 8: The first measurement simulation scenario

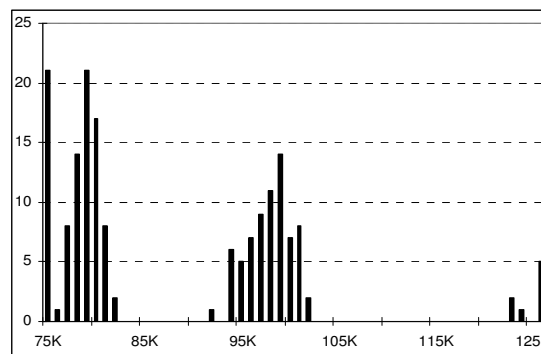


Figure 9: Histogram of reactive available bandwidth measurement in 1 hop with 60pkts/s CBR Connection

Figure 9 shows the histogram of the simulation results of the available bandwidth estimation for 802.11 network between two mobile nodes next to each other as illustrated on Figure 8. We can see that most of the available bandwidth measurement results are on the 90-100KB/s and 78-82KB/s band. The total bandwidth available is 125KB/s. The CBR connection takes 42KB/s. The remaining available bandwidth is 83KB/s on the average. So there're many measurement results are in the 78-82KB/s band. Moreover, there're moments that no CBR packet is transmitted while only the DSDV routing packets are exchanges in the network. DSDV routing packets consume much less bandwidth. Measurements at these moments will report higher available bandwidth – as shown in 90-100KB/s shown in the Figure 9. Also there're the moments, although less frequently, that no packet is transmitted. Measurements at these moments will have the maximum bandwidths as shown in the far right side in Figure 9.

The third simulation setting is shown in Figure 10. There're three mobile nodes in the 802.11 ad hoc networks. And there's no CBR connection between the mobile nodes. MN3 will measure the available bandwidth with MN2 which is 2 hops away. Other parameters are kept the same as in the second simulation scenario. So there's only the DSDV routing traffic running on the network.

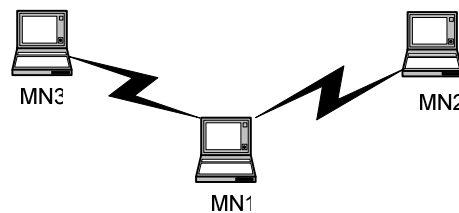


Figure 10: The second measurement simulation scenario

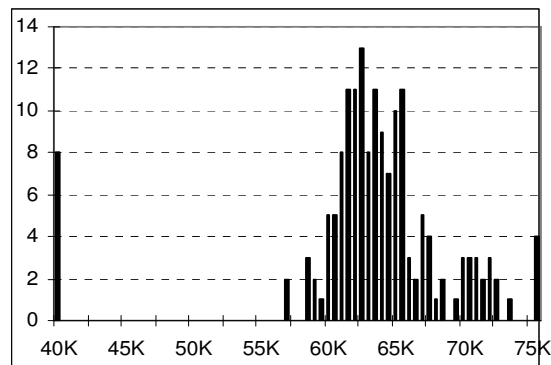
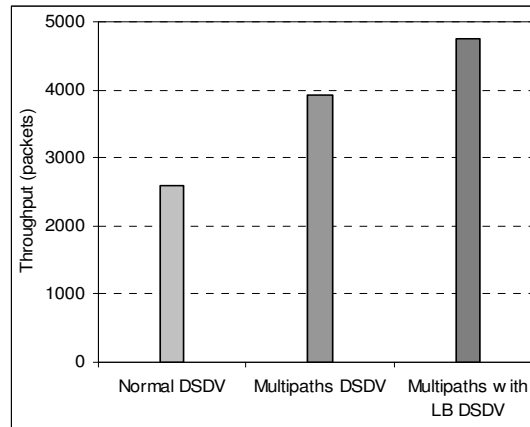


Figure 11: Histogram of reactive available bandwidth measurement in 2 hops with no CBR Connection

