行政院國家科學委員會補助專題研究計畫成果報告

無線網狀網路下考慮多功率與 P2P 應用之跨層繞路設計

計畫類別：□ 個別型計畫 ■整合型計畫
計畫編號：NSC 97－2221－E－004－004－MY2
執行期間： 97 年 8 月 1 日至 99 年 7 月 31 日

計畫主持人：蔡子傑
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計畫參與人員： 劉彩鳳、蔡松達、陳維鴻、羅文卿

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此成果報告為五篇論文的集節：

[1] Tzu-Chieh Tsai, Tsai-Feng Liu, "Multi-Interface Routing with Intra/Inter-flow Interference (MiRii) Considerations in Wireless Mesh Networks", in 3rd Asia-Pacific Symposium on Queueing Theory and Network Applications (QTNA), July 30-August 2, 2008, Taipei, Taiwan.

[2] Tzu-Chieh Tsai, Sung-Ta Tsai, Tsai-Feng Liu, "Cross-Layer Design for Multi-Power, Multi-Interface Routing in Wireless Mesh Networks", accepted to appear in The Second International Conference on Advances in Mesh Networks (MESH 2009), June 18-23, 2009 - Athens, Greece.(EI)

[3] Tzu-Chieh Tsai, Sung-Ta Tsai, "M2iRi2: Multi-power, Multi-interface Routing Protocol for Intra/Inter-flow Interference Considerations in Wireless Mesh Networks", in International Conference on Communications and Networking in China, (CHINACOM 2009), Aug 26-28, 2009, Xi'an, China. (EI)

[4] Tzu-Chieh Tsai, Sung-Ta Tsai, "A Cross-Layer Routing Design for Multi-Interface Wireless Mesh Networks", in EURASIP Journal on Wireless Communications and Networking (EURASIP WCN)(SCI_E, EI), Vol. 2009, Article ID 208524, doi:10.1155/2009/208524, 2009.

[5] Tzu-Chieh Tsai, Wei-Hung Chen, "Quality-Aware Multiple Backbone Construction on Multi-interface Wireless Mesh Networks for P2P Streaming", in Third IEEE International Workshop on Enabling Technologies and Standards for Wireless Mesh Networking, (MeshTech 2009), Oct 12, 2009, Macau SAR, China.

上述其中第四篇為期刊論文，為總結整理[1]~[3]篇的會議論文的擴充版本。接下來首先我們先整理摘錄[4]及[5]二篇論文在本計畫中的關聯度與重要成果，後附上完整論文內容供參考。

一、Abstract

無線網狀網路 (WMNs) 由於它的 self-organized, self-configure 和較低的建置成本等優點吸引許多學術和企業投入研究和探討。 IEEE 802.11 TGs 積極的制定無線網狀網路的標準也使得 WMNs 研究更受到重視。

無線網狀網路的主要特性在於使用 multi-radio 和 multi-channel 並且應用於 multi-hop 的無線網路環境下。在過去的 Ad-hoc Network 針對提升無線網路的傳輸效能做了許多研究，然而 Ad-hoc 下所做的研究並不完全適合於 WMNs，因為在 ad-hoc 下設計的 routing protocol 並沒有把 WMNs 的特性考慮進去(multi-radio, multi-channel etc.)。另外，目前針對 WMNs 的研究大部份主要針對不同的網路協定層獨立研究，以提高網路效能，即使 IEEE 802.11 TGs 雖然提出了一個預設的繞徑方法 HWMP 和一個可選擇的繞徑方法 RA-OLSR，但並未充分利用各個網路層協定的資訊來選擇最佳的繞送路徑。但是封包在網路中繞送時，封包的傳輸是由各網路協定層交互影響，對單一網路協 定層做最佳化無法完整的考量整體網路的變動對封包的影響，尤其 video streaming 對 packet loss 和 delay 的高敏感。因此透過 Cross Layer design 方法來設計 routing protocol，利用各網路協定層的資訊，例如搭配動態調整 physical layer 參數或 application layer 的編碼技術等使影音封包在網路中傳送時能有最好的效能，並提升整體網狀網路的效能。

我們第一年(97/8~98/7)的研究目的，將針對 physical 和 network layer 設計一套 cross layer 的 routing protocol，每個 flow 將利用不同網路協定層的資訊決定我們的繞送路徑。我們將分別先以 inter/intra flow interference 考量繞送路徑，再以 physical 層使用 multi-power 為考

量，研究 intra-flow 的每個 hop 該如何選擇 power，以達到最佳效能。最後，再把 inter/intra flow interference 與不同 power 的影響，在作繞路演算時同時考量，以達到最佳網路效能。

第二年(98/8~99/7)的研究目的，將針對支援 P2P streaming 的應用服務為考量，設計一個與 P2P Application 跨層 routing protocol。為達到更好的 streaming QoS，我們建議 video 的編碼技術將原本的 MDC 修改成 bias MDC，以便我們在計算 P2P 的繞路時，可以試著找出兩個（或以上）disjoint trees (Steiner tree)，根據 disjoint trees 上的 path 來個別傳送不同 MDC video streaming 資料。在建構此 trees 時，我們將整合第一年的研究結果，設計更完善的支援 P2P streaming 資料傳送的跨層網路路徑演算法。

透過第一年和第二年的研究結果結合，我們希望設計出一套 cross layer routing protocol 使得點對點 video streaming 的應用，在 multi-power, multi-radio wireless mesh network 下傳輸時，能夠有好的服務品質保證。

關鍵詞：跨層，繞路，無線網狀網路，多網卡，多頻道，多跳接， P2P，影音串流，服務品質 ，MAODV，MDC

二、緣由與目的、結果與討論

本研究的目的主要在 multi-radio WMNs 上設計一套 cross layer 的 routing protocol，符合所需的 QoS。在第一年先針對 physical layer 和 network layer 設計一套 cross layer 的 routing protocol，在建立繞送路徑時將 inter-flow interference（不同 traffic flow 之間的干擾）和 intra-flow interference(同一個 flow 前後 relay 的干擾）以及 load balance 概念納入考量，透過判斷中繼節點的活躍時間來衡量干擾，活躍時間越短表示干擾越小。

我們採用了 WCETT（Weighted Cumulated Expected Transmission Time）metric ，來考量 intra-flow 干擾，至於 inter-flow 干擾，則修改 LBAR（Load-Balanced Ad hoc Routing）的作法，改以計算節點之活躍值（nodal activity）與訊務流量的干擾來選擇路徑。因此，我們整合上述修正過的方法，提出一個 WMNs 上考量到 Intra/Inter-flow 干擾之多網卡路由協定，稱為 MiRii。模擬結果顯示出我們路由協定可以改善網路效能，包含了封包成功傳送率及平均點對點延遲。並已將成果發表在[1]。

其次，再考量到傳送功率的跨層繞路協定。調整不同的傳送功率會影響繞路的決定，也影響到 intra-flow/inter-flow 干擾的程度，當然也決定 throughput 等網路系統的 QoS。我們修正了 MiRii，同時考量傳輸功率的控制，並將 Intra/Inter-flow 的干擾導入到路由路徑的選擇，提出了跨網路協定層的路由協定，稱作 M2iRi2。節點上的網路卡在物理層(Physical layer）計算目前對潛在可容忍的新增干擾，並將此訊息送到網路層(Network layer)和鄰居節點作交換。透過此資訊的交換，在路由發現時控制路由請求封包的傳輸功率，當路由建立後，封包根據路由表的記載，選擇所對應的路由路徑和傳輸功率。經由 NS-2 模擬結果顯示，我們所提出的跨網路協定層路由協定，可同時兼顧網路的吞吐量和平均點對點的延遲，並比 MiRii 達到更好的 QoS。相關的成果發表在[2]~[4]。

第二年，我們進一步針對 P2P Streaming 的應用為考量，設計一個以 P2P Streaming 應用的跨層網路架構與繞路法則。在 WMN 上進行即時影音播放的時候，影音播放的品質是相當重要的目標。因為多媒體應用服務對於延遲及網路傳輸效能相當敏感，且 WMNs 的傳輸過程中常會面臨同頻道干擾的問題而使得傳輸的效能銳減，當每個網路節點都具有多張無線網路卡時，在第一年我們解決了利用 WMNs 多頻道傳輸的特性提升了效能的問題。在第二年，我們進一步利用 WMNs 多頻道傳輸的特性進行多媒體群播傳輸，參考史坦納樹的概念來改善現有的 MAODV 路由演算法，以傳輸品質較佳的鏈結改良原本尋找最小跳躍數路徑的方式，建立兩棵完全互斥的群播樹作為點對點傳輸的骨幹網路，並以 MDC 的概念將影像串流編碼成兩份獨立的子串流分別經由不同的群播樹傳輸。經實驗評估，我們的方法在網路負載較高的網路環境下能有效的降低延遲並提高整體系統的效能。

接下來，我們就分別摘錄[4][5]的重要成果。完整論文則附於後面。

1. " A Cross-Layer Routing Design for Multi-Interface Wireless Mesh Networks"

1.1 Abstract

In recent years, WMNs (Wireless Mesh Networks) technologies have received significant attentions. WMNs not only accede to the advantages of ad hoc networks but also provide hierarchical multi-interface

architecture. Transmission power control and routing path selections are critical issues in the past researches of multihop networks. Variable transmission power levels lead to different network connectivity and interference. Further, routing path selections among different radio interfaces will also produce different intra/inter-flow interference. These features tightly affect the network performance. Most of the related works on the routing protocol design do not consider transmission power control and multi-interface environment simultaneously. In this paper, we proposed a cross-layer routing protocol called M^2iRi^2 which coordinates transmission power control and intra/inter-flow interference considerations as routing metrics. Each radio interface calculates the potential tolerable added transmission interference in the physical layer. When the route discovery starts, the M^2iRi^2 will adopt the appropriate power level to evaluate each interface quality along paths. The simulation results demonstrate that our design can enhance both network throughput and end-to-end delay.

1.2 Main Results

If we only consider "intra-flow" (means the same flow, but between different hops) interference, the routing metric WCETT can be as follows:

$$WCETT = (1-\beta) * \sum_{i=1}^{n} ETT_i + \beta * \max_{1 \le j \le k} X_j$$

However, the "inter-flow" interference should be also taken into account. We proposed the metric called Activity Time (AT) to represent the inter-flow interference which can be calculated by the following equation:

$$AT_K = \frac{N_K + \sum_{nb=1}^{m} N_{nb}^{K}}{\lambda_K + \sum_{nb=1}^{m} \lambda_{nb}^{K}}$$

Therefore, by combining both intra-flow and inter-flow interferences, the MiRii routing cost is defined as follows.

$$MiRii = \alpha \sum_{i=1}^{n} ETT_i + \beta \max_{1 \le j \le k} chanETT_j + \gamma \sum_{\substack{K \in path \\ K \ne src,dst}} AT_K$$

In the WMNs, the traffic loading changes dynamically due to leaving or entering the network of traffic flows. From the above observation, when the traffic loading is low, the traffic flows should select the higher transmission power to enhance the throughput and reduce delay. As the traffic loading is increased, the high transmission power imposes more interference that may disturb the ongoing transmission. The new traffic flow needs to choose the lower power level to transmit the data to alleviate interference. Further, the packet transmission at each hop on the routing path suffers propagation, handling, and queuing delays. When the traffic loading is low, the queuing day may be insignificant. It is better to use high transmission power to reduce hop count and also reduce the handling delay. However, under high traffic loading, the low transmission power reduces the queuing delay because the queue length will grow due to more neighbors' interference or collisions. Therefore, it is a good policy that we should adapt the appropriate transmission power level according to the surrounding interference constraints. This is one of the basic motivations of our work.

We first look at a simple topology (see Figure 1) which clearly demonstrates the benefits of using the appropriate transmission power level at different interference environments. The flow-based MiRii routing protocol is introduced to evaluate these two cases of power levels. The dash line in Figure 1 means the connectivity using 30mW power, while the communication range is double farther if using 100mW power. Table I shows the throughput and end-to-end delay with different traffic flow numbers. Each traffic flow transmits with data rate 512KBits/sec. "MiRii-30mW" indicates that we fix transmission power at 30mW in the entire network. The average end-to-end delay is defined as the time of packet from leaving the source to successful receiving at the destination. It includes the buffering time before the routing path discovery, the queuing time, the delay of retransmission at MAC layer, and propagation delay. When the number of traffic flow is one, the traffic loading is low and interference is slight. We can utilize high transmission power level (100mW) to reduce end-to-end delay since it can travel through small hop counts. When the numbers of flows are increased, the interference among radio interfaces is increased. MiRii-30mW can perform well since radio interfaces with lower transmission power level reduce the interference generating to its neighbors. The MiRii-30mW has lower end-to-end delay and higher throughput than MiRii-100mW.

