# 무선 메쉬 네트워크에서의 다중 트래픽 흐름을 위한 종단간 처리량 모델링 및 효율적인 라우팅 경로 선택 기법

# (Modeling End-to-End Throughput of Multiple Flows and Efficient Route Selection in Wireless Mesh Networks)

왕 효 비 † 권 태 경 †† 최 양 희 †††
(Xiaofei Wang) (Ted "Taekyoung" Kwon) (Yanghee Choi)

**요 약** 무선 메쉬 네트워크는 최근 주목받는 연구 주제로 부상하고 있다. 무선 메쉬 네트워크는 대규모 무선 랜 장치와 AP들이 서로 연결된 무선 기반 구조로, 무선 메쉬 네트워크의 처리량(throughput)을 향상시키는 것을 목표로 한 수많은 연구가 이루어진 바 있다. 여기에서는 동시에 생겨나는 다수의 트래픽 흐름들을 전송하기 위한 적절한 라우팅 경로를 설정하는 작업이 매우 중요하다. 본 논문에서는 IEEE 802.11 DCF하에서 전송되는 다수의 트래픽 흐름에 대해 신호 감지(Carrier Sensing), 간섭 등의 정보를 이용하여 양 말단간 (end-to-end) 처리량을 수학적으로 모델화하기 위한 방법을 제시하고자 한다. 각 단말에 성공적으로 이루어지는 평균 서비스 시간을 비교하고, 한편으로는 트래픽 흐름 가운데 병목현상이 발생하는 부분을 찾아내어 그로부터 말단간 처리량의 최대치를 계산할 수 있다. 본 논문에서 제시된 모델을 사용하여 동시에 전송되는 다수의 트래픽 흐름을 전달하기 위한 전송 경로에 대한 후보 경로를 얻어낼 수 있으며, 얻어진 경로로부터 처리량을 최대로 높일 수 있는 효율적인 경로를 찾아낼 수 있다. 제시된 모델링 기법과 최적 경로 선택 메커니즘은 무선 메쉬 네트워크에서의 다양한 트래픽 흐름을 사용한 시뮬레이션을 통해 평가하였다.

**키워드** : 다중 트래픽, 종단간 처리량, 모델링, 라우팅 경로, 무선 메쉬 네트워크

***Abstract*** Wireless Mesh Networks (WMNs) have gained a lot of attention recently. Based on the characteristic of WMNs as a highly connected wireless infrastructure, many efforts from research organizations are made in order to improve the performance of the flow throughput in WMNs. Therefore, it is very critical issue to establish efficient routing paths for multiple concurrent ongoing flows. In this paper, we propose a general modeling methodology to analyze the end-to-end throughput of multiple concurrent flows by analytical calculation taking into account the carrier sensing behaviors, interference and the IEEE 802.11 Distributed Coordination Function mechanism. After the comparison of the average service time for each successful transmission at each node, we analyze the bottlenecks of flows, and hence obtain the maximum end-to-end throughput of them. By using our proposed model, it is possible to predicate the throughput of several candidate routing paths for multiple

· 본 연구는 기초기술연구회의 NAP 과제 지원으로 수행되었음. 이 연구를 위해 연구장비를 지원하고 공간을 제공한 서울대학교 컴퓨터연구소에 감사드립니다.
· This work was supported by NAP of Korea Research Council of Fundamental Science & Technology, and the ICT at Seoul National University provides research facilities for this study.
· 이 논문은 2008 하계 컴퓨터통신 워크샵에서 'Modeling End-to-End Throughput of Multiple Flows in Wireless Mesh Networks'의 제목으로 발표된 논문을 확장한 것임

† 비 회 원 : 서울대학교 컴퓨터공학부
dobby@mmlab.snu.ac.kr
†† 비 회 원 : 서울대학교 컴퓨터공학부 교수
tkkwon@snu.ac.kr
††† 종신회원 : 서울대학교 컴퓨터공학부 교수
yhchoi@snu.ac.ckr

논문접수 : 2008년 9월 16일
심사완료 : 2010년 3월 14일



정보과학회논문지: 정보통신 제37권 제4호(2010.8)

concurrent ongoing data flows, so we can select the most efficient route that can achieve the highest throughput. We carry out simulations with various traffic patterns of multiple flows in WMNs to validate our modeling and our efficient route selection mechanism.

