This full text paper was peer reviewed at the direction of IEEE Communications Society subject matter experts for publication in the IEEE ICC 2011 proceedings

Relative Link Quality Assessment and Hybrid Routing Scheme for Wireless Mesh Networks

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Abstract—**We present a link capacity estimation model and a hybrid routing scheme for wireless mesh networks which aims at improving throughput. The multi-source interference between links and frame capture behaviors of nodes are analyzed. Our model provides estimated values which can indicate the relative quality of wireless links. And we present a routing metric which combines multiple factors based on the estimated values. The proposed routing scheme which is independent of special routing protocols adopts different strategies for the traffic of accessing the Internet and the end-to-end traffic. Besides, we introduce a new gateway-assisted routing technique to further improve the performance. Simulation results show that the estimation model provides accurate estimated values enough for route selection, and the routing scheme improves end-to-end throughput by 185% compared with legacy AODV[14] protocol.**

Keywords—Link Capacity Estimation; Routing; Wireless Mesh Network

I. INTRODUCTION

Wireless Mesh Network (WMN) is a universal type of wireless access network that combines advantages of Wireless Local Area Network and Mobile Ad hoc Network. A WMN consists of wireless nodes that can be clients, routers or both. A wireless backbone is created to support end-to-end transmission. Nodes in the backbone are called mesh routers, which have very low mobility. Some mesh routers are connected to wired networks to access the Internet or outer networks, which are called gateways. And some mobile nodes are connected to mesh routers.

Practical models for estimating wireless link capacity are crucial to the efficient operation of WMNs. The performance of network protocols (e.g. routing protocols) can be significantly improved with an accurate estimation model. However, the complicated interaction of CSMA-based MAC layer and interference from multiple sources make accurate estimation rather difficult. Fortunately, many applications such as routing protocols do not rely heavily on the estimation accuracy. It is enough to know the relative capacity of links (i.e. which link has a higher capacity) to select a suitable route.

Routing protocols also play an important role in improving the performance of a WMN. A routing metric indicating path quality is formulated based on the estimated link capacity. Then routing protocols follow on-demand or proactive schemes to complete route discovery, creation and maintenance.

One objective of our work is to present a link capacity estimation model which takes multi-source interference into consideration. We make some assumptions and simplifications to reduce the complexity of analysis and computation without reducing its scalability to suit more complicated environment. Simulation results show that our model can achieve enough accuracy to meet routing protocols' need. The other objective of our work is to present a new hybrid routing scheme which combines advantages of both on-demand and proactive ones. We also formulate a route metric based on the estimated link capacity and use it with our newly-proposed routing scheme.

The main contributions of this paper include:

- We develop a link capacity estimation model based on the classic SINR (Signal-to-Interference-and-Noise Ratio) wireless capture theory taking multi-source interference into account.
- We present a new route metric based on the estimated link capacity. It can indicate which path is the best one among all possible paths.
- We work out a new hybrid routing scheme which combines advantages of on-demand and proactive ones. Also, we give further optimization with the help of gateways.
- We carry out simulations to show that the accuracy of our model supports routing well, and our proposed routing scheme can evidently improve end-to-end throughput.

The rest of this paper is organized as follows. Section II discusses some related works. Section III presents the link capacity estimation model. Then we formulate a routing metric and propose our routing scheme in Section IV. Section V shows the evaluation. Finally, Section VI concludes the whole paper.

II. RELATED WORK

The estimation of link capacity is always one of the most important issues in network research area. It is the basis of resource allocation and management, and has great help for route selection, QoS and network management.

Many studies are based on theoretical analysis and modeling. Analysis for general wireless networks in [5] showed that each node can only share $\Theta\left(W / \sqrt{n \log n}\right)$ (W is theoretical capacity) of capacity even if interference can be wholly avoided as the scale of network increases (with node number n). Ad hoc networks were analyzed in [6], and the authors pointed out that

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This work is co-supported by the National Key Basic Research Program of China (No. 2009CB320504), the National Key Technology R&D Program of China (No. 2008BAH37B09), the National Nature Science Foundation of China (No.61073155) and the MOE-INTEL-10-03.

reducing the distance between sender and receiver is significant for network scalability. Interference was analyzed with the help of conflict graph [7], and a method of computing the capacity of multi-hop wireless networks was presented.

