Multiple-Metric Hybrid Routing Protocol for Heterogeneous Wireless Access Networks

Lijuan Cao Kashif Sharif Yu Wang Teresa Dahlberg
Department of Computer Science, University of North Carolina at Charlotte, USA.
Email: {lcao2,ksharif,yu.wang,teresa.dahlberg}@uncc.edu

Abstract— **The wireless multihop to an access point model appears to be a promising component of future network architectures, including multihop cellular networks and wireless access networks at the edges of mesh networks. Sophisticated software radios and core network protocols are being developed to support the integration of heterogeneous air interfaces within these access networks. A key challenge is managing diverse resources at access points (e.g., 3G, WiFi or WiMax) while discovering efficient multi-hop paths from a source to an access point based on selection criteria specified by various applications or necessitated by network resource constraints. We propose a new routing protocol that integrates multiple metrics to calculate path cost based on diverse selection criteria. In addition, a hybrid proactive/reactive anycast routing paradigm is applied to guide the discovery of an access point among multiple available access points. The result is an integrated, flexible protocol for route discovery and access point discovery. Simulation analysis shows that our approach outperforms single-metric routing protocols while supporting flexible service criteria, including load balancing at access points.**

I. Introduction

The vision of future generation networks is evolving towards one that includes interoperable heterogeneous wireless access technologies to provide seamless access to core networks. Today's markets include a proliferation of cellular, WiFi and WiMax technologies for access to telecom, Internet and entertainment networks via mobile devices such as phones, PDAs, laptops and sensors. Mobile devices equipped with multiple interfaces are already available for consumer use. Recently, there have been active efforts to combine the advantages of cellular and ad hoc wireless access modes, and exploit their added benefits for system performance [1]–[3]. Much of the proposed solutions comprise incremental changes to cellular resource management protocols or to ad hoc routing protocols as a way to extend cellular to ad hoc or vice versa.

Within future generation networks, mobile users may be able to access multiple access points (APs) for connection to the Internet. Thus, it is important for mobile users to locate the best AP from "one or more of a group" of APs, which can be better modeled by an anycast or manycast communication paradigm, rather than unicast or multicast. Here, the notion of "best" can be described as *optimum for communication* based on some selection criteria. As different applications might have different requirements, moreover, the cost of providing services to users varies from one AP to another, as determined by a complex combination of issues including available bandwidth, channel capacity, service availability, etc. The decision of AP selection should be determined by routing method based on both application requirement and services provided by APs. Though anycasting is originally designed for Internet service, it has been applied to routing protocol design for wireless ad hoc and sensor networks [4]–[7], such as AODV-based anycast protocol [6] or DSR-based anyccast protocol [7]. However, these protocols are designed to work purely in ad hoc environments for evenly distributing the load among different available anycast server nodes. Moreover, most existing routing protocols for wireless networks are simply using reactive schemes, which initiate route discovery only for an initial connection, or when an existing route breaks. However, a unique feature of routing in heterogeneous wireless networks, as compared to ad hoc routing, is that only APs serve as possible 'destinations' to the multi-hop path within the access network. These destinations are fixed and have specific access functionality. This calls for a fresh look at the tradeoffs in using proactive or reactive route discovery policies.

In wireless networks, devices are usually resource constrained. Thus, the path cost metric, which guides path selection and resource consumption, is a crucial element of the protocol design. Prior work on multi-hop wireless routing protocols relies largely on the use of single cost metric, for example, the energy consumed along a path [9], [10]. The aim of such protocols is to guide path selection to favor the least-cost path, where the path cost metric reflects the criteria to be minimized. However, this approach does not suffice for future access networks for following reasons: first, applications might have multiple QoS requirements that must be simultaneously considered during route discovery; and second, development of new radio access and wireless communication technologies is producing a wide array of wireless devices, having different levels of constrained resources.