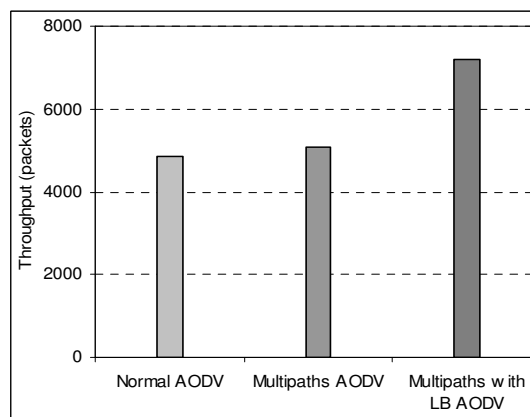
Figure 11 shows the histogram of the simulation results of the available bandwidth estimation of the third simulation scenario. MN2 and MN3 are two hops away from each other so the maximum available bandwidth between MN2 and MN3 is 62.5KB/s,

only half of one hop scenario. This is because the medium is shared among three mobile nodes. If MN3 is transmitting a packet to MN2 through MN1, MN2 could only keep listening and vice versa. Figure 11 shows that the available measurement results are concentrated around the 62.5KB/s point which is closely matched the expected results. Measurements vary due to the DSDV routing traffic.

The last set of simulation scenario is the same scenario in Figure 5. However, the reactive bandwidth measure for balancing the load between the two ARs will be used. DSDV is used on the wireless part in the first simulation run. In the second run, reactive routing protocol – Ad hoc on-demand distance vector (AODV) [20] is used. DSDV and AODV represent the proactive and reactive routing protocols. Using the proposed reactive available bandwidth measurement solution in both type of routing protocols will evaluate the proposed solution more accurately. Reactive available bandwidth measurement module was integrated in the routing module. WMN clients move in a 450m x 450m area.



(a) Proactive DSDV routing protocol



(b) Reactive AODV routing protocol

Figure 12 : Throughput of TCP connection

Figure 12 plots the throughput of a TCP connection from the mobile node 4 to the correspondent node CN in the fixed network. To make the simulation more realistic, there're 5 more TCP connections between mobile nodes. In Figure 12.a, Normal DSDV is the TCP throughput when using normal DSDV routing protocol. Multi-paths DSDV is the TCP throughput when using two paths between the source node and destination node. The traffic load is shared equally between two paths. Multi-paths with LB DSDV is the TCP throughput when using two paths with load balancing. The traffic load shared among these paths is based on their available bandwidth estimated by the proposed solution. Figure 12.b uses the same notions, except that AODV is used in the simulation. Figure 12 shows that using the proposed solution for load balancing in both proactive DSDV and reactive AODV routing protocol significantly increased the connection throughput.

VI. CONCLUSION

In this paper, a novel framework for internetworking between WMNs and the Internet has been proposed. The great idea of this solution is to use more than one ARs simultaneously for the Internet connectivity. By the proposed scheme, the reliability of the connection could be much improved. Within the framework of the MARs, a load balancing scheme based on the estimation on the available bandwidth has been proposed. The idea of the solution is that the probe packets for bandwidth estimation should be sent by the destination node rather than the source node. The benefit of this scheme is that the overhead to the network can be much reduced while the accuracy of the estimation can be improved. The simulation experiments on the proposed solutions, using both proactive (DSDV) and reactive (AODV) routing protocols, in a small and a large network, have proved that utilizing two ARs at the same time can improve network throughput, especially in the small size network. However, in the larger network, using two ARs can produce more routing overhead. But overall performances by using two ARs are very promising in term of throughput and packet delivery ratio. Simulation results have also proved that by using the proposed reactive load balancing scheme, the connection throughput can be increased significantly, in both proactive (DSDV) and reactive (AODV) routing protocols cases. In the future work, we will work on security issues in the wireless mesh networks as many threats have appeared to attack the normal operations of the wireless networks.

REFERENCES

- [1] Akyildiz, I.F., Wang, X., Wang, W., "Wireless Mesh Networks: A Survey", Computer Networks Journal (Elsevier), March 2005.
- [2] U. Jönsson, F. Alriksson, T. Larsson, P. Johansson and G. Maguire, Jr., "MIPMANET - Mobile IP for Mobile Ad Hoc Networks", Proceedings of the MobiHOC'00, Aug. 2000, pp 75-85.