A method of measuring link quality was presented in [8] based on IEEE 802.11 MAC protocol. The occupation time of packets transferred in a unit of time was estimated, and available capacity was computed by multiplying the remaining time with the bit rates on corresponding links. Network cards must work in promiscuous mode and monitor all packets, and computation is done for each packet, so the overhead is rather high.

The work done in [9, 10] is highly related to our work. The relationship between delivery ratio and SINR/RSS (Receive Signal Strength) of any node pair was measured in [9] as input for its model and output is the estimated link delivery ratios with any interference node set. In [10], RSS of any node pair was measured and link delivery ratios with any interference node set were estimated based on traditional SINR model.

There are also numerous studies on routing metric and algorithm, which also affect the performance a lot.

Minimum hopcount is the earliest routing metric, and is widely adopted by early routing protocols such as AODV[14]. However, it neglects link difference so that the performance is far from ideal[1]. ETX[3] used the probability of successful transfer as metric. However, interference, bit rates and traffic loads are not considered, and it cannot be used in multi-channel networks. EAR[13] is similar to ETX[3], but it is based on measurement. WCETT[12] was designed for multi-channel environment, but it is only suitable for small networks.

MR-LQSR combined link-state routing and source routing using WCETT as routing metric[12]. Since it was designed for static networks, the frequent link-state changes in WMNs will greatly increase the protocol overhead. ExOR[2] brought opportunistic routing into WMNs. Source node selects several forwarding nodes, and sorts them by forwarding cost. Then the forwarding nodes forward packets according to the order. This method utilizes every possible successful reception to improve throughput. However, it changes the hop-by-hop forwarding scheme, thus affects transport layer protocols (e.g. TCP).

Compared to existing work, our link capacity estimation model has several features. 1) We need to make no changes on IEEE 802.11 protocols or wireless network cards to apply our model in WMNs and ad hoc networks based on IEEE 802.11. 2) Although models in [9, 10] and ours are based on the same theory, our model can do online estimation. 3) Our model only needs information exchanged between neighbors rather than global information. 4) Our model suits any traffic profile and does not need global traffic profile as input.

Our work on routing is also complementary to many routing studies. First, no changes on other layer protocols are needed to apply our routing scheme. Second, our routing metric combines multiple factors which brings higher accuracy in judging the relative quality of paths. Third, our routing metric can quickly reflect link-state varies. Finally, our routing scheme is a hybrid one and we creatively introduce gateway-assisted optimization.

III. LINK CAPACITY ESTIMATION MODEL

A. Brief Introduction

One of our focuses is to create a model for estimating the available link capacity. We call the estimated value *ELCM*, which is short for *Estimated Link Capacity Metric*.

Our work is based on a widely-applied wireless transfer model, i.e. the following relationship between delivery ratio and SINR is satisfied.

$$dr(SINR) = dr\left(\frac{S_{sr}}{I_{sr} + N}\right) = dr(S_{sr}, I_{sr}) \quad (1)$$

where S_{sr} denotes the signal strength sent from node s to r, I_{sr} denotes the interference at receiving node r, and N denotes the noise. $dr()$ denotes the delivery ratio.

Our link capacity estimation model composes of two parts which will be described in following subsections. Here we give the assumptions of this model: 1) Nodes transfer with a fixed bit rate. 2) The frame length is also fixed. These assumptions may not be met in reality, but they simplify the model creation so that we can concentrate on main factors that affect the link capacity. More over, we only need to have a further extension if we want to take variable bit rates and data frame lengths into account.

Our model needs function $dr(SINR)$ in Equation (1) as input. Many manufacturers provide it in technical white paper. If not provided, we can measure it easily. Connect two nodes through attenuator, and change attenuation values to get different SINRs. Then we measure corresponding delivery ratios. We can also adopt the method in [10], i.e. measure SINRs and delivery ratios between any node pair, and use interpolation to get the function.