In this paper, we assume a general heterogeneous network architecture as shown in Fig. 1. There are two basic entities in the system: mobile nodes (MNs) and access points (APs). MNs are mobile devices which may have multiple interfaces (e.g., 3G, 802.11, or 802.16) as well as the capability to relay traffic between interfaces. APs are physical access points that connect MNs to the core network and terminate the wireless portion of the network. Different APs can use various technologies. We assume existing protocols or system designs

This work of Yu Wang is supported in part by the US National Science Foundation (NSF) under Grant No. CNS-0721666 and funds provided by the University of North Carolina at Charlotte.

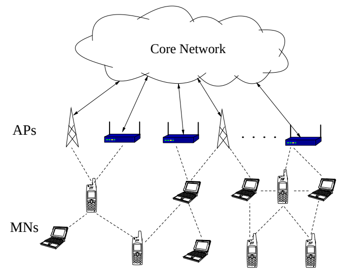


Fig. 1. Network Architecture of Heterogeneous Access Network.

are available to integrate heterogeneous access technologies into the core network. We will only focus on AP discovery and path selection in the multihop part of the architecture. We also assume that all nodes have prior information about anycast group memberships and identities using available protocols.

We propose a new multiple-metric hybrid anycast routing protocol, in Section II, that integrates various cost metrics to guide path selection. Our hybrid mechanism divides the multihop portion of the network into a proactive and a reactive region. A combination of proactive and reactive routing reduces communication overhead and delay, while increasing throughput. The use of multiple cost metrics and anycast routing paradigm provides flexible support of service and resource requirements. Simulation results are presented in Section III. Section IV concludes the paper.

II. Multiple-Metric Hybrid Routing Protocol

We derive our multiple-metric hybrid anycast routing protocol from the AODV [8] architecture; with considerable modifications to support anycasting, distributed regions, and multiple cost metrics. An objective of our protocol is for a mobile node to establish connection with an AP in an anycast group based on multiple path cost metrics. Thus, the selected AP can forward packets to the destination in the core network.

A. Network Regions

In order to support both proactive and reactive approaches, the network is divided into two regions:

- **Proactive Region:** APs and MNs within an m hop radius of an AP are in the proactive region. All MNs maintain active information about AP in this region through periodic Hello packets sent by AP.
- **Reactive Region:** All MNs more than m hops away from an AP are part of the reactive region, and use a reactive anycast routing protocol to discover routes to an AP.

Hybrid routing has been studied in wireless ad hoc networks. It leverages the tradeoff between the reduced delay and overhead provided by proactive approach and reactive approach, respectively.

B. Application Requirements

Classical unicast routing protocols aim to discover the minimum cost path to the single destination specified by the source node, for instance, AODV uses hop count as the cost metric. However, for heterogeneous access networks, anycast routing paradigm is required to locate the best AP among a group, as well as discover the minimum cost path to that AP to fulfill various application requirements. Here, we classify the application requirements into two categories:

1) Requirements for AP Selection: Different applications might have different requirements for certain types of resource at APs. Also, due to device or technology diversity, different APs might have different capabilities. Taking capacity for example, APs utilizing 3G access technology can support simultaneous transmissions to several users by assigning different channels to them. Therefore, the system capacity, can be modeled as maximum number of connections. On the other side, APs with 802.11 access technology only provide one channel to all users by applying Distributed Coordination Function (DCF) MAC protocol, which uses a contention algorithm to provide access to all traffic. Thus, the current traffic load can be used as an indication for the capacity of the AP. To guarantee the quality of communication, AP selection must satisfy such application requirements.

2) Requirements for Path Selection: As the multihop relay service is provided by other MNs in the network, which are usually resource constrained, e.g., constrained battery capacity, limited buffer space, CPU processing capability, etc. As availability of such resources can greatly affect the performance of the connection, applications may require the route discovery to guarantee the sufficiency of certain resource on the selected route. Besides the availability of resources, applications may also require minimizing certain cost metric(s) to optimize the performance, such as energy consumption. Thus, applications require using of multiple metrics for path cost calculation to guarantee the performance. There might be multiple APs that can satisfy the requirements for AP selection, and even with only one AP, there might be multiple paths available between source and the AP(s). Based on the multiple-metric path cost specified by the application requirement, path with the minimum cost value will be selected as the best route.