Key words : Multi-Flow, End-to-End Throughput, Modeling, Route Selection, Wireless Mesh Network

## 1. Introduction

Recently, Wireless Mesh Network (WMN) systems based on the IEEE 802.11 WLAN technology [1] have been proliferated rapidly. WMNs are expected to provide high throughput channels from aggregators through intermediate routers to the gateway(s). Aggregators are mesh nodes that directly collect data from client users. Routers are intermediate mesh nodes relaying data in a multi-hop manner to the gateways connected to the Internet.

The performance of a WMN system is limited by the broadcast nature of the wireless medium. One node has to compete with others within its carrier sensing (CS) range for data transmission, or collision will happen. This can be described as **channel competition**. In IEEE 802.11 series standards, devices are using the CSMA/CA mechanism to share the medium and to avoid collisions with each other. However, there are still other problems, e.g. hidden node problem (HNP) and exposed node problem. HNP is mainly caused by the ignorance of the transmissions outside the CS range. There are two kinds of HNPs which we will discuss in detail later: (1) protocol level HNP and (2) physical level HNP. Normally if we use the RTS/CTS mechanism, we can solve the protocol level HNP. However, the physical level HNP cannot be solved by the RTS/CTS. In many cases, for those nodes that are working in the same channel, one can hear signals from other senders even if they are out of its transmission range or CS range. It induces the SINR (Signal to Interference and Noise Ratio) value lower than the demodulation threshold, then the node can't decode the receiving packet. This phenomenon, which is called **channel interference**, is also one of the main constraints of throughput performance of flows.

Many research efforts are made to theoretically model the throughput from the view of entire WMN system, or from a specified one hop, or a typical path. In realistic scenarios, to analyze throughput of multiple concurrent ongoing flows is viable to evaluate the routing strategy, thus flow modeling can be useful to select efficient routing paths from the perspective of routing agent. Most of current routing protocols don't consider the realistic performance, since they create routing paths by route discovery procedure and assume that paths with least hop count or fast response time will be best routing paths. However, the actual flow throughput is not exactly the same as routing protocols expect, because their strategies don't put end-to-end throughput as the first target. Our contribution in this paper is to provide a model on the end-to-end throughput of multiple concurrent ongoing flows in the WMN systems, and apply this model on route selection by calculating and comparing the end-to-end throughput of several candidate routing paths to guarantee the maximal end-to-end throughput of the flow.

The rest of this paper is organized as follows: In Section II, we briefly introduce background of related work and the constraints of throughput in WMNs. In Section III, we explain the proposed modeling procedure. The modeling-based route selection methodology will be introduced in Section IV. In Section V, we carry out comprehensive simulation experiments to evaluate our modeling, and Section VI is for the evaluation of the routing paths selection method. The paper will be concluded and future work will be briefly mentioned in Section VII.

## 2. Background

### 2.1 Fundamental Constraints of WMNs

WMN systems mainly suffer from three fundamental constraints: channel competition, protocol level HNP that can be resolved by RTS/CTS, and physical level HNP by which interference is induced.

2.1.1 Channel Competition

In WMNs, a node has to compete with others in transmission range in order to occupy the channel to transmit a packet. In IEEE 802.11 series, the Distributed Coordination Function (DCF) based on CSMA/CA is used for nodes to share the common channel in order. Once a node is occupying one channel, all nodes within its CS range can detect and have to be frozen. This significantly limits the performance of WMNs. Recently some techniques are used to reduce the limitation of channel competition, e.g. multi-channel and dynamical channel assignment strategy. However, those techniques come with additional hardware as well as signaling cost and hazards.

2.1.2 Protocol Level Hidden Node Problem

The Hidden Node problem is well-known in wireless networking. There are two kinds of HNPs, protocol level HNP and physical level HNP. Protocol level HNP is caused by the nodes that are in the CS range of receiver but not in the CS range of sender, then sender will keep sending packet to the receiver although HNP nodes even may affect receiver but sender won't know. People developed the RTS/CTS mechanism to solve the protocol level HNP. In our analysis, we only evaluate the scenarios without RTS/CTS for two reasons: (1) it is easy to modify our modeling to analyze scenarios with RTS/CTS, and (2) the overhead of RTS/CTS is not negligible and sometimes it becomes ineffective practically [2].