B. Sender-side Model

As described above, bit rate and frame length are assumed to be fixed. So the number of frames that can be sent in a unit of time is a constant *MaxSlot*. Each frame occupies a slot. *MaxSlot* is conflict-region-concerned, i.e. node s and all its neighbors share the resource of one conflict region.

We believe the largest possible number of slots that sender s can occupy satisfies the empirical equation below.

$$EstSlot_s \approx MaxSlot \times \frac{MaxSlot + TxCount_s}{MaxSlot + TxCount_s + RxCount_s + RxErrCount_s} \quad (2)$$

where $TxCount_i$ denotes the average number of frames sent by node i in a period of time (e.g. 10s, the same below); $RxCount_i$ denotes the average number of frames received successfully by node i in a period of time; $RxErrConut_i$ denotes the average number of frames received but error-decoded by node i in a period of time. We can get these values through promiscuous monitoring or reading from MadWifi[4] driver. Equation (2) implies that the number of slots that a node occupies is positive correlated with the number of frames it wants to send.

C. Receiver-side Model

First, we list definitions of notations in Table I.

Then we can compute the delivery ratio. As proved in [10], if locations of node s and r are fixed, S_{sr} is basically fixed, and the variation of RSS is mainly due to the variation of interference.

TABLE I
DEFINITIONS OF NOTATIONS

Notations	Definitions
$N = \{n_1, n_2, ..., n_n\}$	set of all nodes in the network
$dr_{sr}, s \in N, r \in N$	delivery ratio of link *sr* with no other interference nodes
$dr_{sr}^t, s \in N, r \in N, t \in N$	delivery ratio of link *sr* with interference node *t*
$dr_{sr}^T, s \in N, r \in N, T \subseteq N$	delivery ratio of link *sr* with interference node set *T*
$Prop_{sr}, s \in N, r \in N$	expected delivery ratio of link *sr*
Γ	set of available slots in a unit of time
X_i	set of slots occupied by node *i*
$f_T, T \subseteq N$	proportion of time when nodes in *T* simultaneously transfer
$t_T, T \subseteq N$	proportion of time when nodes in *T* simultaneously transfer and nodes in *N-T* do not transfer

Similar as [10], we assume that there is at least one frame with no interference. So we have

$$S_{sr} \approx \min(RSS_{sr}) \qquad (3)$$

$$I_{sr} \approx \overline{I_{sr}} = \overline{RSS_{sr}} - \min(RSS_{sr}) \qquad (4)$$

where RSS_{sr} denotes the set consisted of RSS of all frames sent from node *s* to *r*. When no external interference exists, we have

$$\begin{aligned} dr_{sr} &= dr(S_{sr}, I_{sr}) \\ &\approx dr\left(\min(RSS_{sr}),\ \overline{RSS_{sr}} - \min(RSS_{sr})\right) \end{aligned} \qquad (5)$$

When interference node *t* exists, we have

$$\begin{aligned} dr_{sr}^t &= dr(S_{sr}, I_r + S_{tr}) \\ &\approx dr\left(\min(RSS_{sr}),\ \overline{RSS_{sr}} - \min(RSS_{sr}) + \min(RSS_{tr})\right) \end{aligned} \qquad (6)$$

When interference node set *T* exists, we have

$$\begin{aligned} dr_{sr}^T &= dr(S_{sr}, I_r + \sum_{t\in T} S_{tr}) \\ &\approx dr\left(\min(RSS_{sr}),\ \overline{RSS_{sr}} - \min(RSS_{sr}) + \sum_{t\in T}\min(RSS_{tr})\right) \end{aligned} \qquad (7)$$

According to the definition of expectation, we have

$$Prob_{sr} = \sum_{T\in P(N-\{s\})} t_{T\cup\{s\}} \times dr_{sr}^T \qquad (8)$$

And we can compute t_T by f_T as below.