- [3] J. Broch, D. Maltz, and D. Johnson. "Supporting Hierarchy and Heterogeneous Interfaces in Multi-Hop Wireless Ad Hoc Networks", Proceedings of the 4th International Symposium on Parallel Architectures, Algorithms, and Networks (I-SPAN'99), Perth, Australia, pp 370–375, Jun. 1999.
- [4] C. E. Perkins, "Mobile IP", IEEE Communications Magazine, 3(5), pp. 84–99, May 1997.
- [5] D. Johnson, C. Perkins and J. Arkko, "Mobility Support in IPv6", Internet Draft, draft-ietf-mobileip-ipv6-24.txt, Jul. 2003 (Work in progress).
- [6] C. E. Perkins, J. T. Malinen, R. Wakikawa, E.M. Belding-Royer and Y. Sun, "Ad hoc Address Autoconfiguration", Internet Draft, draft-ietf-manet-autoconf-01.txt, Nov. 2001. (Work in Progress).
- [7] C. Jelger and T. Noel, "Gateway and address autoconfiguration for IPv6 adhoc networks", Internet Draft, draft-jelger-manet-gateway-autoconf-v6-00.txt, Aug. 2003 (Work in progress).
- [8] R. Wakikawa, J. T. Malinen, C. E. Perkins, A. Nilsson and A. J. Tuominen, "Global connectivity for IPv6 mobile ad hoc networks", Internet Draft, draft-wakikawa-manet-globalv6-02.txt, Nov. 2002 (Work in progress).
- [9] Y. Sun, E. M. Belding-Royer and C. E. Perkins, "Internet Connectivity for Ad hoc Mobile Networks", Int'l Journal of Wireless Information Networks special issue on "MANETs: Standards, Research, Applications", 9(2), pp 75-88, Apr. 2002.
- [10] U. Jönsson, F. Alriksson, T. Larsson, P. Johansson and G. Maguire, Jr., "MIPMANET - Mobile IP for Mobile Ad Hoc Networks", Proceedings of the MobiHOC'00, pp 75–85, Aug. 2000.
- [11] Lee, S.-J., Gerla, M., "Split Multipath Routing with Maximally Disjoint Paths in Ad Hoc Networks", IEEE International Conference on Communications, Vol. 10 (2001).
- [12] Garcia-Luna-Aceves, J. J.; Mosko, M. Multipath routing in wireless mesh networks. First IEEE Workshop on Wireless Mesh Networks (WiMesh 2005); 2005 September 26; Santa Clara; CA.
- [13] Marina, M.K., Das, S.R.: "On-demand Multipath Distance Vector Routing in Ad Hoc Networks", Proceedings of the International Conference for Network Protocols (2001)
- [14] H. Soliman, C. Castelluccia, K. El-Malki and L. Bellier, "Hierarchical Mobile IPv6 mobility management (HMIPv6)", Internet Draft, draft-ietf-mobileip-hmipv6-08.txt, Jun. 2003 (Work in progress).
- [15] N. Montavont and T. Noel, "Handover management for mobile nodes in IPv6 networks", IEEE Communications Magazine, pp. 38 –43, Aug. 2002.
- [16] H. Soliman, C. Castelluccia, K. El-Malki, L. Bellier, Hierarchical Mobile IPv6 mobility management (HMIPv6), Internet Draft, draft-ietf-mobileip-hmipv6-08.txt, June 2003 (Work in progress)
- [17] S. Deering and R. Hinden, "Internet Protocol, Version 6 (IPv6) Specification", RFC 2460, pp 12-17, Dec. 1998.
- [18] K. Fall and K. Varadhan. ns Manual. The VINT Project. <http://www.isi.edu/nsnam/ns/doc/>.
- [19] C. Perkins, P. Bhagwat. "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers", In ACM SIGCOMM '94 Conference on Communications Architectures, Protocols and Applications, pages 234–244, 1994.
- [20] C. E. Perkins, E. M. Belding-Royer, and S. R. Das, "Ad hoc on-demand distance vector (AODV) routing", IETF Internet Draft. <http://www.ietf.org/internet-drafts/draft-ietfmanet-aodv-11.txt>, June 2002.
- [21] J. Broch, D. A. Maltz, D. B. Johnson, Y.-C. Hu, and J. Jetcheva, "A Performance Comparison of Multihop Wireless Ad Hoc Network Routing Protocols", Proceedings of the 4th ACM/IEEE International Conference on Mobile Computing and Networking (MobiCOM'98), pp. 85–97, Oct. 1998