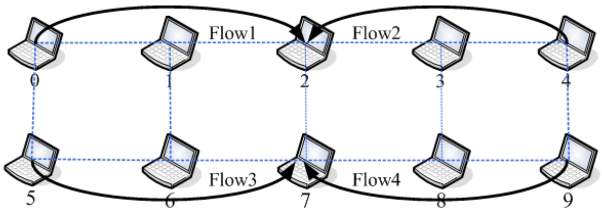

Fig. 1. A simple network topology

TABLE I: DELAY-THROUGHPUT VALUES WITH DIFFERENT POWER LEVELS

Number of flows		1	2	3	4
MiRii	Delay(msec)	14.0	37.9	102.3	157.7
30mW	Throughput(Kbps)	511.1	884.7	1119	1294
MiRii	Delay(msec)	11.8	16.8	141.5	210.6
100mW	Throughput(Kbps)	510.2	1004	1057	931

We consider a 4×4 uniform topology which is placed in a 500m×500m region. Each node locates 80 meters apart. The light color (red) bars represent the high traffic loading with data rate 1Mbps and the dark color (blue) bars represent the low traffic loading with data rate 512Kbps. We consider the traffic flow in the WMNs randomly start and termination. The CBR traffic flow is randomly on/off but there are average five flows in the network to keep the traffic stable. The number of traffic flows and traffic pattern are the same in both cases. Fig. 2 shows that all the routing protocols can operate well in the low traffic loading. It is because the traffic flows are randomly on/off and choose the source-destination pairs randomly. The destination-based routing protocol also increases RREQ broadcast times and increases the packets waiting in the buffer before the routing path establishment. The flow-based routing protocol has the delay better than destination–based routing protocol. Even the flow-based routing protocol needs to broadcast RREQ packets for each flow, it can discovery better routing paths than destination-based routing protocol. When the data rate increases to 1Mbps, the transmission power fixed at 30mW has throughput better than 100mW and same with the end-to-end delay. In this case, M^2iRi^2 have the throughput similar to MiRii-30mW and improve the throughput 13% contrasting with MiRii-100mW. In Fig. 3, the results of average end-to-end delay of M^2iRi^2 are decreased 30% and 48% contrasting with MiRii-30mW and MiRii-100mW respectively.

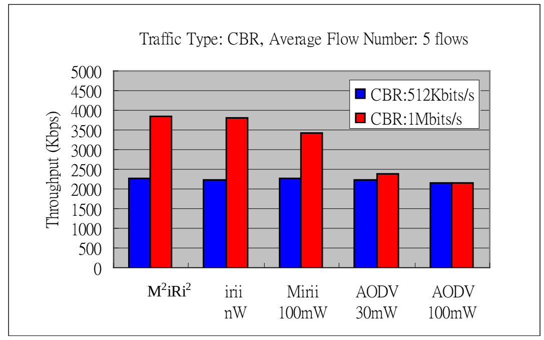

Fig. 2. Throughput of different traffic load in a uniform network topology

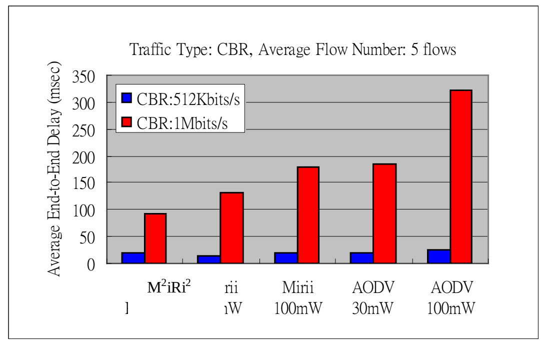

Fig. 3. Average end-to-end delay of different traffic load in a uniform network topology

We next simulate a topology that nodes are randomly placed in a 500m×500m area (Fig. 4). The simulation parameters are the same as those for the uniform topology. The throughputs are almost the same in these routing protocols at low traffic loading as we observe in the uniform topology. In Fig. 5, the throughput of M^2iRi^2 is better then MiRii-30mW and MiRii-100mW about 7% and 14% at the high data rate case. Fig. 6 shows the average end-to-end delay in the high and low data rate cases. The delay of M^2iRi^2 is further lower than that in MiRii-100mW and is better than in MiRii-30mW about 28% at the high traffic data rate case. The simulations results indicate that our proposed cross-layer routing protocol utilized the advantages of different power levels in different network environments and performed well by controlling the transmission power of per-flow traffic.

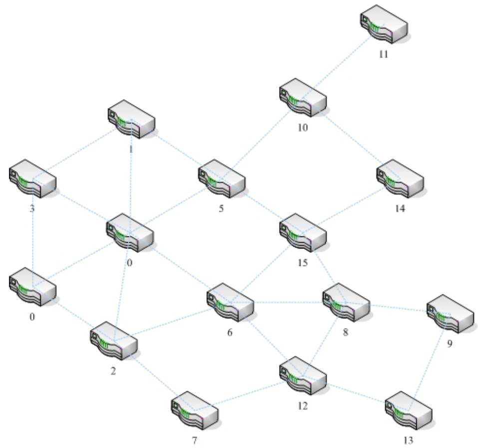

Fig. 4. A random network topology

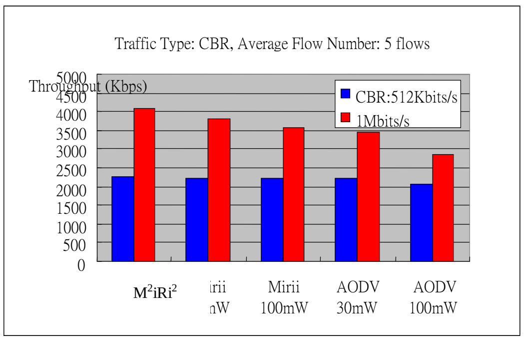

Fig. 5. Throughput of different traffic load in a random network topology

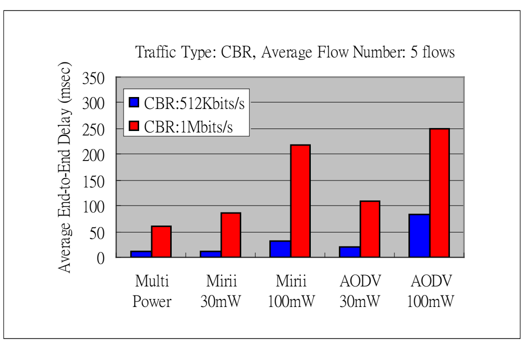

Fig. 6. Average end-to-end delay of different traffic load in a random network topology

Finally, we simulate a WMN with gateways, we choose two nodes in Fig. 4 to play the roles of mesh gateways. The transmissions send the data packets to mesh gateways instead of random Source-Destination pairs. The traffic patterns tightly affect the performance of the routing protocol. Figure 7 and Figure 8 show the simulation results in this case. We observe that M^2iRi^2 still has better throughput and end-to-end delay than MiRii-30mW and MiRii-100mW when the traffic data rate is 1Mbits/s. All the routing protocols also operate well when the flow data rate is 512Kbits/s. The destination-based AODV routing protocol might have the lower end-to-end delay depending on whether the traffic flows have the same destination (gateway) or not, which will reduce the route discovery time. The results also indicate that our M^2iRi^2 routing protocol operates well when the traffic are all going towards gateways in the WMN.

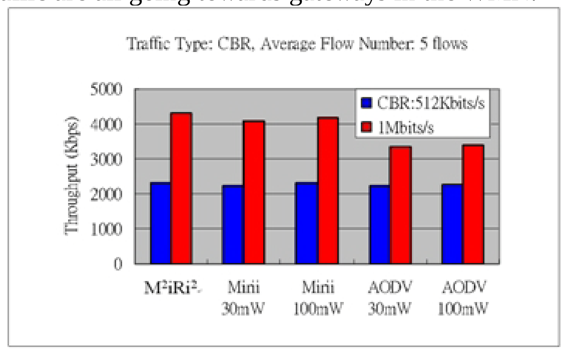

Fig. 7. Throughput of different traffic load in a random network topology with gateway

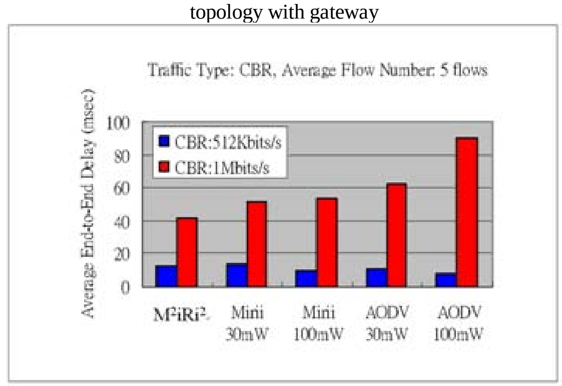

Fig. 8. Average end-to-end delay of different traffic load in a random network topology with gateway

2. "Quality-Aware Multiple Backbone Construction on Multi-interface Wireless Mesh Networks for P2P Streaming"

2.1 Abstract

In Wireless Mesh Networks(WMNs), users can enjoy the real-time video streaming service anytime and anywhere through the service. Compared to the client/server model, the P2P(Peer-to-peer) approach is more suitable for video streaming applications because of its efficient usage of network resources. However, the multimedia applications are very sensitive to delay time and the performance of packets transmission which is significantly influenced by the co-channel interference. In our approach, we choose the better quality links for routing instead of the minimum hop-count path in MAODV(Multicast Ad hoc On-demand Distance Vector). Then we distribute the video streaming to receivers by using multicasting in multi-channel WMNs, and modify the MAODV routing

protocol to construct two disjoint multicast trees as the backbone for the P2P structure. Therefore, we can adopt the MDC(Multiple Description Coding) scheme to encode the video into two independent sub-streams and transmit separately along these trees. Experiment results show that in higher traffic load environment, our scheme is more effective to reduce the latency and improve overall system performance.

2.2 Main Results

We use the concept of the Steiner tree to modify MAODV routing protocol, and propose a new multi-channel multicast tree algorithm called ST-MAODV. In order to efficiently use channel bandwidth, we use ETTs as link metrics in stead of hop counts to enhance the overall system throughput. And we also adopt the concept of the MDC video application. Without loss of generality, we assume that each MAPs in the WMN are equipped two wireless interface cards, and each card is using the predefined channel with total of two channels for all MAPs.

We find out two disjoint Steiner trees with minimum cost as two multicast trees. For each node joining the multicast group, we will first take into account all the costs to find the minimum cost path to construct the first Steiner tree. And then from the remaining unused links to find out the other minimum cost path for the second Steiner tree. If the remaining links are insufficient to construct the second tree, we can use the portion of used links of the first tree to construct.

ETT of each interface card is estimated by probing on that channel used for it. ETT can be interpreted as the loading or inverse of link quality associated with the link. Intuitively, when constructing the tree by adding links one by one, the total cost of the tree is the sum of ETTs with all links on the tree. However, due to broadcast characteristic of wireless channels, using the same channel for multicast, one transmission is enough for all the down-stream nodes. For example, as shown in Figure 9, the number indicated on the link means ETT estimated by using the associated channel/interface. If node A uses the same channel 0 to multicast to nodes B and C (Figure 9(a)), node A transmits only once, as result of total cost of maximum of 5 and 3, which is 5, not sum of 5 and 3, which is 8. If node A uses different channels to multicast, say using channel 0 to node B, and channel 1 to node C, the total cost will be the sum of the two costs which is 8 (Figure 9(b)). Therefore, if the node A and B are already in the multicast group using the channel 1 as the connection, and sometime later node C wants to join the tree. It will cause less additional cost (which is 2) if using the channel 1 connection to establish the link from node A to C.

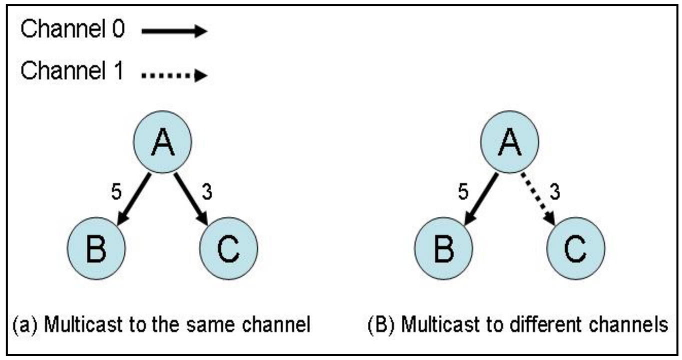

Fig. 9. Multicast uses the same or different channels.

The following is the procedure for our ST-MAODV protocol:

- Nodes send probing messages once in a while for each channel to calculate the value of ETT for each link to the adjacent nodes.
- When a node wants to join the multicast group, broadcast RREQ packets to adjacent nodes.
- When a node receives the RREQ, check whether it belongs to the group member. If yes, reply RREP via the reserve path to the requesting node. If not, keep broadcasting RREQ packets to other nodes until the group member has received.
- When the requesting node receives RREPs, decide a path with minimum path ETT to construct the first multicast tree.
- Then keep finding out the next minimum path ETT to construct the second multicast tree from the remaining unused links.

When propagating RREQ, the cost of the associated path is incremented with the rule presented in Figure 9. Because the cost of multicast tree depends on the use of the same or different channels, the incremental cost of unused links should be subtracted by the cost of the used links' maximum cost using the same channel. So we update the unused links' cost of the nodes in the first multicast tree, and then find out the second one using the updated additional cost.

For nodes in accordance with the order to join the group, repeat steps 2 to 5 until all the nodes have joined the two multicast trees.