$$\begin{aligned} t_T &= f_T - \left|\left(\bigcap_{n_i\in T} X_i\right) \cap \left(\bigcup_{n_j\in N-T} X_j\right)\right| / |\Gamma| \\ &= \sum_{Y\in P(N-T)} (-1)^{|Y|} f_{Y\cup T} \end{aligned} \qquad (9)$$

Now we only need to compute f_T. It is easy to know

$$f_i = \frac{EstSlot_i}{MaxSlot} \qquad (10)$$

When nodes *i* and *j* cannot hear each other, we have

$$f_{\{i,j\}} = f_i \times f_j = \frac{EstSlot_i}{MaxSlot} \times \frac{EstSlot_j}{MaxSlot} \qquad (11)$$

Similarly, when nodes in *T* cannot hear each other, we have

$$f_T = \prod_{i\in T} f_i = \prod_{i\in T} \frac{EstSlot_j}{MaxSlot} \qquad (12)$$

Contrarily, when nodes *i* and *j* can hear each other, we have

$$f_{\{i,j\}} = f_i \times f_j \times \frac{2}{W} = \frac{EstSlot_i}{MaxSlot} \times \frac{EstSlot_j}{MaxSlot} \times \frac{2}{W} \qquad (13)$$

where *2/W* is the conflict probability[10].

Finally, we can compute *ELCM* as below.

$$ELCM_{sr} = EstSlot_s \times Prob_{sr} \qquad (14)$$

IV. HYBRID ROUTING SCHEME

A. Path Quality Indicator

In multi-hop wireless networks, there usually exist several paths between source and destination node. Routing protocols need to evaluate each path and choose a best one. In previous section, we present a model to estimate the link quality. Here we need to convert it to the path quality.

We classify the interference into two types. One is intra-flow interference which appears after the data flow begins between nearby links. The other is inter-flow one which always exists and comes from other data flows.

We present the following *Path Quality Indicator* (*PQI*).

$$\begin{aligned} PQI &= \alpha \times \frac{hopcount}{MaxHopcount} \\ &+ \beta \times \sum_{link\ ij \in path} \frac{MaxCapacity \times InterfLink_{ij}}{ELCM_{ij}} \\ &+ \gamma \times \frac{MaxCapacity}{\min_{link\ ij\in path}(ELCM_{ij})} \end{aligned} \qquad (15)$$

where *hopcount* denotes the path hopcount; *MaxHopcount* denotes the maximum hopcount of all paths; *MaxCapacity* denotes the capacity measured without any interference, any contention or any packet loss; *IntefLink*$_{ij}$ denotes the number of links interfered by link *ij* included in the path; α, β, γ are adjustable constants used to balance the three items. The first item focuses on hopcount which has been widely used by routing protocols. The second item cares about link capacity. *ELCM*$_{ij}$ is the estimated link capacity acquired from our model. Note that inter-flow interference is considered in the model, and *IntefLink*$_{ij}$ captures the influence of intra-flow interference. The last item concerns the bottle-neck link. *MaxHopcount* and *MaxCapacity* are introduced to normalize each item into (0, 1).

The presented *PQI* has two features. 1) It combines multiple factors including hopcount, link capacity (both intra-flow and inter-flower interference are considered) and bottle-neck link. 2) It does not need any global information. Computation can be done with only local information.

PQI presented above suits single-channel networks, and it is easily extended to suit multi-channel environment as below.

$$
\begin{aligned}
PQI = {} & \alpha \times \max_{1 \le i \le k} \left(\frac{hopcount_i}{MaxHopcount} \right) \\
& + \beta \times \sum_{link\ ij \in path} \frac{MaxCapacity \times InterfLink_{ij}}{ELCM_{ij}} \qquad (16) \\
& + \gamma \times \frac{MaxCapacity}{\min\limits_{link\ ij \in path} (ELCM_{ij})}
\end{aligned}
$$

where $hopcount_i$ denotes the hopcount of the path working on the ith channel and k is the number of channels. The main difference lies in the first item. Hopcount is computed respectively on different channels, because interference only exists between links working on the same channel. Similarly, $IntefLink_{ij}$ in the second item also refers to the number of links working on the same channel as link ij.