2.1.3 Physical Level Hidden Node Problem

Physical level HNP is caused by the nodes that are out of the CS range of both sender and receiver, but their transmission signals can still affect the signal-to-interference-noise-ratio (SINR) value of receiver, so that the receiver cannot demodulate the sender's packet. The physical level HNP cannot be solved by the RTS/CTS mechanism. The Capture Effect [3] is substantially intertwined with the physical level HNP. In this paper, we follow a simple capture model, where the SINR value must be always higher than the capture threshold during the entire transmission to obtain a whole packet successfully. Physical HNP is considered as interference in common knowledge.

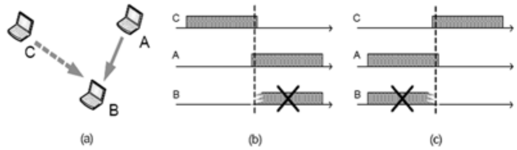



Fig. 1 Interference Model and Relationship

We demonstrate interference in our modeling as shown in Fig. 1, where A is sending packet to B, and C is the interferer. During the period in which A's transmission is going on, the packet reception is vulnerable to C's interference. By above capture effect model, this vulnerable period is twice as long as the transmission time of a packet. That is, when A's transmission time overlaps with that of C, the receiver (or B) cannot demodulate the packet, and a packet can only be demodulated if from the packet header to the ACK of MAC layer transmission, all bits are heard by B successfully without any interference from C.

### 2.2 Current Related Work

Realistic modeling of WMN systems is crucial for further WMN resource management, such as channel allocation, dynamic routing, load balancing, and adjustment of topology and so on. Bianchi [4] initially proposed the basic analysis on DCF for saturated traffic case for WMNs in infrastructure mode. Ken Duffy's Model [5] made an effort for analyzing accurately with the non-saturated traffic by extending the Bianchi's model. However, both consider only single hop WLAN cases. Mukesh Hira's Model [6] analyzed a single flow in wireless multi-hop networks by considering the probability of PHY/MAC layer behaviors but neither multiple flows nor physical HNPs is not considered. Yan Gao's Model [7] presented the probabilistic analysis of the link throughput. It considers multiple flows from the perspective of links, not of nodes. Furthermore, there are still many models and analysis works [8-12] for WLAN systems. Our work extends the Mukesh's modeling methodology for scenarios with multiple flows from the perspective of nodes considering channel competition and both protocol level and physical level HNPs, also we apply this modeling into routing paths selection to improve the performance of WMNs.

## 3. Modeling and Analysis

### 3.1 Preliminaries

In our analytical modeling, a homogeneous WMN with one channel is assumed, and WMNs equipped with multi-channel technique will be analyzed later. Since we consider the throughput analysis of the predefined paths, we assume if there are concurrently multiple interferers, our model considers interference signals one by one, not cumulatively. The main idea of modeling is to locate the bottleneck of each flow. Bottleneck nodes in WMNs are the nodes that will be constrained by much more CS neighbors and both kinds of HNPs than others. Even if the downstream nodes of a bottleneck node in the flow have less constraints and hence higher link capacity, the flow's end-to-end achievable throughput is limited by the bottleneck node already. We adjust the input traffic load to be equal to the capacity of the bottleneck node; the maximum end-to-end throughput can be achieved.

In a WMN, there are total N concurrently ongoing flows, denoted by $F_i, i \in \{1, 2, ..., N\}$. As $F_i$ will go from an aggregator through zero or more intermediate routers to gateway, we can denote the flow $F_i$'s hop count by $M_i$. We denote all nodes belonging to the flow $F_i$ by $n_{i,j}$, and $j$ is the node's hop count number counting from the aggregator through the flow until gateway, $j \in \{0,1,..., M_i\}$. $n_{i,0}$ is the first node which should be the aggregator, and $n_{i,M_i}$ is the destination which should be a gateway.