We perform the simulation using NS-2 and compare the following four cases: (C1) Video multicast with MDC and MAODV, (C2) Video multicast with MDC and two-channel MT-MAODV [6], (C3) Video multicast with MDC and ST-MAODV for one tree, and (C4) Video multicast with MDC and ST-MAODV for two disjoint trees. The NS-2 is modified to support MAODV routing protocol and multi-interface operation with multi-channels on each wireless node. Three scenarios for different flow settings are evaluated.

Scenario 1

In the first scenario, all receivers join the multicast group per 5 seconds. Figure 10 shows the average delay time with different number of receivers. The average delay time is for data transfer from a sender to a receiver. We can see that our ST-MAODV protocol is better than others, because the link with less ETT means that it may need less time to transfer packets successfully.

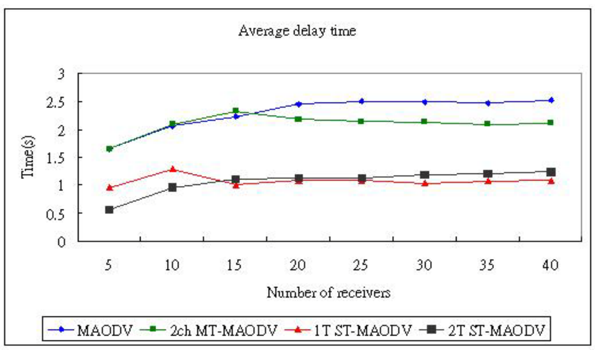

Fig. 10. Average delay time.

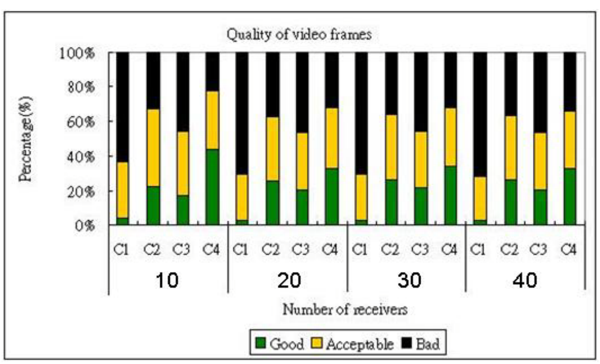

Fig. 11. Quality of video frames.

Figure 11 gives the distribution of video frames according to their quality. With the MDC scheme, using multiple disjoint trees can significantly reduce the number of 'bad' frames (both descriptions of a particular frame are lost), as shown in case C2 and C4, because the probability of losing both video descriptions together is smaller. Different from the minimum hop-count path of MT-MAODV, our approach selects paths with higher link quality, and thus avoids local congestion so that the quantity of good frames (both descriptions are received) and acceptable frames (one description is received, and one is lost) of C3 are better than C1.

Scenario 2

In scenario 1, there is just one video traffic flow in the simulation environment. Here we add one FTP flow to be the background traffic to make some interference. The FTP flow is between two nodes which were selected randomly, and the data rate is 500 kbps. With some background traffic, there might be more contention and traffic congestion. We can see from Figures 12 & 13 that both C3 and C4 perform better than C1 and C2, because with some interferences, our ST-MAODV can still build trees from those better quality links, and with two disjoint trees, the quality of C4 is superior to C3.

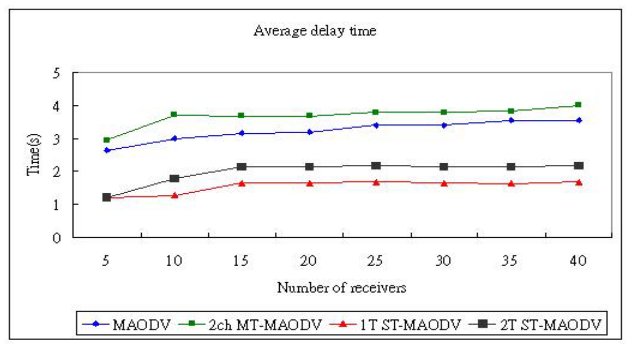

Fig. 12. Average delay time.

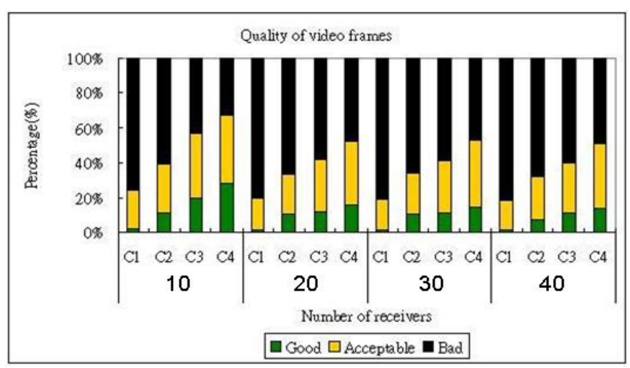

Fig. 13. Quality of video frames.

Scenario 3

Now we compare the two-channel MT-MAODV and ST-MAODV with different data rate. As shown as Figure 11 to Figure 14, only ten receivers join the multicast group at the same time. We compare the packet deliver ratio and average delay time with different data rate from 10 kbps to 11 Mbps. In Figures 14 and 15, the two-channel MT-MAODV is better than our ST-MAODV when the data rate is less than 100 kbps. This means that when lower network traffic load, the performance of two-channel MT-MAODV is better. However, with the increasing of traffic loading, our approach is more suitable for data transmission.

Figures 16 & 17 show the average delay time and the latency ratio between C2 and C4, respectively. When data rate increases, delay time also increases significantly. However, ST-MAODV still has lower delay time. This shows that our approach is more suitable in the environment with higher network traffic load.

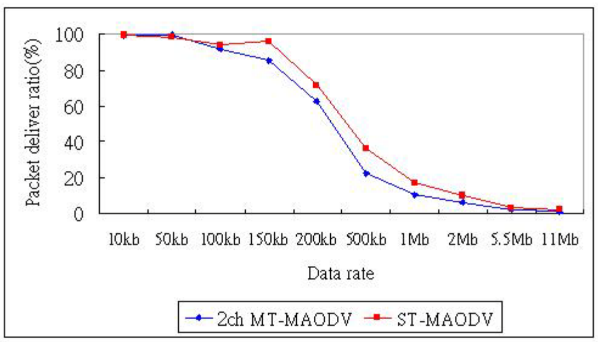

Fig. 14. Compare PDR with different data rate.

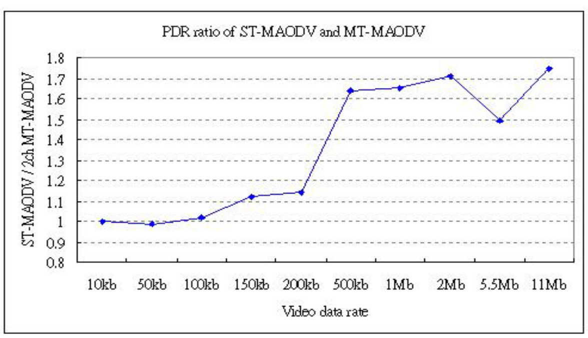

Fig. 15. PDR ratio of C2 and C4.

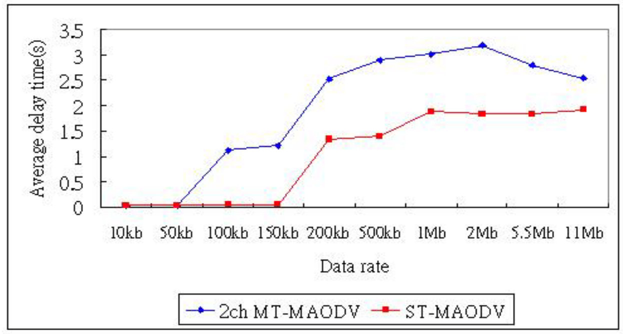

Fig. 16. Compare average delay time with different data rate.

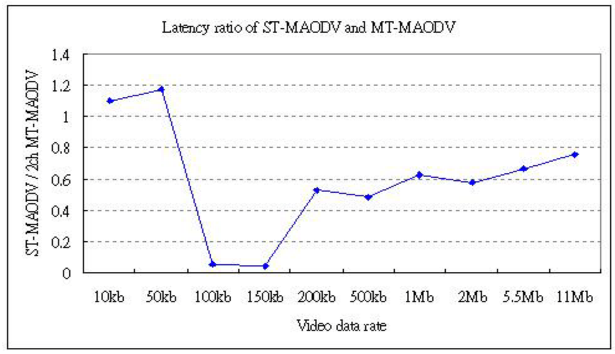

Fig. 17. Latency ratio of C2 and C4.

三、計畫成果自評

本計畫的主要的貢獻在研究如何透過跨層網路協定，去設計一個有效率且具一定 QoS 之繞路法則。

在多傳送功率與鏈結傳輸品質的跨層繞路演算法設計方面，乃修正之前相關研究修改並加以整合而成，使得更適用在多網卡之無線網狀網路上，未來如果相關產業或網路服務提供業者，將可依據本研究成果加以應用，則可以得到網路最大的使用效率，不只服務品質提昇，相對的也提高了整體網路的吞吐量，因此讓相關業者提供了一個非常好的管理平台作參考。

在 P2P Streaming 應用的服務上，提供了一個建構多重傳輸數的建置方式，結合串流應用的 MDC 編碼機制，如此使得跨應用層的網路繞路演算法可以有更佳的影音服務品質。

綜合以上兩部份，成就了跨應用層和實體層的網路繞路協定，使得相關 WMN 的網路服務提供業者，在建置與管理網路時可以有好的依循與參考。

附件二

可供推廣之研發成果資料表

■ 可申請專利　■ 可技術移轉　　　日期：98 年 5 月 27 日

國科會補助計畫	計畫名稱：無線網狀網路下考慮多功率與P2P應用之跨層繞路設計 計畫主持人：　蔡子傑 計畫編號：　NSC 97-2221-E-004-004-MY2　　學門領域：電信(網路)
技術/創作名稱	**A Cross-Layer Routing Design for Multi-Interface Wireless Mesh Networks**
發明人/創作人	蔡子傑，蔡松達
技術說明	中文：近年來無線網狀網路(Wireless Mesh Networks)備受矚目，無線網狀網路繼承原有的 ad hoc networks 的特性並提供階層式及多網卡的網路存取架構。在 multi-hop networks 下，傳輸功率的控制和網路路由的選擇是重要的議題，因為不同的傳輸功率產生不同的網路拓墣連結性和干擾。此外，在不同網路卡間的路由選擇也會產生不同程度的 intra/inter-flow 干擾。這些特性對網路效能有密切的影響，過去相關的路由協定設計也大多未同時考量傳輸功率控制與多網路卡的特性。 　我們提出了跨網路協定層的路由協定，稱作 M^2iRi^2，同時考量傳輸功率的控制並將 Intra/Inter-flow 的干擾導入到路由路徑的選擇。節點上的網路卡在物理層(Physical layer) 計算目前對潛在可容忍的新增干擾，並將此訊息送到網路層(Network layer)和鄰居節點作交換。透過此資訊的交換，在路由發現時控制路由請求封包的傳輸功率，當路由建立後，封包根據路由表的記載，選擇所對應的路由路徑和傳輸功率。經由 NS-2 模擬結果顯示，我們所提出的跨網路協定層路由協定可同時兼顧網路的吞吐量和平均點對點的延遲。

	英文： In recent years, WMNs (Wireless Mesh Networks) technologies have received significant attentions. WMNs not only accede to the advantages of ad hoc networks but also provide hierarchical multi-interface architecture. Transmission power control and routing path selections are critical issues in the past researches of multi-hop networks. Variable transmission power levels lead to different network connectivity and interference. Further, routing path selections among different radio interfaces will also produce different intra/inter-flow interference. These features tightly affect the network performance. Most of the related works on routing protocol design do not consider transmission power control and multi-interface environment simultaneously. We proposed a cross-layer routing protocol called M^2iRi^2 which coordinates transmission power control and intra/inter-flow interference considerations as routing metrics. Each radio interface calculates the potential tolerable added transmission interference in the physical layer. When the route discovery starts, the M^2iRi^2 will adopt the appropriate power level to evaluate each interface quality along paths. The simulation results demonstrate that our protocol can enhance both network throughput and end-to-end delay.
可利用之產業 及 可開發之產品	相關 802.11s or Wireless ISP 的產業
技術特點	我們採用了 WCETT（Weighted Cumulated Expected Transmission Time）metric ，來考量 intra-flow 干擾，至於 inter-flow 干擾，則修改 LBAR（Load-Balanced Ad hoc Routing）的作法，改以計算節點之活躍值（nodal activity）與訊務流量的干擾來選擇路徑。因此，我們整合上述修正過的方法，提出一個 WMNs 上考量到 Intra/Inter-flow 干擾之多網卡路由協定，稱為 MiRii。 其次，再考量到傳送功率的跨層繞路協定。調整不同的傳送功率會影響繞路的決定，也影響到 intra-flow/inter-flow 干擾的程度，當然也決定 throughput 等網路系統的 QoS。我們修正了 MiRii，同時考量傳輸功率的控制，並將 Intra/Inter-flow 的干擾導入到路由路徑的選擇，提出了跨網路協定層的路由協定，稱作 M^2iRi^2。節點上的網路卡在物理層(Physical layer)計算目前對潛在可容忍的新增干擾，並將此訊息送到網路層(Network layer)和鄰居節點作交換。透過此資訊的交換，在路由發現時控制路由請求封包的傳輸功率，當路由建立後，封包根據路由表的記載，選擇所對應的路由路徑和傳輸功率。