C. Multiple Metrics Path Cost

Since applications require simultaneous use of multiple metrics to determine the path cost, we use a simple linear combination of different routing metrics, as shown in following equation:

$$cost = cost' + \sum_{\forall i} \alpha_i \times metric_i \tag{1}$$

where $cost'$ is the accumulated cost of previous nodes along the path; $metric_i$ is scaled value from $(0, 1)$; and α_i is the weight factors (or called coefficients) for $metric_i$ to calculate the cost. Based on application requirement, these weight factors can be flexibly varied to change the importance of the cost metrics during route discovery. In [11], the authors propose to apply Analytic Hierarchy Process (AHP) [12] for the calculation of combined four QoS metrics. Even though AHP can normalize the value of metrics from $(0, 1)$ based on relevant cost among paths, it requires route discovery message to carry information of multiple metrics. This causes more control overhead as well as space cost at nodes to maintain the path information. Moreover, the complexity of the calculation is higher. Thus, in our design we use the linear combination. With simple modification (additional fields in RREQ and AHP implementation at APs), AHP can be easily applied to our anycasting method to combine multiple metrics.

Furthermore, in heterogeneous networks, different mobile devices might have different levels of constraint for the resources, e.g., laptop might have more powerful processing capability compared to cell phone. To fit the device diversity for heterogeneous networks, the protocol can also adaptively change the weight factor value based on the device class during the route discovery phase. Device classes could be defined based on the battery type, the amount of memory, or the air interfaces present in a particular type of mobile device.

D. Packet Format

Four types of control packets are designed for the protocol, as explained in this section. Hello packet (HELLO) is a special type of packet generated only by the APs, which is broadcasted periodically inside the proactive region. For MNs that do not have any valid route available to any member of the anycast group in its routing table, Route Request packet (RREQ) is generated to initialize the route discovery. RREQ is similar to that of AODV protocol. The major differences are: instead of using unicast address as destination address, the packet has the anycast group ID as the destination address; two more fields are added for adapting application requirements and utilizing multiple metrics as path cost. Route Reply packet (RREP) is generated by APs or MNs in proactive region for corresponding RREQ packets. The format of the packet, has two more fields compared to that of AODV. While destination anycast group ID represents the anycast group that the destination node belongs to, the accumulative path cost is the accumulative cost along the path from the destination node to the source node. Route ERROR Packet (RERR) is the same as that of AODV protocol.

E. Protocol Operation

Functionality of our proposed anycast protocol can be divided into following different phases.

1) ***Hello Message Transmission****:* All APs periodically transmit HELLO, which only traverse m hops (i.e., inside the proactive region), as defined by using the TTL value in the IP header. Upon receiving a Hello packet, the route to the AP is created or updated, including the current capacity of the AP, as well as the generic cost of the path to the AP. Only nodes within $m-1$ hops distance from the AP decrease the TTL value and rebroadcast the packet.

2) ***Route Discovery (Proactive Region)****:* An MN determines that it is in the proactive region if it has received HELLO from any AP that belongs to the anycast group in the previous *Route Expiration* time interval. If the capacity of that AP can satisfy its application requirement, it can start sending data using the information in the routing table without performing route discovery; otherwise, it performs route discovery as reactive region nodes.