B. Routing Scheme

B.1. Brief Introduction

This section focuses on unicast routing in WMN backbones. In WMN backbones, nodes have low mobility, and although wireless links are time-varying, the rate and range of variation are much smaller than ad hoc networks. So in the design of routing scheme, we can take less consideration on mobility while concentrating on improving the performance.

In WMNs, accessing the Internet from mobile terminals is the main traffic, so routes between mesh routers and gateways are most used, which should deserve great attention. Our design is a hybrid scheme, which has advantages of both proactive and on-demand ones to improve routing performance.

B.2. Routing Scheme Description

Our routing scheme is named Mesh Network Hybrid Routing (MHR). It adopts suitable routing policy for different traffic.

We classify unicast traffic into the traffic of accessing the Internet and the end-to-end traffic inside WMNs. For the traffic of accessing the Internet, MHR adopts proactive scheme. Each node selects a default gateway, creates and maintenances the route to it. For the end-to-end traffic, MHR adopts on-demand scheme. When a node wants to communicate with another node inside WMNs, MHR dynamically creates a hop-by-hop route, and the route will be deleted when the conversation is over.

In fact, the proposed scheme is a general routing scheme which can merge most existing routing metrics and algorithms. Any proactive routing protocol can be used in the selection of default gateway, and any on-demand routing protocol can be used in the end-to-end route selection. Here we give an example (called PQI + MHR) based on our path metric *PQI* and the traditional routing protocol AODV[14].

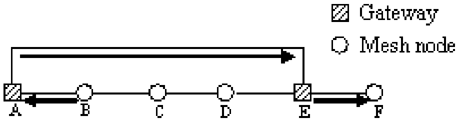
The steps of proactive scheme are as follows. Each gateway floods a Gateway Service Broadcast (GSB) message (which is a modified RREQ) periodically. When an ordinary node receives a GSB message, it appends *ELCM* of the link from upstream into the GSB message before forwarding. Each node may receive several GSB messages from different gateways. It can compute the *PQI* of each path through appended *ELCM*. It selects the gateway to which the path has a minimum *PQI* as its default gateway and sets other gateways as backup ones. Then it replies a RREP message, which is unicast to the gateway along the reverse forward-path of the GSB message. Thus the node creates a bidirectional hop-by-hop route to its default gateway.

The steps of on-demand scheme are as follows. Source node creates a RREQ message and broadcasts it if corresponding route is not in its route table. When a node (not destination) receives a RREQ message, it appends *ELCM* of the link from upstream into the RREQ message before forwarding. Destination node collects RREQ messages, and computes the *PQI* of each path. Then it chooses the path with minimum *PQI* and replies a RREP message, which is unicast to source node along the reverse forward-path of RREQ message. Thus the hop-by-hop route from source to destination is created.

B.3. Gateway-assisted Routing Optimization

There are usually several gateways connected to the wired network in WMNs, and other nodes access the Internet through them. The gateways are often connected with each other through wired links. These wired links have higher quality than wireless ones. So we can utilize them to optimize the route performance.

a) Routing without the help of gateways



b) Gateway-assisted routing

Fig. 1. Illustration of gateway-assisted routing

Fig. 1 gives an example of gateway-assisted routing. Without the help of gateways, node *B* has to choose a path of 4-hop wireless links when it wants to send a frame to node *F* as shown in Fig. 1(a). There are interferences existing between these links (which is intra-flow interference), and also coming from nearby outside nodes (which is inter-flow interference). So the end-to-end throughput will be reduced a lot. When we introduce the gateway-assisted routing, a wired link A->E will be added as shown in Fig. 1(b), which has much higher quality than wireless links. So the path B->A->E->F will be chosen rather than B->C->D->E->F. The new path has only half wireless links, and intra-flow interference hardly exists so that the end-to-end throughput must be greatly increased.