推廣及運用的價值	在技術的不斷提昇下，使得建置隨時隨地能無線上網的城市成為可能。而 802.11s Wireless Mesh Network 就是可能的技術之一。然能有效降低營運成本與提昇服務品質，有效的網路資源管理是相當重要的課題。本研究成果可供相關業者一個很重要的參考依據。

國科會補助計畫	計畫名稱：無線網狀網路下考慮多功率與 P2P 應用之跨層繞路設計 計畫主持人：　蔡子傑 計畫編號：　NSC 97-2221-E-004-004-MY2　　　學門領域：電信(網路)
技術/創作名稱	**Quality-Aware Multiple Backbone Construction on Multi-interface Wireless Mesh Networks for P2P Streaming**
發明人/創作人	蔡子傑， 陳維鴻
技術說明	中文：無線網狀網路(WMNs)為目前熱門的廣域無線網路接取技術。使用者可以透過 WMNs 隨時在各處使用即時影音播放的服務。相較於傳統的主從式架構，低成本且容易建置的點對點架構更適用於影音串流的應用；在進行即時影音播放的時候，影音播放的品質便為相當重要的目標。因為多媒體應用服務對於延遲及網路傳輸效能相當敏感，且 WMNs 的傳輸過程中常會面臨同頻道干擾的問題而使得傳輸的效能銳減，當每個網路節點都具有多張無線網路卡時，如何善用 WMNs 多頻道傳輸的特性提升效能更是顯得特別重要。 　我們利用 WMNs 多頻道傳輸的特性進行多媒體群播傳輸，參考史坦納樹的概念來改善現有的 MAODV 路由演算法，以傳輸品質較佳的鏈結改良原本尋找最小跳躍數路徑的方式，建立兩棵完全互斥的群播樹作為點對點傳輸的骨幹網路，並以 MDC 的概念將影像串流編碼成兩份獨立的子串流分別經由不同的群播樹傳輸。經實驗評估，我們的方法在網路負載較高的環境下能有效的降低延遲並提高整體系統的效能。

	英文：In WMNs, users can enjoy the real-time video streaming service anytime and anywhere through the services. Compared to the client/server model, P2P approaches is more suitable for video streaming applications because of its low cost and easy deployment. But when using the real-time multimedia service in WMNs, the multimedia applications are very sensitive to delay time and the performance of packets transmission. And the performance is significantly influenced by the co-channel interference, so that it is important to know how to transmit by multi-channel to enhance the performance. In our approach, we choose the better quality links for routing instead of the minimum hop-count path in MAODV. Then we distribute the video streaming to receivers by multicast in multi-channel WMNs, and refer to the Steiner tree concept to modify the MAODV routing protocol to construct two disjoint multicast trees as the backbone for the P2P structure. Therefore, we can adopt the MDC scheme to encode the video into two independent sub-streams and transmit separately along these trees. Experiment results show that in higher network traffic load environment, our scheme is more effective to reduce the latency and improve overall system performance.
可利用之產業 及 可開發之產品	相關 802.11s or Wireless ISP 的產業
技術特點	我們採用了 ETT（Expected Transmission Time）metric ，來考量 x 鏈結的品質，以此作為繞路計算的基本。並在建置 multicast tree 時同時併入不同頻道的不同計算方式，此方式是無線多網卡網路上才特有的特性。如此才可更真實的選擇到較少的繞路成本的多重傳輸的 P2P 樹，達到較佳的效能與延遲。 其次，再利用到串流影音的 MDC(Multiple Description Coding)編碼特性，建置兩個 multicast 骨幹，彼此間幾近互斥，因此可以更充份享受到 MDC 編碼的好處，同時加上第一部份的成本考量，在雙重的受益下，整體系統的傳輸效能達到更大的改善。
推廣及運用的價值	在技術的不斷提昇下，使得建置隨時隨地能無線上網的城市成為可能。而 802.11s Wireless Mesh Network 就是可能的技術之一。而 WMN 的重要應用之一，就是提供大眾媒體如影音串流服務，如果能建置有效的管理依循，將可使提供此服務更能經濟有效，進而降低營運成本與提昇服務品質。本研究成果可供相關業者一個很重要的參考依據。

※　1.每項研發成果請填寫一式二份，一份隨成果報告送繳本會，一份送　貴單位研發成果推廣單位（如技術移轉中心）。

※　**2.本項研發成果若尚未申請專利，請勿揭露可申請專利之主要內容。**

※　3.本表若不敷使用，請自行影印使用。

附錄

已發表之論文全文

[4] Tzu-Chieh Tsai, Sung-Ta Tsai, "A Cross-Layer Routing Design for Multi-Interface Wireless Mesh Networks", in EURASIP Journal on Wireless Communications and Networking (EURASIP WCN)(SCI_E, EI), Vol. 2009, Article ID 208524, doi:10.1155/2009/208524, 2009.

[5] Tzu-Chieh Tsai, Wei-Hung Chen, "Quality-Aware Multiple Backbone Construction on Multi-interface Wireless Mesh Networks for P2P Streaming", in Third IEEE International Workshop on Enabling Technologies and Standards for Wireless Mesh Networking, (MeshTech 2009), Oct 12, 2009, Macau SAR, China.

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Research Article

A Cross-Layer Routing Design for Multi-Interface Wireless Mesh Networks

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Recommended by Naveen Chilamkurti

In recent years, Wireless Mesh Networks (WMNs) technologies have received significant attentions. WMNs not only accede to the advantages of ad hoc networks but also provide hierarchical multi-interface architecture. Transmission power control and routing path selections are critical issues in the past researches of multihop networks. Variable transmission power levels lead to different network connectivity and interference. Further, routing path selections among different radio interfaces will also produce different intra-/interflow interference. These features tightly affect the network performance. Most of the related works on the routing protocol design do not consider transmission power control and multi-interface environment simultaneously. In this paper, we proposed a cross-layer routing protocol called M^2iRi^2 which coordinates transmission power control and intra-/interflow interference considerations as routing metrics. Each radio interface calculates the potential tolerable-added transmission interference in the physical layer. When the route discovery starts, the M^2iRi^2 will adopt the appropriate power level to evaluate each interface quality along paths. The simulation results demonstrate that our design can enhance both network throughput and end-to-end delay.

1. Introduction

Wireless Mesh Networks (WMNs) have the characterisitcs of low deployment cost, easy maintenance, and reliable service coverage technologies to form robustness networks. The task group "s" (TGs) of IEEE 802.11 develops a flexible and extensible standard for wireless mesh networks based on the original IEEE 802.11. However, IEEE 802.11 TGs adopts two main proposals—SEE-Mesh (Intel) and Wi-Mesh (Nortel) intending to specify a framework for WLAN Mesh networking [1]. In WMNs, nodes are comprised of mesh routers and mesh clients [2]. Mesh routers form a wireless backbone of WMNs, which provide multi-hop connectivities between mesh clients and mesh gateways that have wired connectivity with Internet (Figure 1).

WMNs are dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves and compatible with conventional Wi-Fi clients. Multi-interface WMNs provide multiple radio interfaces of a node that can improve the throughput capacity [3]. This feature enables nodes to transmit and receive simultaneously, hence nodes can use nonoverlapping channels to transmit and receive at the same time via different interfaces. WMNs technologies accede to the advantages of ad hoc networks. Traditional ad hoc network routing protocols may not be suitalbe for WMNs since they do not fully consider the features of WMNs such as multi-interface. In IEEE 802.11s, it presents the prototype of default path selection protocol-HWMP (Hybrid Wireless Mesh Protocol) and routing metric-airtime cost. The implementation details can be based on user demands. Several routing protocol designs for WMNs [4, 5] focus on single layer of network protocol stacks and do not consider coordinating with different protocol layers. Specifically, in the physical layer, the transmission power level decides the signal strength and determines the neighbor nodes which can hear the packet. This thus affects the network layer to select the forwarding nodes at the route discovery. The transmission power also causes the interference that affect the link quality among nodes. The appropriate transmission power level selection can improve network performance [6–8]. Traditional transmission power control problems in wireless ad hoc networks mainly focus on reducing energy consumption. Some researches address power selection problems but still use minimum hop-count as the routing metric. Power control indeed impacts multiple network protocol layers. Transmission power control tightly affects network performance [9]. The theoretical studies [10] have demonstrated that transmission power control can improve wireless network capacity. The result in [11] presents that the need to design future protocols is based on variable-range power control, not on common-range transmission power control. The higher transmission power increases network connectivity and gives lower end-to-end delay in the low traffic load with slight interference. However, the higher transmission power will create high interference when concurrent transmissions in the vicinity are increased. This will decrease the spatial reusability. In this high loading case, using lower transmission power will result in lower interference, and thus increase the throughput. The motivation of our cross-layer routing protocol development is inspired from the above features we observed.

We previously proposed the MiRii (Multi-Interface Routing with Intra/Inter-flow Interference) [5] routing protocol that measures intra-/interflow interference and applies to routing path selection in the network layer. The multi-interface feature is utilized by considering the channel diversity of the routing path. By contrast with AODV [12], ETX [13], and WCETT [4] (will be introduced later in Section 2.2), the simulation results demonstrate that our MiRii routing protocol can improve packet delivery ratio and decrease end-to-end delay. To further improve the performance, the routing protocol has to work together with the physical layer. In this paper, we propose our cross-layer routing protocol, namely, M^2iRi^2 (Multi-power, Multi-interface Routing with Intra/Inter-flow Interference), that incorporates MiRii routing protocol with perflow transmission power control. M^2iRi^2 routing protocol jointly coordinates the transmission power at each traffic flow and route selection among multi-interface nodes. The protocol interplays between the network and the physical layers. It aims to select appropriate transmission power to reduce the noise interference more efficiently when the traffic loading in the network is increased.

The rest of the paper is organized as follows. Section 2 reviews the past work related to link quality routing, load-balancing routing, and the transmission power control on the physical layer. Section 3 describes our cross-layer routing protocol in detail. Section 4 presents the simulation result and analysis. Finally, Section 5 concludes the paper with a summary and proposes the future work.

2. Related Work

We first introduce some related work to our cross-layer routing protocol M^2iRi^2, namely the transmission power control and routing metrics in WMNs, including our previous MiRii routing protocol.

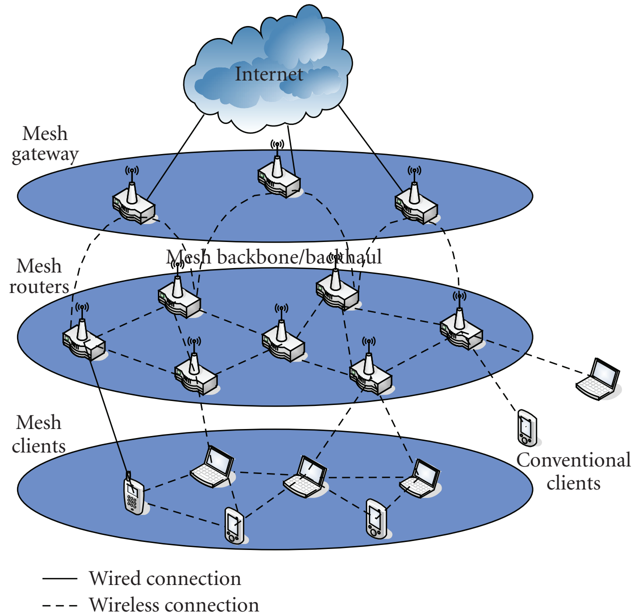

Figure 1: Wireless Mesh Networks.

2.1. Transmission Power Control. Previous transmission power control schemes for ad hoc networks have focused on throughput improvement or power consumption. We do not consider the power consumption in our work becasue WMN backbone does not have power consumption issues. In [10], the author shows that reducing the transmission power can increase the carrying capacity of the network. The work in [11] concludes that variable-range transmission power can improve the overall network performance. Some researches address the power-controlled problem on the network layer [6, 7]. The COMPOW protocol [6] relies on the DSDV routing protocol to discover the smallest common power level at which the entire network is still connected. However, it suffers when some nodes can only use high power to be connected. In [7], the proposed CLUSTERPOW protocol performs the routing protocol several times with different power levels at each run and independently builds a routing table at each power level. A node consults the routing table with the lowest power to forward packets to the next hop. This consumes too much network resource.