Suppose the set of total nodes in a WMN is $S$, we can define several specific subsets based on relationships:

- $S_{CS}(n_{i,j})$ : the set of nodes within the CS range of $n_{i,j}$, excluding $n_{i,j}$
- $S_{CS}(n_{i,j})^+$ : the set of nodes within the CS range of $n_{i,j}$, including $n_{i,j}$
- $\overline{S_{CS}(i)^+} = S - S_{CS}(i)^+$ : the set of nodes out of the CS range of $n_{i,j}$
- $S_I(i)$ : the set of nodes that are out of $n_{i,j}$'s CS range, but within the interference range of $n_{i,j}$
- $S_{RTS}(n_{i,j})$ : the set of nodes within RTS range of $n_{i,j}$
- $S_{CTS}(n_{i,j})$ : the set of nodes within CTS range of $n_{i,j}$

The above set information can be obtained by the ideal propagation model, or by some measurement methodologies (e.g RSS-based Prediction Method [13]).

We first focus on the analysis and modeling of one single flow in the WMN. Suppose one flow $F_x$ spans over $Mx$ hops, and hence it has $M_x+1$ nodes, (from $n_{x,0}$ to $n_{x,M_x}$). For the purpose of understanding, we skip the index $x$ in the following and describe our modeling from the standpoint of a single flow chosen among multiple flows. As the chosen flow goes from $n_0$ to $n_M$, we can pick up two intermediate adjacent nodes $n_i$ and $n_{i+1}$ for analysis, where $n_{i+1}$ is the next hop of $n_i$.

The key to finding the bottleneck is to calculate the expectation of the service time, $E[T_i]$, for each node $n_i$, which is taken to transfer one packet successfully. The bottleneck node in the flow must have the largest $E[T_i]$, because it will take the longest time to successfully transmit one packet since it will suffer from channel competitions and HNPs more severely than any other nodes in the flow.

We denote by $\rho_i$ as the probability of having a non-empty queue at node $n_i$. By the similar technique as the fixed point approximation, we first suppose the source node has always packets to send, so $\rho_0 = 1$. For the downstream nodes along the path of the flow, they can only receive packets that are successfully sent from the previous hop. Then an intermediate node can only receive packets at a rate determined by the maximum average service time among the previous (upstream) nodes in the flow. Therefore,

$$\begin{cases} \rho_0 = 1 \\ \rho_i = Min\left(1, \lambda_i E\left[T_i\right]\right) \\ \quad = Min\left(1, \dfrac{E\left[T_i\right]}{Max_{j<i}\left(E\left[T_j\right]\right)}\right) \qquad 1 \le i \le M_i \end{cases}$$

where $\lambda_i$ is the arrival rate of packets at node $n_i$. If node $n_i$ is not the bottleneck in the flow, it will receive the traffic whose rate is the reciprocal of the maximum among the average service times of all the upstream nodes. Let us detail the the average service time for node $n_i$. We can divide its working time into 4 periods:

$$E[T_i] = T_s + E[TBackoff_i] + E[TU_i] + E[TC_i]$$

where $T_s$ is the transmission time consumed by $n_i$ to transmit a packet successfully, and $E[TBackoff_i]$ is the average time spent by node $n_i$ for the backoff procedure. $E[TU_i]$ is the average time consumed by a successful transmission of other nodes in $S_{CS}(n_i)$, and $E[TC_i]$ is the average time consumed by collisions regardless of whether node $n_i$ is involved.

3.1.1 $T_s$

$T_s$ is the time for a successful packet transmission. For simplicity, we assume the payload is a fixed length. Then, we can calculate the corresponding $T_s$ value for basic mode and RTS/CTS mode respectively.

$$\begin{aligned} T_s^{Basic} &= MAC + PHY + Payload + \\ &\quad SIFS + ACK + DIFS \\ T_s^{RTS/CTS} &= RTS + SIFS + CTS + SIFS \\ &\quad + MAC + PHY + Payload \\ &\quad + SIFS + ACK + DIFS \end{aligned}$$

3.1.2 $E[TBackoff_i]$

$E[TBackoff_i]$ is the average time period used by node $n_i$ for the backoff procedure:

$$E[TBackoff_i] = \sum_{n=0}^{m}\left(\frac{CW_n}{2}\sigma\right)\beta_i^n$$

where $\frac{CW_n}{2}$ is the mean of the randomly chosen backoff slots before $n$-th transmission attempt, and $m$ is the maximum retry number. $CW_n$ value changes from minimum window size $CW_{min}$ to maximum window size $CW_{max}$. $\sigma$ is the time slot duration specified by IEEE802.11 standard (e.g. IEEE802.11a, it is 9$\mu$s). Therefore, if we define $\Psi_i$ as the fraction of time that node $i$ spent in backoff between two successive successful transmissions, it can be calculated as : $\psi_i = \frac{E[TBackoff_i]}{Max_{j<i}(E[T_i])}$