We only need a small modification of previous routing scheme to utilize wired links. These wired links should also be added into network in the route discovery process. When a gateway receives a RREQ message, it will forward the message through wired links to other gateways besides forwarding in wireless network. And the RREQ message forwarded on wired links is also appended an *ELCM* which is very small. So when it arrives at the destination node, paths with wired links can have a better *PQI* than those without wired links and will be chosen.

Note that *ELCM* will quickly reflect current link state, and bottle-neck link in the path significantly affect *PQI*, so the possible congestion near gateways will be avoided efficiently.

Besides, gateway-assisted routing optimization does not rely on specific routing metric or protocol. It can be applied without any changes to original routing protocols.

V. EVALUATION

We have conducted many simulations on NS-2 simulator to evaluate our link capacity estimation model and hybrid routing scheme. We make some extensions on NS-2 simulator to meet the need of our simulations. We adopt Dei 802.11 Multi-rate extension package[11] as basis and focus on the wireless network module. The extended simulator has some new features. 1) Use SINR to judge whether a frame can be received successfully. 2) Superpose simultaneous interference using Gauss model. 3) The signal can transfer to every node although the signal strength may be rather small.

A. Evaluation of ELCM

A.1. Implementation

We set counters on nodes to get *RxCount* and *RxErrCount*, and there is a neighbor table on each node to count frames from different neighbors respectively. Nodes record RSS of each successfully-received frame. So link-state information, average RSS, average interference, etc. can be obtained and output to trace file as parameters of link capacity estimation model.

The computation of *ELCM* is implemented independent of NS-2. It takes trace file as input, and outputs *ELCM*. Then we can compare this estimated value with the actual measured value in simulation. Note that we simplify Equation (12) by dropping items $t_{T\cup\{s\}}$ with $|T|>3$ because they are actually rather small.

A.2. Results

We test on chain topology and random topology.

In chain topology, 10 nodes are distributed uniformly on a line. We repeat simulation for 10 times with each lasting 10s.

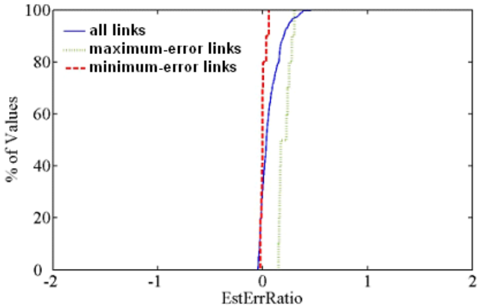


Fig. 2. CDF of *ELCM* error in chain topology

Fig. 2 gives CDF curves of *ELCM* error. The average error of all links is 7.92%; the average error of maximum-error links is 21.01%; the average error of minimum-error links is 1.66%.

In random topology, we have 30 nodes in 1000mX1000m and the simulation is repeated for 18 times with different random topologies. Fig. 3 gives CDF curves of estimation error of all links. The average error is 16.28%.

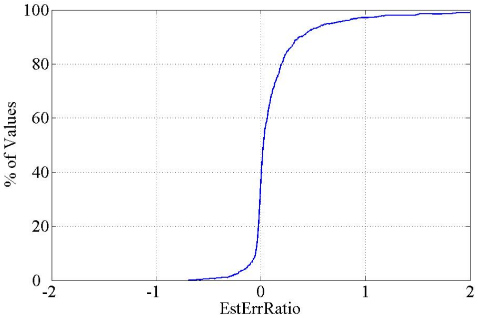


Fig. 3. CDF of *ELCM* error in random topology

B. Evaluation of PQI + MHR

B.1. Implementation

We separate routing system and simulator due to developing difficulty. Routing system reads node information beforehand, takes *ELCM* values as input, and then simulates the routing process to compute paths. The routing results are inserted into simulation scripts so that simulator can set static route table for each node. The defect of this implementation is that the simulator cannot simulate the route creation process, thus the routing protocol overhead cannot be obtained. However, the overhead is not the focus of this paper, and the simulated routing algorithm is based on AODV[14], the protocol overhead of which has been thoroughly analyzed in previous research.

B.2. Results

We compare the TCP end-to-end throughput of PQI + MHR and AODV. We adopt random topology with 30 nodes in 500mX500m, and then randomly select 15 pairs to measure the TCP end-to-end throughput between source and destination.