Several researches [8, 14, 15] introduce the interference tolerance in their transmission power control architecture. The interference tolerance represents how much interference a node can allow the potential transmission of its neighbors. Nodes transmit the packets with the power level that does not disturb the ongoing receptions of its neighbors. In [8], the authors proposed a power controlled multiple access wireless MAC protocol (PCMA) within the collision avoidance framework. In PCMA, each receiver sends busy tone pulses to announce its interference tolerance. If the trasmitter has data to send to the receiver, it will determine its power bound according to the interference tolerance declared by the receiver's busy tone. It then sends Request-Power-To-Send (RPTS) with appropriate power level setting accordingly. The receiver will calculate its tolerable power level and send acceptable-power-to-send (APTS) back to the sender. In other words, the protocol design is based on CSMA/CA and modifies the RTS/CTS to RPTS/APTS (Request-Power-To-Send/Acceptable-Power-To-Send) to support potential interfering transmissions to transmit concurrently rather than to silence it. However, PCMA uses the additional separate control channel to send the busy tone pulses. PCDC (Power Controlled Dual Channel) [14] also uses dual channels for data and control packets. A single channel solution for transmission power control (POWMAC) is used in [15]. In POWMAC, the interference tolerance is inserted into the CTS packet and an additional control packet DTS (Decide-To-Send) is used by transmitter to confirm the transmission. Furthermore, the DTS is utilized to inform the neighbors of transmitter about the power level that the transmitter will use for its data transmission. The neighbors of the transmitter can determine whether or not they can receive the data packets form other nodes simultaneously through DTS.

From the comparisons of [8, 14, 15], we finally adopt the interference tolerance concept to be integrated into our cross-layer routing protocol design. We will facilitate concurrent interference-tolerable transmissions in the same vicinity of the receiver to enhance the WMN backbone capacity. Furthermore, we piggyback the interference tolerance information in probe packets which are integrated in the network layer routing protocol. It is not using a separate control channel to alert the neighboring nodes.

2.2. Routing Metrics in WMNs. Most of the routing protocols use "hop count" as the routing metric. The minimum hop-count routing is not suitable for wireless networks because of dynamic wireless link quality characteristics. The work in [4, 13] proposes new routing metrics considering the link quality dynamics. MiRii proposed in [5] further considers the intra-/interflow interferences in multi-interface routing path selections.

The work in [13] proposed the concept of the expected transmission count (ETX) as the routing metric. ETX is calculated by measuring the delivery ratios for probe packets in bidirectional transmissions of each link. It predicts the number of data transmissions required to send a packet and get a successful acknowledgment. Therefore, the ETX accounts for interference among the successive links of a path. Although ETX does well in single-radio wireless ad hoc network, it does not perform well in multiradio and multichannel wireless mesh networks. Reference [4] presents a new routing metric for multiradio, multihop wireless mesh networks, called WCETT (Weighted Cumulative Expected Transmission Time). WCETT assigns weights to individual links based on the Expected Transmission Time (ETT) of a packet over the link. As a result, the WCETT of a route with n hops can be the sum of the ETTs of all hops along the path. Further, WCETT assumes that the network has a total of k channels in an n-hop path. However, X_j is the sum of transmission time of hops that uses channel j along the path. The total path throughput will be dominated by the bottleneck channel, which has the highest X_j. WCETT takes both link quality (ETT) and channel diversity (X_j) into considerations. Thus, WCETT combines these two features by taking their weighted average as follows:

$$\mathrm{WCETT} = (1-\beta) * \sum_{i=1}^{n} \mathrm{ETT}_i + \beta * \max_{1 \le j \le k} X_j. \quad (1)$$

In fact, the WCETT metric takes "intraflow" (means the same flow, but between different hops) interference into consideration, but does not capture "interflow" (means between different neighboring flows) interference. In our previous work [5], we propose a new routing metric, MiRii, that considers both intraflow and interflow interference in the multi-interface WMNs. In order to capture the interflow interference, we calculate the nodal activity and intertraffic flow interference. We introduce Little's Result into the routing metric design that makes the interflow interference unit cost compatible with WCETT. To this end, we assume node k and node k's neighboring nodes as a closed system and the Activity Time (AT) of node k is shown in (2). Also, N_k and λ_k are the average queue length and average packet receiving rate of node k, respectively. The sum of average queue length of k's neighboring nodes is the second parameter of numerator, and the sum of average packet receiving rate of k's neighboring nodes is the second parameter of denominator in (2). The Activity Time (AT_k) regarding to k is the total average queue length divided by total average packet receiving rate of the system:

$$\mathrm{AT}_k = \frac{N_k + \sum_{nb=1}^{m} N_{nb}^{k}}{\lambda_k + \sum_{nb=1}^{m} \lambda_{nb}^{k}}. \quad (2)$$

Therefore, by combining both intraflow and interflow interferences, the MiRii routing cost is defined as (3)

$$\mathrm{MiRii} = \alpha \sum_{i=1}^{n} \mathrm{ETT}_i + \beta * \max_{1 \le j \le k} \mathrm{chanETT}_j + \gamma \sum_{k \in \mathrm{path}\,\&\, k \neq \mathrm{src,dst}} \mathrm{AT}_k, \quad (3)$$

where α, β, and γ are the constant weights subject to $\alpha + \beta + \gamma = 1$. Also, $\sum \mathrm{ETT}_i$ means the total link quality considerations and end-to-end delay over an n-hops path. The $\sum \mathrm{chanETT}_i$ is the sum of transmission times of hops using channel j, and represents the channel-diversity in multiradio WMNs. Finally, $\sum \mathrm{AT}_k$ is the interflow interference, and represents the load-balanced routing cost.

3. Cross-Layer Routing Protocol Design

In the WMNs, the traffic loading changes dynamically due to leaving or entering the network of traffic flows. From the above observation, when the traffic loading is low, the traffic flows should select the higher transmission power to enhance the throughput and reduce delay. As the traffic loading is increased, the high transmission power imposes more interference that may disturb the ongoing transmission. The new traffic flow needs to choose the lower power level to transmit the data to alleviate interference. Further, the packet transmission at each hop on the routing path suffers

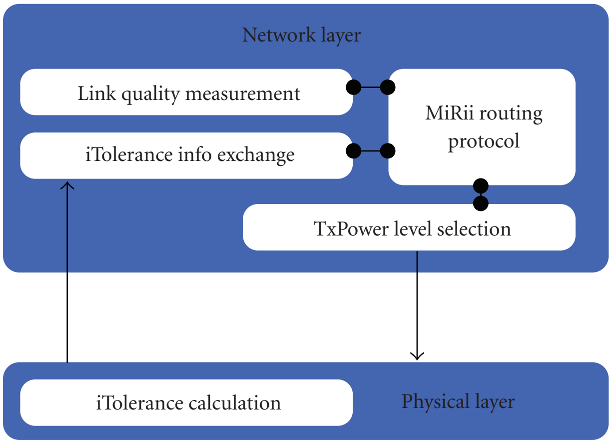

FIGURE 2: The cross-layer routing protocol architecture.

propagation, handling, and queuing delays. When the traffic loading is low, the queuing day may be insignificant. It is better to use high transmission power to reduce hop count and also reduce the handling delay. However, under high traffic loading, the low transmission power reduces the queuing delay because the queue length will grow due to more neighbors' interference or collisions. Therefore, it is a good policy that we should adapt the appropriate transmission power level according to the surrounding interference constraints. This is one of the basic motivations of our work.

3.1. Overview of Protocol. The scheme of the proposed M^2iRi^2 cross-layer routing protocol is shown in Figure 2. The routing protocol is based on AODV [12]. We modify it to support MiRii routing metric and transmission power level selection on a perflow basis. The network layer coordinates with the physical layer to choose the appropriate transmission power level and to find a routing path with better link quality. The proposed M^2iRi^2 routing protocol is operated among mesh routers. The mesh clients can access the network by directly connecting to mesh routers. The protocol does not consider dynamic channel assignment for simplicity at this point. In the physical layer of the model, there are several discrete transmission power levels for each NIC (network interface card). The function of "iTolerance Calculation" calculates the interference tolerance of each ongoing receiving NIC at the node. The "Link Quality Measurement" function measures the ETT and AT that are used in the MiRii routing protocol. All the measurement and information exchanges are through probe packets that are broadcasted proactively by each NIC.

3.2. iTolerance Calculation. Suppose that a packet transmission from node i to node j is a successful reception if the received SINR (Signal-to-Interference Noise Ratio) is above a certain threshold:

$$\mathrm{SINR}_i = \frac{P_i G_{ij}}{\sum_{l \neq i} P_l G_{lj} + N_j} \geq \mathrm{SINR\_Threshold}, \quad (4)$$

P_i means the transmit power for node i and $P_i G_{ij}$ is the received power at node j, where G_{ij} is the propagation gain for the direct transmission from node i to j. Also, N_j is the thermal noise at node j, and $\sum_{l \neq i} P_l G_{lj}$ is the sum of interferences that transmit concurrently with node i.

However, iTolerance is defined as the interference tolerance that a receiver node can tolerate a new joining neighboring interference without destroying its existing ongoing receptions. So, the radio interface at node j, regarding to the flow from node i, can allow its iTolerance as follows:

$$\mathrm{iTolerance}_j = \frac{P_i G_{ij}}{\mathrm{SINR\_Threshold}} - \left(\sum_{l \neq i} P_l G_{lj} + N_j \right). \quad (5)$$

In the protocol design, we measure the actual propagation gain based on the received power of the probe packet at the receiver side. Nodes can locally measure their interference tolerance according to the sum of the strengths of all the interfering signals. Each radio interface on the node will advertise its interference tolerance to its one hop neighbors.

In the network layer, each node updates its neighbors' iTolerance through the probe packet. When the route discovery starts, the node looks up its neighbors' iTolerance and chooses the appropriate TxPower (transmission power) level to send RREQ or forward RREQ messages. From the (6), the routing protocol will select the highest TxPower when the iTolerance constraints can be satisfied:

$$\max\left\{ \mathrm{TxPower\_level} \mid \mathrm{TxPower\_level} \leq \min_{\mathrm{neighbor}\, l} \left\{ \frac{\mathrm{iTolerance}_l}{G_{il}} \right\} \right\}. \quad (6)$$

We also apply for the MiRii routing metric which is referred in (3) in our M^2iRi^2. Hence, each traffic flow select the appropriate transmission power to send its route request messages and use the MiRii routing metric to choose a routing path that has the smallest MiRii cost. In M^2iRi^2, we use the probe packet to measure the link quality and piggyback the iTolerance information with the neighbors.

3.3. Perflow-Based Transmission Power Control and Routing. The original AODV is a destination-based routing protocol, and suffers the route flapping problem. For example, we assume that both flows 1 and 2 route through node A to the same destination node B. Some time later, the route entry of A's routing table to destination B changes for some reason. It will affect both flow 1 and switch their routing paths simultaneously. The destination-based routing protocol cannot balance the traffic loading. In this case, perflow routing will be a good choice to solve the problem. In order to achieve the idea of perflow-based transmission power control and routing, the routing table should keep records for not only the destination (Dst) of the route but also flow id (Fid) of pertraffic flow. Further, the routing table records each traffic flows TxPower level that it uses to reach next hop. Hence, each interface on the node looks up the routing table according to the parameters (Dst, Fid) and

Type	J	R	G	D	U	Reserved	Hop count
RREQ ID							
Destination IP address							
Destination sequence number							
Originator IP address							
Originator sequence number							
$\Sigma\,\mathrm{ETT}_{\mathrm{link}}$							
$\Sigma\,\mathrm{chanETT}_{\mathrm{link}}$							
$\Sigma\,\mathrm{AT}_{\mathrm{node}}$							
Fid							
TxPower							

Figure 3: The format of RREQ packet.

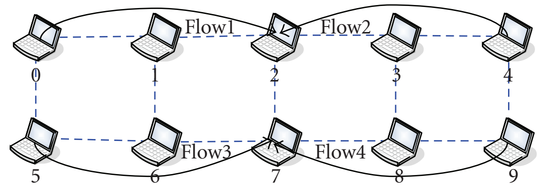

Figure 4: A simple network topology.

Table 1: Delay-Throughput with different power levels.

Number of flows	1	2	3	4
MiRii-30 mW delay (ms)	14.0	37.9	102.3	157.7
MiRii-30 mW throughput (Kbps)	511.1	884.7	1119	1284
MiRii-100 mW delay (ms)	11.8	16.8	141.5	210.6
MiRii-100 mW throughput (Kbps)	510.2	1004	1057	931

adjusts the transmission power level for this traffic flow to forward to the next hop.

The data transmission is based on CSMA/CA and the iTolerance value at the radio interface changes dynamically. So, we still transmit the data packet by using the lowest transmission power level even if there is no power level satisfied the iTolerance constraints. Notice that here, for simplicity and fair performance comparisons later, we do not apply call admission control to reject any new flows. The Route Request (RREQ) packet format is illustrated in Figure 3. The fields of ($\sum \mathrm{ETT}_{\mathrm{link}}, \sum \mathrm{chanETT}_{\mathrm{link}}, \sum \mathrm{AT}_{\mathrm{node}}$) are used to calculate the MiRii value. The fields of (Fid, TxPower) are utilized to achieve the per-flow transmission power control.

In reality, the channel fading and interference change dynamically. It is difficult to calculate exact tolerable power level or link quality. There are some papers [16, 17] that proposed different approaches to deal with these. However, in concern with complexity of the algortihm, we are not dealing with the fading channel problem here. Instead, in our design, we use the "moving average" estimation to find the path in the sense of "statistically approximation". Thus, it may combat the slow fading but not fast fading channels. Our proposed $\mathrm{M}^2\mathrm{iRi}^2$ can find the path with considering both existing and tolerable adding intereference. In this way, the throughput is increased with reducing the failed transmissions due to suffering too much intereference. Therefore, energy consumption from the system view is reduced, and efficiency is increased.