3) ***Route Discovery (Reactive Region)****:* If an MN does not have any valid route available to any member of the anycast group in its routing table, it broadcasts a RREQ. Upon receiving the RREQ, an intermediate node first checks whether it has received this RREQ before. If yes, it drops the RREQ. Otherwise, it updates the hop_count entry by adding one, and updates the cost field with Equation (1). The intermediate node then creates a new entry in its routing table to record the previous hop and rebroadcasts the RREQ. RREP can only be generated by APs of the anycast group or MNs in proactive regions that have an active path to any member of the anycast group. Therefore, when they receive the first RREQ message, they check whether the AP's capacity can satisfy the requirement in the RREQ message. If the requirement is satisfied, RREP is generated and sent back to the source along the reverse path; otherwise, RREQ message will be dropped. For later RREQ messages, RREP is only generated for those with smaller path cost value. Upon receiving the first RREP, an intermediate node records the previous hop and relays the packet to the next hop. Similarly, later RREP message will be forwarded only if it has a smaller path cost value.

4) ***Route Selection****:* Route selection is related to the cost metric used in the protocol. With combined multiple-metric included in the RREQ, our anycast protocol selects the route with the smallest cost value out of all received RREPs. After the source node receives the first RREP, it starts sending out data. It will switch to the other path only if the cost value in the corresponding RREP is smaller.

5) ***Route Maintenance****:* is the same as for AODV.

III. Performance Evaluation

In this section, we conduct several sets of simulations with NS-2 to evaluate our proposed multiple-metric hybrid protocol. Our simulations use the IEEE 802.11 distributed coordination function (DCF) MAC protocol. We assume that different APs may have different capacity, i.e., they can only serve up to certain amount of traffic. We use the total possible data rate at each AP as the measurement of its capacity. In our simulation, for a simple demonstration, our protocol adopt three path cost metrics: hop count, energy cost, and traffic load. Therefore, the path cost equation becomes:

$$cost = cost' + \alpha_1 \times 1 + \alpha_2 \times load + \alpha_3 \times energy\_cost \quad (2)$$

Here, "1" is the hop count; $load$ represents the traffic load at the current node; and $energy\_cost$ denotes the normalized energy cost for the link from the previous hop to the current node. Different applications can define their requirement by including different sets of weight factors in RREQ. For example, an application might only want to consider energy consumption, thus, $(\alpha_1, \alpha_2, \alpha_3) = (0, 0, 1)$. In order to demonstrate how different requirements and path cost metrics guide route discovery and resource consumption, we conduct simulations with three different network deployment.

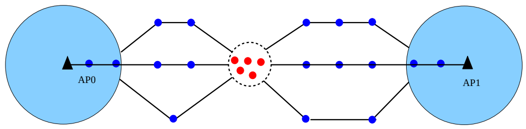


Fig. 2. Network Deployment.

TABLE I

AP CAPACITY AND DATA RATE OF EVERY TRAFFIC SOURCE.

	AP0	AP1	Src1	Src2	Src3	Src4	Src5
Set 1	25	25	4	4	4	4	4
Set 2	15	15	4	4	4	4	4
Set 3	10	50	4	5	8	4	5

The network topology is shown in Fig. 2, which includes two APs located on the left and right side. There are 5 CBR traffic sources that start generating traffic one by one, and the beginning point is 10, 15, 20, 25, 30 seconds, respectively. The distance between sources and AP_0 is smaller than that between sources and AP_1. We vary APs' capacity and the data rate of traffic sources to conduct three sets of simulations with this scenario. The configuration of these parameters are listed in Table I. Within each simulation set, there are eight simulations that use various requirements to guide the route discovery, as shown in Table II. For example, in Simulation 1, the application informs routing agent its data rate (as shown in the first row of Table I) as well as the weight factors, which is $(1, 0, 0)$; Simulation 2 uses the same values, however, it does not include the requirement for AP selection. Basically, we consider four routing methods with various metrics: hop count, load, transmission power, and combined metric.