In the simulation we set $\alpha = \beta = \gamma = 1/3$ in Equation (15), with the assumption that the three factors have equal importance in route selection. However, they would not have equal affects in all topologies and they might not be completely independent. We leave the relationship of them as our future work.

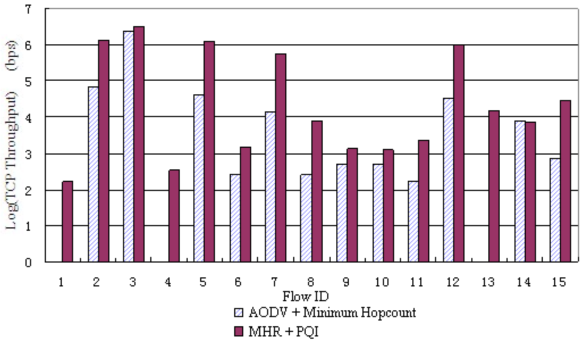


Fig. 4. Comparison of TCP end-to-end throughput

Fig. 4 shows the comparison between the TCP end-to-end throughput of AODV and PQI + MHR. It can be easily seen that PQI + MHR evidently improves the throughput for most TCP flows. PQI + MHR improves the throughput by about 185% in sum compared to AODV.

As stated in [12], throughput achieved by WCETT is 16%

better than that by ETX, and 38.6% better than that with shortest-path routing. So in comparison, our routing scheme provides a much higher throughput.

C. Evaluation of Gateway-assisted Routing

We also carry out simulations to verify the efficiency of gateway-assisted routing technique. In order to eliminate the affect of routing metric and algorithm, we adopt minimum hopcount as routing metric and Dijkstra shortest-path algorithm to compute routing path in simulations.

We adopt four topology setups. Setup 1 has no gateways. Setup 2 has two gateways distributed uniformly. Setup 3 has four gateways distributed uniformly. Setup 4 has four gateways with centralized distribution. We randomly select 10 pairs of nodes as source and destination of TCP flows and measure the end-to-end throughput in each setup.

The average TCP end-to-end throughput of Setup 1 is 25.4Kbps, while those of Setups 2, 3, 4 are 29.4Kbps, 49.6Kbps, 27.5Kbps, respectively. Compared to Setup 1, Setup 2 and Setup 3 improve the throughput by 15.75% and 59.8%, respectively, while Setup 4 has similar performance as Setup 1.

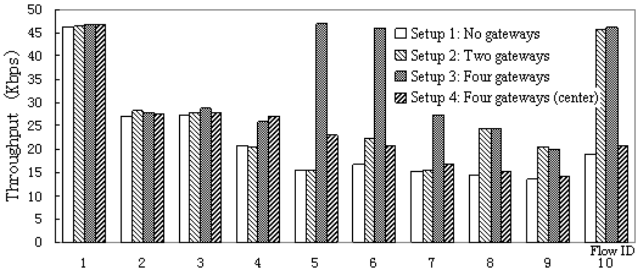


Fig. 5. Comparison of TCP end-to-end throughput in different topology setups

Fig. 5 shows the comparison of TCP end-to-end throughput of four topology setups. Some short-path flows (e.g. Flows 1, 2, 3) do not choose gateway-assisted route so the performances are nearly same, while other flows benefit more or less from gateway-assisted routing technique. The quantity of increase in performance has some relevance to the number and distribution of gateways. Compared to Setup 2, Setup 3 has more gateways, thus has more increase in performance. Centralized gateways in Setup 4 make it difficult to apply gateway-assisted routing, so the performance is almost not increased.

VI. CONCLUSION

In this paper, we first present a link capacity estimation model. It analyzes the interaction between wireless links, describes the relationship between delivery ratio and RSS, interference, etc., and then gives a reliable estimation of link capacity. Simulation results show that the model estimates link capacity effectively.