3.1.3 $E[TU_i]$

From Bianchi's modeling, given the collision probability $\beta_i$, which contains all situations that make node $n_i$ go into the backoff procedure and extend the contention window accordingly. We can calculate the probability that node $n_i$ wishes to transmit a packet (i.e., when it has a non-empty queue). We denote the probability by $\tau''$,

$$\tau_i'' = \frac{2(1-2\beta_i)}{W(1-2\beta_i) + \beta_i(W+1)\left(1-(2\beta_i)^L\right)}$$

where $W$ is the minimum contention window size $CW_{\min}$ and $L = \log_2\left(\frac{CW_{\max}+1}{CW_{\min}+1}\right)$. We use the symbol $\tau'$ to denote a relative probability that a packet transmission is not affected by the hidden nodes and $\alpha'$ is the overall probability of node $n_{i+1}$ expecting a transmission from node $n_i$.

$$\alpha_i' = \rho_i\tau_i' = \rho_i(1-\theta_i)\tau_i''$$

Suppose $\theta_i$ is the fraction of transmission attempts from hidden nodes to all nodes in $S_{CS}(n_i)^+$. We compute it by:

$$\theta_i = \frac{1-\prod_{k\in S_{cs}(n_i)\cap\overline{S_{cs}(n_{i+1})^+}}(1-\alpha_k)}{1-\prod_{k\in S_{cs}(n_i)^+}(1-\alpha_k)}(1-\psi_i)$$

However, node $n_{i+1}$ cannot successfully receive every packet that $n_i$ transmits. So, there is a probability that $n_{i+1}$ can receive and demodulate the packet from $n_i$. The probability of the successful reception is $1-\beta_i$, thus

$$\begin{aligned} 1-\beta_i = (1-\delta_i)&\prod_{k\in S_{cs}(n_{i+1})^+\cap S_{cs}(n_i)}(1-\alpha_k) \\ &\prod_{j\in S_{cs}(n_{i+1})\cap\overline{S_{cs}(n_i)^+}}(1-\alpha_j)^{\psi_i V^{BASIC}} \\ &\prod_{h\in S_I(n_i)\cap\overline{S_{cs}(n_{i+1})^+}}(1-\alpha_h)^{\psi_i V^{ACK}} \end{aligned}$$

where $V^*$ is the vulnerable period in unit of slots, during which transmission from $n_i$ to $n_{i+1}$ might fail because of potential interference from hidden nodes. It is categorized as:

$$\begin{aligned} V^{Basic} &= TS \\ V^{RTS/CTS} &= RTS + SIFS \\ V^{ACK} &= ACK \end{aligned}$$

$\delta_i$ is the fraction of the transmission attempts from nodes in $S_{CS}(n_{i+1})$ that are hidden from node $n_i$ to the transmission attempts from all nodes in $S_{CS}(n_{i+1})$, it can be calculated the same as $\theta_i$

$$\delta_i = \frac{1-\prod_{k\in S_{cs}(n_{i+1})\cap\overline{S_{cs}(n_i)^+}}(1-\tau_k)}{1-\prod_{k\in S_{cs}(n_{i+1})^+}(1-\tau_k)}(1-\psi_i)$$

Now, we obtain the final successful transmission probability $\tau_i$ given that $n_i$ has a packet to transmit.

$$\tau_i = (1-\beta_i)\tau_i^{'} = (1-\theta_i)(1-\beta_i)\tau_i^{''}$$

So, $\rho_i\tau_i$ will denote the overall probability of a successful transmission of $n_i$, which we use symbol $\alpha_i$ to represent,

$$\alpha_i = \rho_i\tau_i = \rho_i(1-\beta_i)\tau_i^{'} = \rho_i(1-\theta_i)(1-\beta_i)\tau_i^{''}$$

In order to figure out how many successful transmissions have made during two successive successfully transmitted packets of $n_i$, we denote by $\gamma_i$ the probability when the next transmission is a successful transmission given that a successful transmission has already achieved. So,

$$\gamma_i = \frac{\tau_i}{\left(\sum_{k\in S_{cs}(n_i)} \alpha_k\right) + \tau_i}$$