In the first set of simulations, as the capacity of both APs are enough to hold all the traffic load, therefore, the requirement for AP selection does not take effect, and route discovery is determined by requirement for path selection. It is easy to see that different routing methods take different paths to connect the access points. In Simulations 1-2 and 5-6, nearly all the traffic are directed to AP_0 which has the smaller cost in hop count or energy to the source. But they use different paths (shortest path or least energy path) to connect to AP_0. When using traffic load as the only metric, both APs attract certain traffic. If multiple metrics are used as path selection criteria, the protocol can more evenly distribute the traffic to some extent. Due to page limit, we ignore the detailed results here.

The simulation result of the second set is shown in Table III, and the throughput of the APs is shown in Fig. 3. In this set of simulation, we have the same data rate on the source side, but we decrease the capacity to 15 for both APs. Therefore, at most, each AP can only accommodate 3 connections simultaneously. In Simulation 1 and 5 (Fig. 3(a) and (e)), we observe that connections are distributed across two APs. Once AP_0 reaches its maximum possible capacity, new connections are directed to AP_1. In Simulation 2 and 6 (Fig. 3(b) and (f)) , as there is no capacity requirements on APs, all the connections are formed with AP_0 which has smaller cost. However, this reduces the overall delivery ratio as shown in Table III. Simulations 3, 4, 7 and 8 (Fig. 3(c), (d), (g) and (h)) depict similar behavior as in Set 1. Interestingly, the figures for load metric or combined metric with and without requirement for AP selection are almost the same. This shows just using load metric or combined metric can spread the traffic among different APs.

TABLE II

REQUIREMENTS FOR AP AND PATH SELECTION.

Requirements for	AP Selection	Path Selection
Simulation 1/2	data rate/NULL	(1, 0, 0)
Simulation 3/4	data rate/NULL	(0, 1, 0)
Simulation 5/6	data rate/NULL	(0, 0, 1)
Simulation 7/8	data rate/NULL	(1/3, 1/3, 1/3)

TABLE III

PERFORMANCE COMPARISON OF SIMULATIONS IN SET 2.

Simulation	DeliveryRate %	Delay	Overhead	Energy
Sim 1/2	99.84/83.66	0.036/0.034	0.377/0.477	6.927/7.050
Sim 3/4	99.52/99.52	0.035/0.035	0.372/0.372	6.555/6.555
Sim 5/6	100.0/83.06	0.040/0.041	0.422/0.530	5.767/5.617
Sim 7/8	99.84/99.84	0.038/0.038	0.393/0.393	5.832/5.820

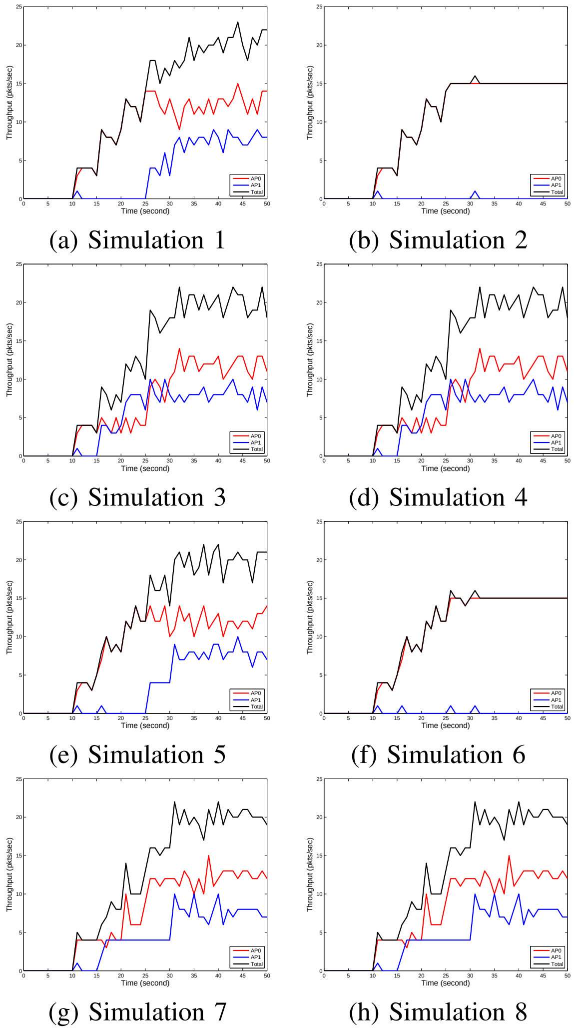
TABLE IV

PERFORMANCE COMPARISON OF SIMULATIONS IN SET 3.