4. Simulation Results and Analysis

In this section, we evaluate the throughput and delay for $\mathrm{M}^2\mathrm{iRi}^2$ using NS-2 and contrast it with the flow-based MiRii and AODV routing protocol. The radio propagation model adopts Two-Ray Ground model in NS-2. Each node is equipped with two NICs. The off-the-shelf Cisco Aironet 350 series client adapters or access points allow different transmit power setting for one of 1, 5, 20, 30, 50, and 100 mW. We adopt the 30 mW and 100 mW in our NS-2 simulation. The SINR threshold is setting to 6.02 dB and the noise floor at each node is −120 dBm. The traffic flow type is CBR (Constant Bit Rate) during the ON period of an equally ON-OFF model and the packet sizes are 1000 Bytes.

We first look at a simple topology (see Figure 4) which clearly demonstrates the benefits of using the appropriate transmission power level at different interference environments. The flow-based MiRii routing protocol is introduced to evaluate these two cases of power levels. The dash line in 4 denotes the connectivity using 30 mW power, while the communication range is double farther if using 100 mW power. Table 1 shows the throughput and end-to-end delay with different traffic flow numbers. Each traffic flow transmits with data rate 512 KBits/s. "MiRii-30 mW" indicates that we fix transmission power at 30 mW in the entire network. The average end-to-end delay is defined as the time of packet from leaving the source to successful receiving at the destination. It includes the buffering time before the routing path discovery, the queuing time, the delay of retransmission at MAC layer, and propagation delay. When the number of traffic flow is one, the traffic loading is low and interference is slight. We can utilize high transmission power level (100 mW) to reduce end-to-end delay since it can travel through small hop counts. When the numbers of flows are increased, the interference among radio interfaces is increased. MiRii-30 mW can perform well since radio interfaces with lower transmission power level reduce the interference generating to its neighbors. The MiRii-30 mW has lower end-to-end delay and higher throughput than MiRii-100 mW.

Now we consider a 4×4 uniform topology in a $500\,\mathrm{m} \times 500\,\mathrm{m}$ region. Each node locates 80 meters apart. In Figure 5, the light color (red) bars represent the high traffic loading with data rate 1 Mbits/s and the dark color (blue) bars represent the low traffic loading with data rate 512 Kbits/s. We consider the traffic flows in the WMNs randomly start and terminate. We let the CBR traffic flow randomly on/off but keep the number of active flows in the network to be five in average. The numbers of traffic flows and traffic pattern are the same in both cases. Figure 5 shows that all the routing protocol can operate well in the low traffic loading. Because the traffic flows are randomly

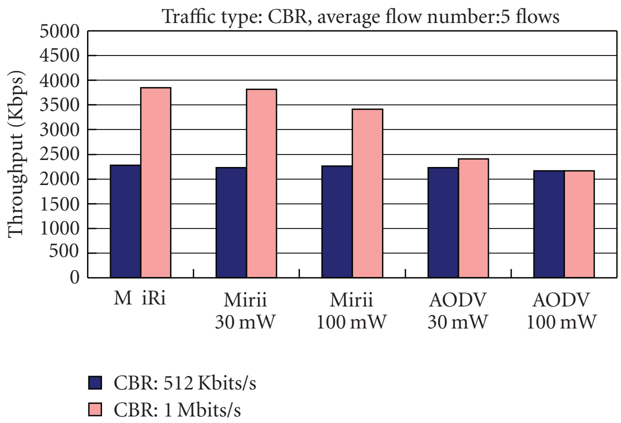

Figure 5: Throughput of different traffic load in a uniform network topology.

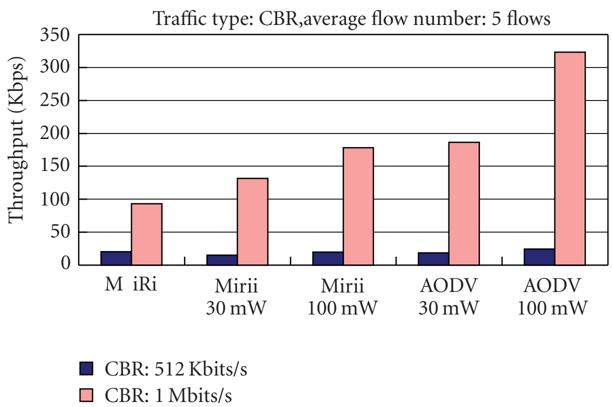

Figure 6: Average end-to-end delay of different traffic load in a uniform network topology.

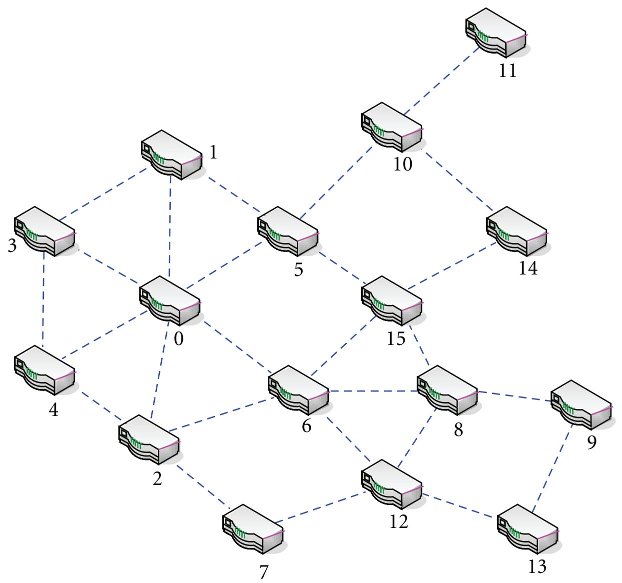

Figure 7: A random network topology.

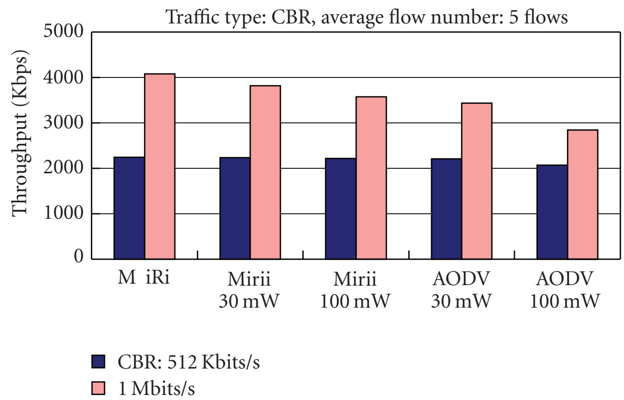

Figure 8: Throughput of different traffic load in a random network topology.

on/off and choose the source-destination pair randomly. The destination-based routing protocol also increases RREQ broadcast times and increases the packets waiting in the buffer before the routing path establishment. The flow-based routing protocol has the delay better than destination-based routing protocol. Even if the flow-based routing protocol needs to broadcast RREQ packets for each flow, it can discover better routing path than destination-based routing protocol. When the data rate increases to 1 Mbits/s, the transmission power fixed at 30 mW has throughput better than 100 mW, and the end-to-end delay has the same result. In this case, M^2iRi^2 have the throughput similar to MiRii-30 mW, and improve the throughput 13% contrasting with MiRii-100 mW. In Figure 6, the results of average end-to-end delay of M^2iRi^2 are decreased by 30% and 48% contrasting with MiRii-30 mW and MiRii-100 mW, respectively.

We next simulate our protocol on a topology that nodes are randomly placed in a 500 m $\times$ 500 m area (Figure 7). The simulation parameters are the same as the uniform topology. The throughputs are almost similar in these routing protocols at low traffic loading as we observe in the uniform topology case. However, from Figure 8, the throughput of M^2iRi^2 is better than MiRii-30 mW and MiRii-100 mW about 7% and 14% at high data rate. Figure 9 shows the average end-to-end delay in the high and low data rate. The delay of M^2iRi^2 is further lower than MiRii-100 mW and is better than MiRii-30 mW about 28% at high traffic data rate. The simulation results indicate that our proposed cross-layer routing protocol utilizes the advantages of different power levels in different network environments and performs well by controlling the transmit power efficiently for perflow per hop transmission.

Finally, we simulate a WMN with gateways, we choose two nodes in Figure 7 to play the roles of mesh gateways. The transmissions send the data packets to mesh gateways instead of random Source-Destination pairs. The traffic patterns tightly affect the performance of the routing protocol. Figures 10 and 11 show the simulation results in this case. We observe that M^2iRi^2 still has better throughput and end-to-end delay than MiRii-30 mW and MiRii-100 mW when the traffic data rate is 1 Mbits/s. All the routing protocols

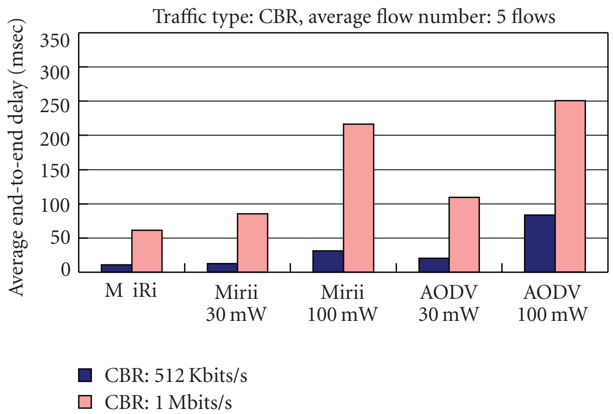

Figure 9: Average end-to-end delay of different traffic load in a random network topology.

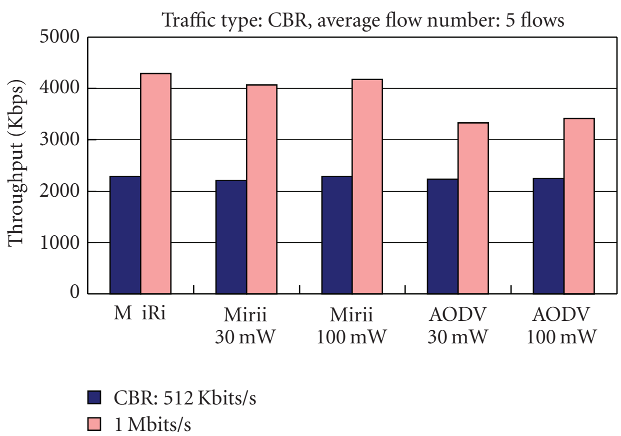

Figure 10: Throughput of different traffic load in a random network topology with gateway.

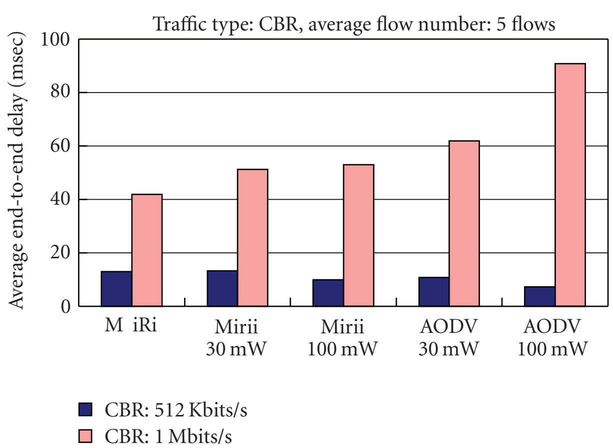

Figure 11: Average end-to-end delay of different tra0-40pt

also operate well when the flow data rate is 512 Kbits/s. The destination-based AODV routing protocol might have the lower end-to-end delay depending on whether the traffic flows have the same destination (gateway) or not, which will reduce the route discovery time. The results also indicate that our M^2iRi^2 routing protocol operates well when the traffic are all going towards gateways in the WMN.

5. Conclusion and Future Work

In the paper, we proposed M^2iRi^2 routing protocol for multi-interface WMNs. The main purpose is to coordinate the physical layer and the network layer for a cross-layer routing protocol development. Previous researches show that variable transmit power level control can improve network performance but they still use minimum hop counts as the routing metric. We introduce the iTolerance to constrain the transmit power level and incorporate it to the route discovery. The MiRii routing metric is utilized to evaluate the routing path with consideration of both intraflow and interflow interferences. Furthermore, the power control is designed on perflow, perhop basis. We thoroughly observe the performance of M^2iRi^2 at different traffic loadings. When the traffic loading is high, the newly traffic flow chooses the appropriate transmission power level along less interference path to transmit the data packets in order not to create intolerable interference to the existing transmissions. Through the simulation results, we have demonstrated that our M^2iRi^2 routing protocol can enhance both network throughput and end-to-end delay.

In the current version of M^2iRi^2 routing protocol, the traffic flow selects the lowest power level even if it would violate the interference tolerance constraint. In the future, we may incorporate M^2iRi^2 with the traffic flow admission control and extends the M^2iRi^2 to more stability and even better performance.