Then we will focus on total average amount of the collision probability. Suppose $A_i$ is a random variable which is the average amount of successful transmissions by other nodes in $S_{CS}(n_i)$ between two successive transmissions by $n_i$.

$$E[TU_i] = E\left[\sum_{k=0}^{A_i} t_{k,i}\right] = E[A_i]E[t_{k,i}]$$

Here, the independence between $A_i$ and $t_{k,i}$ is assumed, where $t_{k,i}$ is the time used by the $k$ th successful transmission of a node in $S_{CS}(n_i)$. Then,

$$E[A_i] = \frac{1-\gamma_i}{\gamma_i} = \frac{1}{\gamma_i} - 1 = \frac{\sum_{k\in S_{cs}(i)} \alpha_k}{\tau_i}$$

and

$$E[t_{k,i}] = \sum_{j\in S_{cs}(n_i)} \left( \frac{\alpha_j}{\sum_{k\in S_{cs}(n_i)} \alpha_k} Ts \right)$$

We can get the final $E[TU_i]$:

$$E[TU_i] = \frac{\sum_{k\in S_{cs}(i)} \alpha_k}{\tau_i} \cdot \sum_{j\in S_{cs}(n_i)} \left( \frac{\alpha_j}{\sum_{k\in S_{cs}(n_i)} \alpha_k} Ts \right)$$

$$= \frac{1}{\tau_i} \sum_{j\in S_{cs}(n_i)} \left( \frac{\sum_{k\in S_{cs}(n_i)} \alpha_k \alpha_j}{\sum_{k\in S_{cs}(n_i)} \alpha_k} Ts \right)$$

$$= \frac{1}{\tau_i} \sum_{j\in S_{cs}(n_i)} (\alpha_j Ts)$$

3.1.4 $E[TC_i]$

$E[TC_i]$ is the average time period spent in collisions regardless of whether node $n_i$ is involved or not. In other words, in order to transmit one packet successfully, we can estimate how many collisions will happen within $n_i$'s CS range on the average. There are two types of events that can induce $E[TC_i]$: A successful transmission by $n_i$ or a collision occurs involved in $S_{CS}(n_i)$. Then we denote by $x_i$ the probability that a successful transmission is made by $n_i$ given that at least one node in $S_{CS}(n_i)$ has transmitted. Then,

$$x_i = \frac{\tau_i}{1-(1-\tau_i^{'}) \prod_{k\in S_{cs}(n_i)} (1-\alpha_k^{'})}$$

$y_i$ is the probability that a collision occurs in $S_{CS}(n_i)$ given that at least one node within $n_i$'s CS range has attempted a transmission already. Then,

$$y_i = 1 - \frac{\left(\sum_{k\in S_{cs}(n_i)} \alpha_k\right) + \tau_i}{1-(1-\tau_i^{'}) \prod_{k\in S_{cs}(n_i)} (1-\alpha_k^{'})}$$

The number of unsuccessful transmission attempts that can be known by $n_i$ between its two successful transmissions is a geometric distribution with parameter $\frac{x_i}{x_i+y_i}$. Then the average time spent in the collisions between two successive transmissions by $n_i$ is given by $n_i$,

$$E[TC_i] = \frac{y_i}{x_i} Tc$$

$$= \frac{1-\tau_i - \left(\sum_{k\in S_{cs}(i)} \alpha_k\right) - (1-\tau_i^{'}) \prod_{k\in S_{cs}(i)} (1-\alpha_k^{'})}{\tau_i} Tc$$

Here $T_C$ is the time wasted for each collision. It can be calculated by the parameters in the IEEE802.11 standard for basic and RTS/CTS modes, respectively:

$$T_c^{Basic} = PHY + MAC + Payload + DIFS$$
$$T_c^{RTS/CTS} = RTS + DIFS$$

After analysis, we get the same number of equations as the number of nodes in all the flows, and equations are numerical solvable by fixed point solution.

3.1.5 Calculation for Multiple Flows

The calculation for multiple flows follows the same procedure. What we need to do is accurately analyze the CS neighbor and interference neighbor nodes of each node, including not only the nodes in the same flow, but also the the nodes in other flows.