Simulation	DeliveryRate %	Delay	Overhead	Energy
Sim 1/2	99.88/47.49	0.037/0.036	0.284/0.622	8.836/9.306
Sim 3/4	99.49/91.29	0.046/0.040	0.301/0.342	8.697/8.420
Sim 5/6	100.0/56.86	0.045/0.046	0.316/0.579	7.744/7.124
Sim 7/8	99.75/78.88	0.040/0.039	0.303/0.395	8.309/8.327

In the third set of simulations, we consider different AP capacities and various traffic demands. The simulation result is shown in Table IV, and the throughput of the APs is shown in Fig. 4. Here, the data rate for the five traffic sources are 4, 5, 8, 4 and 5 packets, in the order of the start time of traffic. The capacity is configured as 10 and 30 packets for AP_0 and AP_1, respectively. Therefore, unlike previous simulation settings (Sets 1 and 2), the connection distribution is different due to the different data rates and AP capacities. In Simulations 1 and 5 (Fig. 4(a) and (e)), AP_0 only accepts the first two connections. Simulation 2 (Fig. 4(b)) has the similar trend as compared to that in Set 2, except that the upper bound is decreased to 10 packets. In Simulation 6 (Fig. 4(f)), due to the heavy traffic load along the path to AP_0 which causes MAC layer collisions, the last connection is directed towards AP_1. In Simulation 3 (Fig. 4(c)), with the capacity requirement, the connections are directed as follow: sources 1 and 4 are connected to AP_0 while sources 2, 3 and 5 are connected to AP_1. Simulation 7 (Fig. 4(g)) follows the same trend. Without limitation of capacity requirement, it is easy to understand the trend in Fig. 4(d) and (h) for Simulations 4 and 8.

In summary, our simulations show different requirements and routing metric can affect the AP selection and routing performances. Our multiple metric anycast routing provide flexibility of picking appropriate metrics for applications and