Acknowledgment

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Quality-Aware Multiple Backbone Construction on Multi-interface Wireless Mesh Networks for P2P Streaming

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Abstract—**In Wireless Mesh Networks(WMNs), users can enjoy the real-time video streaming service anytime and anywhere through the service. Compared to the client/server model, the P2P(Peer-to-peer) approach is more suitable for video streaming applications because of its efficient usage of network resources. However, the multimedia applications are very sensitive to delay time and the performance of packets transmission which is significantly influenced by the co-channel interference. In our approach, we choose the better quality links for routing instead of the minimum hop-count path in MAODV(Multicast Ad hoc On-demand Distance Vector). Then we distribute the video streaming to receivers by using multicasting in multi-channel WMNs, and modify the MAODV routing protocol to construct two disjoint multicast trees as the backbone for the P2P structure. Therefore, we can adopt the MDC(Multiple Description Coding) scheme to encode the video into two independent sub-streams and transmit separately along these trees. Experiment results show that in higher traffic load environment, our scheme is more effective to reduce the latency and improve overall system performance.**

Keywords-Wireless Mesh Networks, P2P, MAODV, multi-interface, MDC

I. INTRODUCTION

Wireless mesh networks (WMNs) support applications like real-time applications such as video streaming and voice conferencing. Multimedia streaming over the WMNs has become a reality with the development of media compression methods [1], high-throughput storage systems, and broadband networking technology. However, there are still many challenges towards building cost-effective, robust, and scalable multimedia streaming systems due to the stringent bandwidth, packet loss, and delay requirements for media streaming.

For supporting real-time video streaming in the WMN, QoS provisioning for such applications is an essential requirement. Figure 1 shows an example of video streaming over WMNs. If a station (STA) wants to watch the real-time video streaming, it will send a request message to the mesh access point (MAP). After receiving the message, MAP relays the request to the mesh point (MP), then MP (for simplicity without loss of generality, assuming that it has the source of the video, or obtain the video content from the Internet source) begins to transmit the video streaming to the requested MAP along the reverse routing path. Here MAP can play as the role of 'agent' for those STAs with the same video request under its coverage. Once the MAP receives the video content, it can broadcast to all its stations. If there are many stations that want to watch the same video simultaneously, then each corresponding agent MAP will request to the same source MP. In this case, the source MP will be a bottleneck and the performance will be severely degraded due to lack of network bandwidth, or congestion. Therefore, P2P streaming approach is a better choice to reduce the overloading of the source. In P2P, each peer contributes its share of resources and cooperates with other peers according to some predefined rules for communications. Besides, the most important difference between P2P and the server/client paradigms, a P2P streaming system uses the 'play-while-downloading' mode. And, the requesting peers playback and store the media data during the streaming session, and they become supplying peers of the media file after the streaming session.

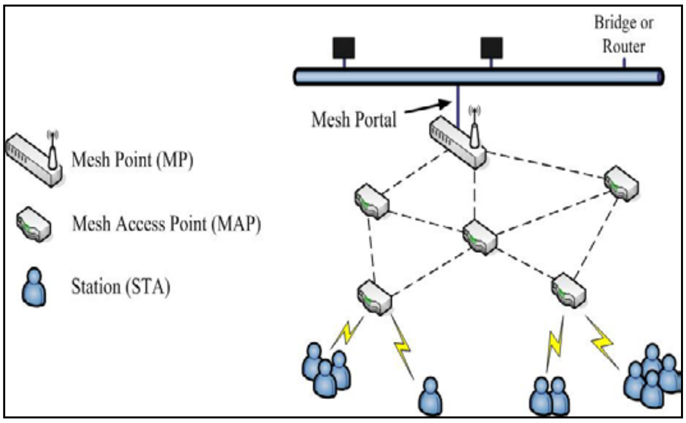

Figure 1. Video streaming over WMNs

Here, in supporting P2P overlay network, a multicast tree among all the corresponding agents (MAPs) will be constructed. Although the mesh topology for P2P overlay networks can be an alternative, the tree topology is suitable for easy deployment and quick response. It is because video multicast is an efficient bandwidth-saving technology which intends to transmit the packets from the source to a set of nodes.

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In most of mesh networks, MAPs are usually equipped with multiple interfaces to improve the system throughput, recent researches have focused on how to assign channels to different wireless interfaces in unicast routing to improve system throughput in WMNs. However, the multicast routing for multiple channels is a more complex problem. Multicast Ad hoc On-demand Distance Vector (MAODV)[4] proposed a multicast version for AODV, and [6] proposed a multiple tree multicast AODV (MT-AODV) for multiple channel cases.

For real-time video streaming, the most important thing is the quality of video playback, and the delay time. The quality of each link along the routing path should be the most important factor with the performance in stead of hop counts which basically AODV families use. On the other hand, multicast is a UDP transmission and will not retransmit packets to ensure the packets are received by these receivers. Many researches use multiple paths to transmit duplicate packets along separate paths, thus, wasting too much bandwidth and network resources.

From the above consideration, in this paper, we take into account the link quality of each interface for constructing two disjoint multicast trees, and used multiple description coding (MDC) for video coding to enhance the efficiency. Through the proposed routing protocol design, simulation results show that we can improve the network performance and look after both network throughput and average end-to-end delay.

The rest of the paper is organized as follows. Section II reviews the related works. In section III, we present a Steiner tree based routing protocol in details. Section IV shows the simulation results and analysis. Finally, we conclude the paper with in Section V.

II. RELATED WORK

Reference [2] discussed the difference between shortest path trees (SPTs) and minimum cost trees (MCTs). The SPT algorithms construct a tree rooted at the sender and spanning all the receivers such that minimize the distance between the sender and each receiver along the tree. As a result, the SPT algorithms minimize the end-to-end delay as well. To construct a SPT, we usually apply the point-to-point shortest path algorithm repeatedly, once for each sender–receiver pair. Different from the SPT algorithms, the goal of MCT algorithms is to minimize the overall cost of the multicast tree. MCT algorithms for multicast routing are based on the minimum Steiner tree (MST) problem [3], which is NP-complete. The total cost of a Steiner tree is less than the total cost of a corresponding SPT, by definition of MST.

MAODV [4] is an example of SPTs, which uses the minimum-hop count paths to construct the multicast tree. MAODV is a multicast extension of AODV [5], and is capable of unicast, broadcast, and multicast. In the MAODV algorithm, the first node that requests membership to the group would become the group leader. When a node wants to join the multicast group and the node can not find a path to the multicast group leader, it will broadcast a Route Request (RREQ) packet. When a group member receives the RREQ, it will send a RREP packet along the reverse route to that node. After receiving the RREP packets from the multicast group members, this node will choose the shortest distance (minimum hop-count) path between itself and the member of the group to establish the connection, as a branch of the multicast shard tree of the multicast group. Thus the path to the multicast tree will be the shortest distance.

In [6], they used multiple description coding (MDC) [7] for video coding, which is a video coding concept to a single video source coding into two or more independent descriptions. These description packets are sent via a number of different routing paths. Any one of the flows can separate out the complete decoding of the video stream. But after receiving a number of descriptions, the video quality will be significantly improved. MT-MAODV [6] is a modified MAODV, which constructs two highly-disjoint trees. By using MDC, the video is divided into two independent sub-streams which will be transmitted separately along these trees. MT-MAODV can reduce the correlation of packet loss of MDC video descriptions if the multicast trees are highly disjoint. However, the transmission goes with only one channel, there must be some shared links in both trees. Without extension to multiple channels of disjoint tree construction, the performance is significantly influenced by the co-channel interference. Therefore, we consider the broadcasting characteristics of wireless channels, and use more accurate link quality measure to propose a quality-aware multiple backbone construction on multi-interface WMNs. We also used the Steiner tree concept to build the tree such that it is more likely our case that not necessary all the MAPs appear as members and can be only helpers to construct the trees. Compared with MAODV or MT-AODV, all the members should be on the tree eventually.

Considering the quality of the links, we used the expected transmission time (ETT) [8] to calculate the expected time for sending a packet successfully. ETT is estimated by sending out probes and measuring the delivery ratios in both directions. The delivery ratio can be viewed as a factor of co-channel interface. This means that the link with lower ETT will have better quality. Using ETTs as the cost for the Steiner tree problem and considering integrated multiple channel interference, we can get a tree with less total cost, thus higher transmission performance.

III. PROPOSED MECHANISM

We use the concept of the Steiner tree to modify MAODV routing protocol, and propose a new multi-channel multicast tree algorithm called ST-MAODV. In order to efficiently use channel bandwidth, we use ETTs as link metrics in stead of hop counts to enhance the overall system throughput. And we also adopt the concept of the MDC video application. Without loss of generality, we assume that each MAPs in the WMN are equipped two wireless interface cards, and each card is using the predefined channel with total of two channels for all MAPs.

We find out two disjoint Steiner trees with minimum cost as two multicast trees. For each node joining the multicast group, we will first take into account all the costs to find the minimum cost path to construct the first Steiner tree. And then from the remaining unused links to find out the other minimum cost path for the second Steiner tree. If the remaining links are insufficient to construct the second tree, we can use the portion of used links of the first tree to construct.

ETT of each interface card is estimated by probing on that channel used for it. ETT can be interpreted as the loading or inverse of link quality associated with the link. Intuitively, when constructing the tree by adding links one by one, the total cost of the tree is the sum of ETTs with all links on the tree. However, due to broadcast characteristic of wireless channels, using the same channel for multicast, one transmission is enough for all the down-stream nodes. For example, as shown in Figure 2, the number indicated on the link means ETT estimated by using the associated channel/interface. If node A uses the same channel 0 to multicast to nodes B and C (Figure 2(a)), node A transmits only once, as result of total cost of maximum of 5 and 3, which is 5, not sum of 5 and 3, which is 8. If node A uses different channels to multicast, say using channel 0 to node B, and channel 1 to node C, the total cost will be the sum of the two costs which is 8 (Figure 2(b)). Therefore, if the node A and B are already in the multicast group using the channel 1 as the connection, and sometime later node C wants to join the tree. It will cause less additional cost (which is 2) if using the channel 1 connection to establish the link from node A to C.

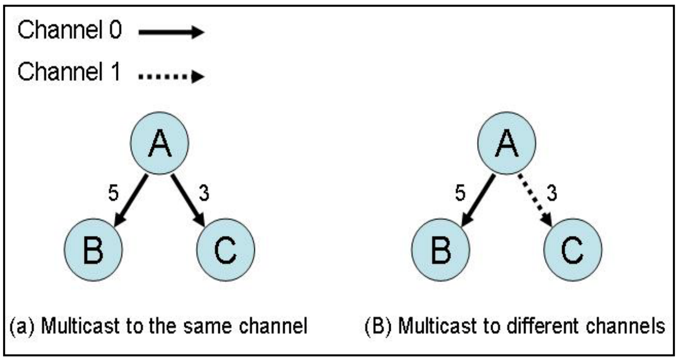

Figure 2. Multicast uses the same or different channels.

The following is the procedure for our ST-MAODV protocol:

- Nodes send probing messages once in a while for each channel to calculate the value of ETT for each link to the adjacent nodes.
- When a node wants to join the multicast group, broadcast RREQ packets to adjacent nodes.
- When a node receives the RREQ, check whether it belongs to the group member. If yes, reply RREP via the reserve path to the requesting node. If not, keep broadcasting RREQ packets to other nodes until the group member has received.
- When the requesting node receives RREPs, decide a path with minimum path ETT to construct the first multicast tree.
- Then keep finding out the next minimum path ETT to construct the second multicast tree from the remaining unused links.

When propagating RREQ, the cost of the associated path is incremented with the rule presented in Figure 2. Because the cost of multicast tree depends on the use of the same or different channels, the incremental cost of unused links should be subtracted by the cost of the used links' maximum cost using the same channel. So we update the unused links' cost of the nodes in the first multicast tree, and then find out the second one using the updated additional cost.

For nodes in accordance with the order to join the group, repeat steps 2 to 5 until all the nodes have joined the two multicast trees.

Figure 3 is a simple example. The node A is the source node; nodes B, C, D, E and F are the destination nodes and have not yet joined the multicast group. Each node has two interface cards using channel 0 and 1, respectively. The number indicated on the link represents ETT cost associated with that channel. Figure 4 shows how node C joins the multicast group. First of all, find a minimum total-cost path from node C to node A and add the path to the first multicast tree. This tree is indicated as dart blue path in Figure 4. Then we find another minimum total-cost path from the remaining unused links to construct the second multicast tree which is indicated as dark red path in Figure 4.

After constructing two disjoint trees for node C, update the costs of these unused links of the nodes in the tree paths as shown as Figure 5. The path of the first tree (blue color) is through node H and node I. The link between node A and node H uses channel 1 and the cost is 2, so that if node A connects to node F with channel 1 later, then it only needs to spend an additional 2 unit of cost. In other words, node A can just spends 4 unit of cost to multicast to node H and node F by channel 1, so the cost of the link between node F to the first tree by channel 1 could be updated to 2 unit. Similarly, update the costs of the unused channel 1 links to other neighbors from node H and node I. After all, update the costs of the unused links of the nodes in the second tree indicated after '/' sign.