Based on *ELCM*, we present a new routing metric *PQI*. *PQI* uses *ELCM* as an indicator of link quality, and extends it to indicate path quality. It combines hopcount, hop-by-hop link capacity and bottle-neck link capacity so that it can reflect the quality of the whole path. We also propose a hybrid routing scheme MHR. MHR adopts proactive scheme for the traffic of accessing the Internet and on-demand scheme for the traffic of end-to-end transmission. Simulation results show that PQI + MHR improves TCP end-to-end throughput by about 185%. Besides, we present gateway-assisted technique which utilizes wired links between gateways to improve routing performance.

In the end, we give some discussion on our recent work which can be probably used to improve the routing metric. Our recent work focuses on the measurement of inherent FDR (frame delivery ratio) of wireless links[15]. We have presented a realtime and low-cost mechanism which gives effective and accurate measurement of inherent FDR. Since FDR directly reflects link quality, the measurement result can replace *ELCM* so that the complex computation is avoided and no parameters need to be obtained beforehand. Note that the measurement gives inherent FDR reflecting inherent link quality, so the interference between links is not considered. However, as inherent FDR is independent of traffic loads, the phenomenon of route flapping will hardly happen, and the interference can be peeled off as a separate problem which can be solved from the whole-network view. This is our future work.

REFERENCES

[1] John Bicket, Daniel Aguayo, Sanjit Biswas, and Robert Morris. Architecture and Evaluation of an Unplanned 802.11b Mesh Network. In *Mobicom*, Aug 2005.
[2] Sanjit Biswas and Robert Morris. Opportunistic Routing in Multi-Hop Wireless Networks. In *SIGCOMM*, Aug. 2005.
[3] Douglas S. J. De Couto, Daniel Aguayo, John Bicket, and Robert Morris. A High-Throughput Path Metric for Multi-Hop Wireless Routing. In *MobiCom* 03, September 2003.
[4] Madwifi project. http://madwifi.org.
[5] Gupta, P., Kumar, P.R.. The Capacity of Wireless Networks. *IEEE Transaction on Information Theory*, 46(2), March 2000.
[6] Jinyang Li, Charles Blake, Douglas S. J. De Couto, Hu Imm Lee, and Robert Morris. Capacity of Ad Hoc Wireless Networks. In Proc. *ACM MobiCom*, July 2001.
[7] K. Jain, J. Padhye, V. N. Padmanabhan, L. Qiu. Impact of Interference on Multi-hop Wireless Network Performance. In Proc. *ACM MobiCom*, pp. 66-80, September 2003.
[8] M. Deziel, L. Lamont. Implementation of an IEEE 802.11 Link Available Bandwidth Algorithm to Allow Cross-layering. In Proc. *IEEE International Conference on Wireless and Mobile Computing, Networking and Communications (WiMob'2005)*, Volume: 3, pages 117- 122. 2005
[9] C. Reis, R. Mahajan, M. Rodrig, D. Wetherall, and J. Zahorjan. Measurement-based Models of Delivery and Interference. In Proc. *ACM SIGCOMM*, Sept. 2006.
[10] A Kashyap, S Ganguly, SR Das. A Measurement-based Approach to Modeling Link Capacity in 802.11-based Wireless Networks. In Proc. of *ACM MOBICOM*, 2007.
[11] Dei80211mr project: A New 802.11 Implementation for NS-2. http://www.dei.unipd.it/wdyn/?IDsezione=5090.
[12] R. Draves, J. Padhye, and B. Zill. Routing in Multi-radio, Multi-hop Wireless Mesh Networks. In Proc. *MobiCom*, September 2004.
[13] KH Kim, KG Shin. EAR: On accurate measurement of link quality in multi-hop wireless mesh networks. In *MOBICOM*, 2006.
[14] C. Perkins, E. Belding-Royer, and S. Das. RFC 3561: Ad hoc On-demand Distance Vector (AODV) Routing. July 2003.
[15] Bin Liu, Chaoyi Bian, Xin Jin, Tong Zhao, Wei Yan. MiFDR: Measurement of Inherent Frame Delivery Ratio of Wireless Links in Multi-rate Wireless Network, Under Review, 2010.