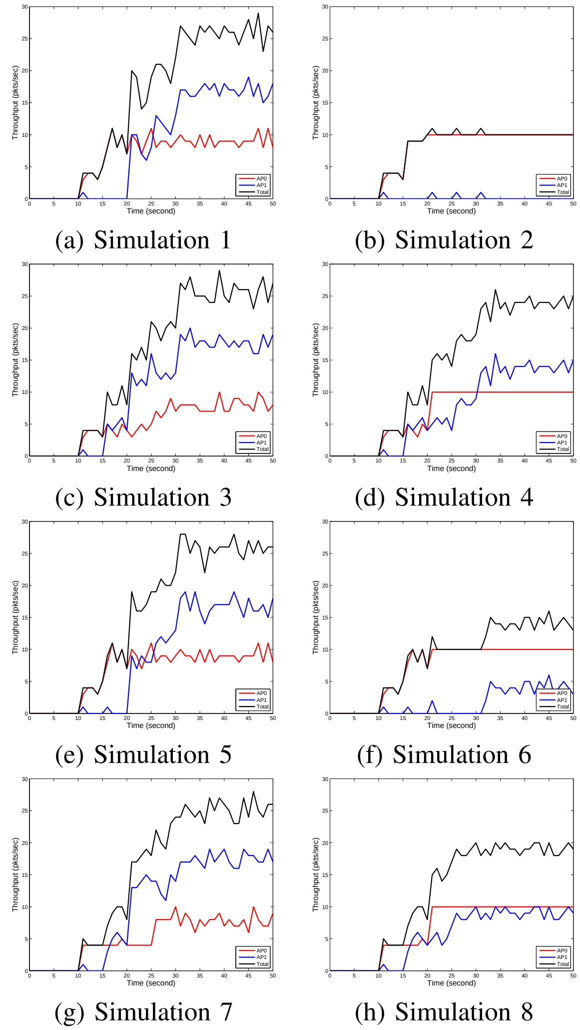
(a) Simulation 1 (b) Simulation 2

(c) Simulation 3 (d) Simulation 4

(e) Simulation 5 (f) Simulation 6

(g) Simulation 7 (h) Simulation 8

Fig. 3. Throughput of simulations in Set 2.



(a) Simulation 1 (b) Simulation 2

(c) Simulation 3 (d) Simulation 4

(e) Simulation 5 (f) Simulation 6

(g) Simulation 7 (h) Simulation 8

Fig. 4. Throughput of simulations in Set 3.

users. On the other hand, AP capacity should be considered in the AP selection phase to guarantee the performance.

IV. Conclusion

We presented a hybrid anycast routing protocol for heterogeneous access networks which enables MNs to select one of multiple eligible access points. To satisfy various application requirements (both AP capacity and path metrics), we used combined multiple-metric to guide the route discovery and AP selection. Simulations showed that the utilization of multiple-metric is important and effective to guide route discovery and AP selection in heterogeneous wireless access networks.

References

[1] B. Bhargava, X. Wu, Y. Lu, and W. Wang, "Integrating heterogeneous wireless technologies: A cellular aided mobile ad hoc networks," *ACM Mobile Network and Applications*, vol. 9, no. 4, pp. 393–408, Aug 2004.

[2] H.-Y. Hsieh and R. Sivakumar, "On using the ad-hoc network model in cellular packet data networks," in *Proc of ACM MobiHoc*, 2002.

[3] H. Wu, C. Qiao, S. De, and O. Tonguz, "Integrated cellular and ad hoc relaying systems: ICAR," *IEEE Journal on Selected Areas in Communications*, vol. 19, no. 10, pp. 2105–2115, Oct 2001.

[4] N. Thepvilojanapong, Y. Tobe, and K. Sezaki, "HAR: Hierarchy-based anycast routing protocol for wireless sensor networks," in *Proc. of 2005 Symposium on Applications and the Internet*, 2005.

[5] V. Lenders, M. May, and B. Plattner, "Density-based vs. proximity-based anycast routing for mobile networks," in *Proc. of IEEE ICC*, 2006.

[6] J. Wang, Y. Zheng, and W. Jia, "An AODV-based anycast protocol for mobile ad hoc network," in *Proc of IEEE PIMRC*, 2003.

[7] G. Peng, Y. Yang, and C. Gao, "ARDSR: An anycast routing protocol for mobile ad hoc network," in *Proc of IEEE CSSET*, 2005.

[8] C. Perkins, E. Belding-Royer, and S. Das, "Ad hoc on-demand distance vector routing," IETF RFC 3561, 2003.

[9] S. Singh and C. S. Raghavendra, "PAMAS-power aware multi-access protocol with signaling for ad hoc networks," *ACM SIGCOMM Computer Communication Review*, Volume 28, 3 Jul. 1998, Pages: 5-26

[10] D. Kim, J. Garcia-Luna-Aceves, K. Obraczka, and et al., "Power-aware routing based on the energy drain rate for mobile ad hoc networks," *Proc. of IEEE Int'l Conf. on Computer Comm. and Nets*, 2002

[11] A.M.S. Alkahtani, M.E. Woodward and K. Al-Begain, "Prioritised best effort routing with four quality of service metrics applying the concept of the analytic hierarchy process," *Computers & Operations Research*, Vol. 33, 2006, 559-580.

[12] T.L. Saaty, "The Analytic Hierarchy Process: Planning, Priority, Setting and Resource Allocation," first edition. McGraw Hill, 1980