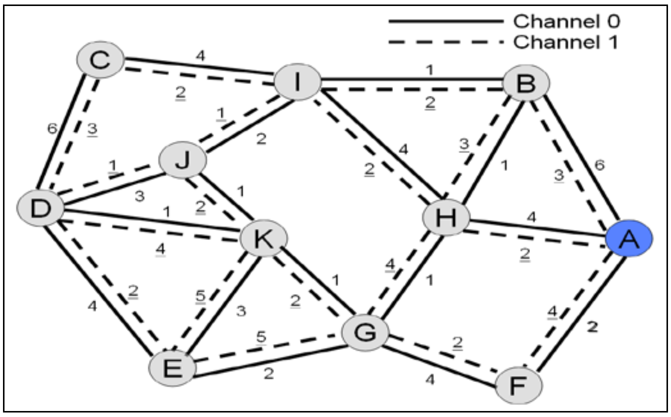

Figure 3. Each node transfers data with two channels.

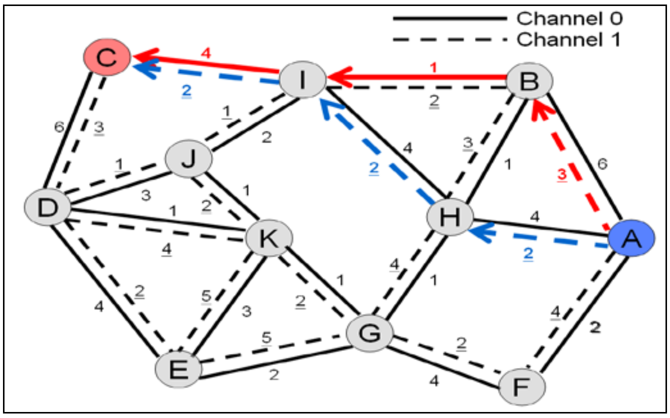

Figure 4. Node C joins the multicast group.

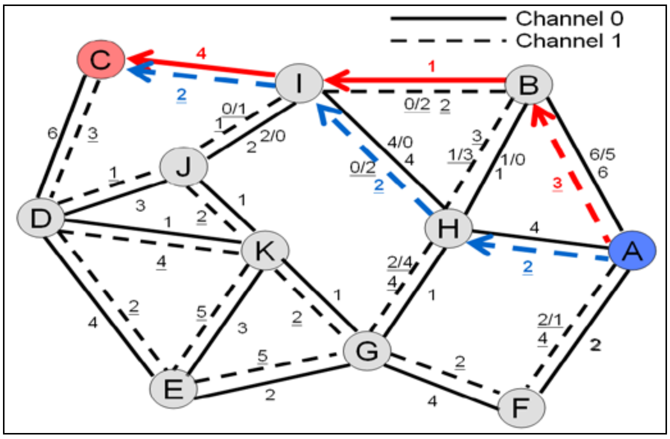

Figure 5. Update cost after node C joins.

Repeat the above steps with the joining sequence: C,F,D,E, and B. We can get two disjoint Steiner trees as shown in Figure 6, after all nodes joining the two multicast trees. The cost of the first Steiner tree is 12, and the second one is 13, resulting in 25 of the total cost.

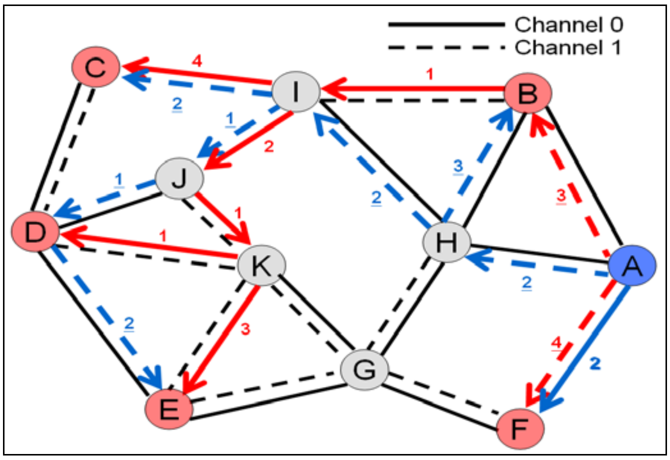

Figure 6. Two disjoint Steiner trees.

IV. PROTOCOL EVALUATION

In this section, we evaluate the performance of the proposed ST-MAODV routing protocol. We perform the simulation using NS-2 and compare the following four cases: (C1) Video multicast with MDC and MAODV, (C2) Video multicast with MDC and two-channel MT-MAODV [6], (C3) Video multicast with MDC and ST-MAODV for one tree, and (C4) Video multicast with MDC and ST-MAODV for two disjoint trees. The NS-2 is modified to support MAODV routing protocol [9] and multi-interface operation with multi-channels on each wireless node [10]. Four scenarios for different flow settings are evaluated.

A. Scenario 1

In the first scenario, all receivers join the multicast group per 5 seconds. Figure 7 shows the average delay time with different number of receivers. The average delay time is for data transfer from a sender to a receiver. We can see that our ST-MAODV protocol is better than others, because the link with less ETT means that it may need less time to transfer packets successfully.

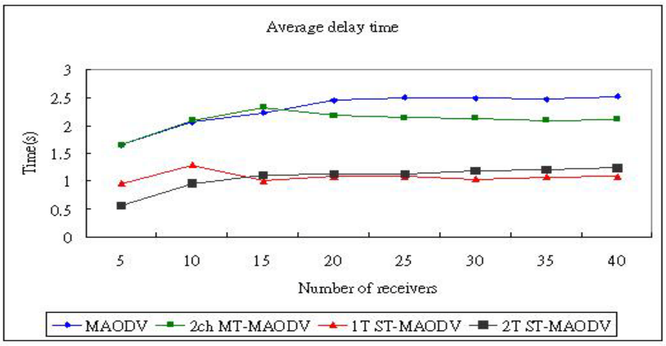

Figure 7. Average delay time.

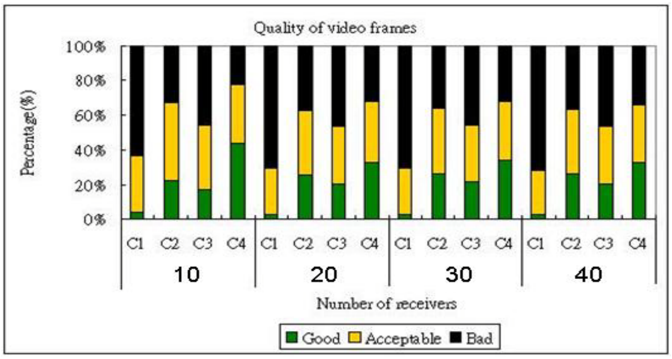

Figure 8. Quality of video frames.

Figure 8 gives the distribution of video frames according to their quality. With the MDC scheme, using multiple disjoint trees can significantly reduce the number of 'bad' frames (both descriptions of a particular frame are lost), as shown in case C2 and C4, because the probability of losing both video descriptions together is smaller. Different from the minimum hop-count path of MT-MAODV, our approach selects paths with higher link quality, and thus avoids local congestion so that the quantity of good frames (both descriptions are received) and acceptable frames (one description is received, and one is lost) of C3 are better than C1.

B. Scenario 2

In scenario 1, there is just one video traffic flow in the simulation environment. Here we add one FTP flow to be the background traffic to make some interference. The FTP flow is between two nodes which were selected randomly, and the data rate is 500 kbps. With some background traffic, there might be more contention and traffic congestion. We can see from Figures 9 & 10 that both C3 and C4 perform better than C1 and C2, because with some interferences, our ST-MAODV can still build trees from those better quality links, and with two disjoint trees, the quality of C4 is superior to C3.

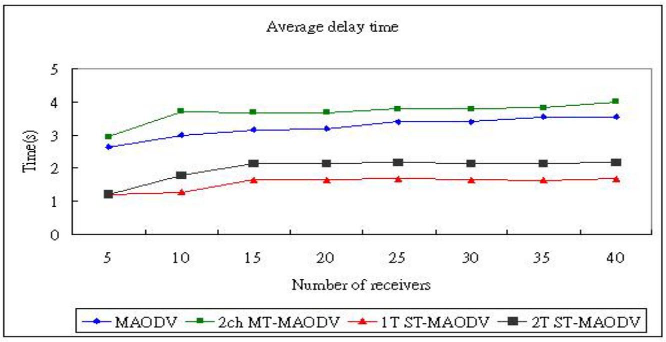

Figure 9. Average delay time.

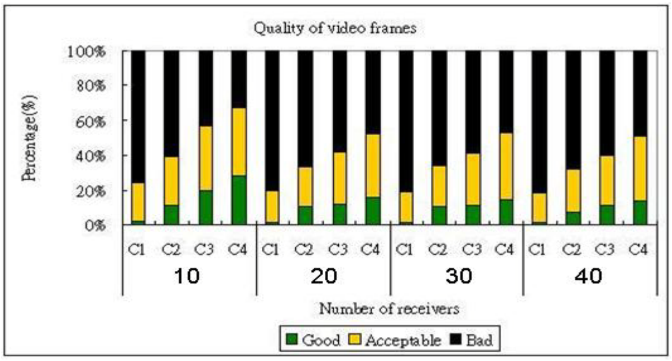

Figure 10. Quality of video frames.

C. Scenario 3

Now we compare the two-channel MT-MAODV and ST-MAODV with different data rate. As shown as Figure 11 to Figure 14, only ten receivers join the multicast group at the same time. We compare the packet deliver ratio and average delay time with different data rate from 10 kbps to 11 Mbps. In Figures 11 and 12, the two-channel MT-MAODV is better than our ST-MAODV when the data rate is less than 100 kbps. This means that when lower network traffic load, the performance of two-channel MT-MAODV is better. However, with the increasing of traffic loading, our approach is more suitable for data transmission.

Figures 13 & 14 show the average delay time and the latency ratio between C2 and C4, respectively. When data rate increases, delay time also increases significantly. However, ST-MAODV still has lower delay time. This shows that our approach is more suitable in the environment with higher network traffic load.

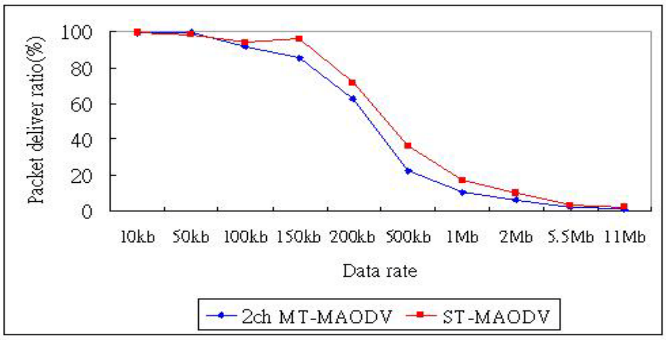

Figure 11. Compare PDR with different data rate.

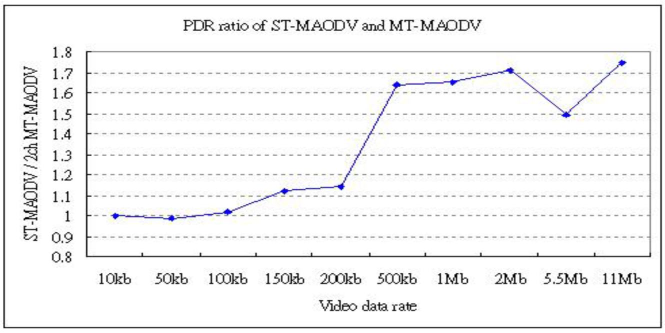

Figure 12. PDR ratio of C2 and C4.

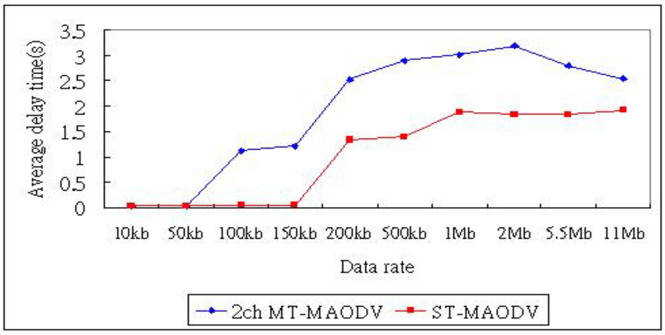

Figure 13. Compare average delay time with different data rate.

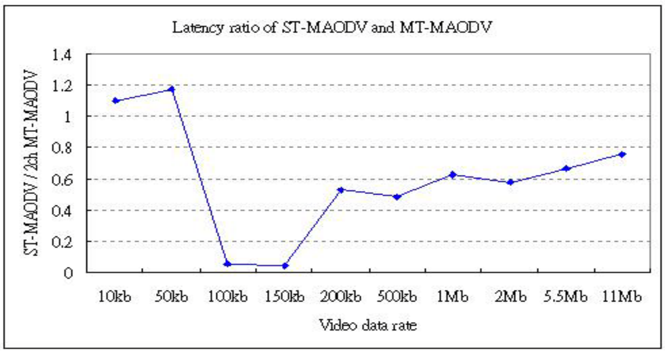

Figure 14. Latency ratio of C2 and C4.

V. Conclusion

In this paper, we present a ST-MAODV routing protocol for multi-interface wireless mesh networks. The main purpose is to enhance the throughput of multicasting the video streaming to the receivers in the multi-channel environment. We refer to the Steiner tree concept to modify the MAODV routing protocol to construct two disjoint trees. By the MDC scheme, we transmit the sub-streams separately along these trees. Finally, we evaluate the results on NS-2, and get significant performance.

Acknowledgment

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