From the example, in the Fig. 2(a), between two flows, the red line means CS relationship, and the dash lines means nodes are in interference relationship. Node $n_{m,1}$ in flow $F_m$ has $S_{CS}(n_{m,1})$ set $\{n_{m,0}, n_{m,2}, n_{n,2}\}$. Note that even node $n_{n,2}$ should be included in $S_{CS}(n_{m,1})$, while $S_{CS}(n_{n,2})$ is $\{n_{n,1}, n_{n,3}, n_{m,1}\}$ as well. Also, interference relationship set $S_I(n_{m,1})$ must contain $n_{n,1}$ and $n_{n,3}$. After we get the relationship sets, by the modeling procedure, and calculation of massive equations, throughput of each flow can be obtained.

3.1.6 Calculation for WMNs with Multi-Channel

By using multi-channel technique, nodes can work in different orthogonal channels, so channel competition and interference between nodes can be eliminated and significantly performance improvement may be achieved. Simply our modeling can adapt to this scenario much easily. The calculation procedure will change little. In the Fig. 2(b), in the same topology as Fig. 2(a), nodes are working in channels from 1 to 4, which are denoted near the links, and links with different channels are in different colors. If we assume each node have multiple radios that respectively carrying channels, node $n_{m,1}$ in flow $F_m$ has an empty set $S_{CS}(n_{m,1})$, and $S_{CS}(n_{n,2})$ is empty as well, since the potential neighbors are adjusted to different channel, then they will have no channel competition at all. Interference relationship set $S_I(n_{m,1})$ will contain $n_{n,1}$ but no $n_{n,3}$, since $n_{n,3}$ will work in channel 3. Then, after we get the accurate relationship sets, the same calculation procedure will be processed.

## 4. Modeling-based Route Selection

Based on our modeling method, we propose one general route selection method for efficient route selection, so called modeling-based route selection algorithm. Our algorithm is combined with any general routing protocols, such as AODV, DSR and so on. We illustrate our method as shown in Fig. 3.

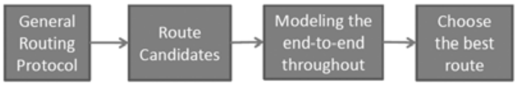
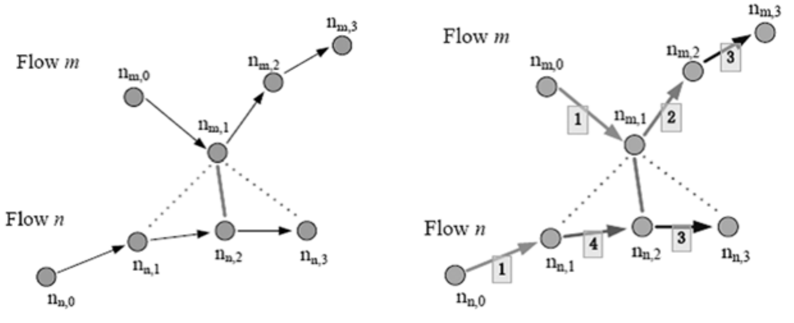



Fig. 3 Method of Modeling-based Route Selection

Firstly we need to obtain multiple route candidates from the routing protocol, which requires modification of routing layer. After the generation of multiple route candidates, based on our modeling methodology, we theoretically calculate the estimation of end-to-end throughput of each candidate based on the pattern of existing flows in the topology. Finally we select the best route that can achieve the maximal end-to-end throughput as the result of routing.

Fig. 4(a) shows an existing flow $n$ and two other flow routes $m$ and $p$ established by general routing




(a) Single Channel (b) Multi-channel

Fig. 2 Modeling Multi-flow and Multi-channel Senarios protocols. Those routes may have various partitions like CS neighborhood, joint and merging. Routing path for flow $m$ and flow $p$ join at $n_{m,3}$ and $n_{p,1}$, and merge to go to each destination. $n_{n,1}$ in flow $n$ will be in the CS range of $n_{m,2}$. In practice, potentially those routes are obtained from general routing protocol based on evaluation of some metrics, but they potentially can't guarantee maximum end-to-end throughput. Fig. 4(b) shows that actually each flow route has multiple candidates, and several candidates are unselected by the routing protocol, as they may have longer hop count or longer round trip time. However those unselected routes may have better performance actually. It is easy to predicate the approximate end-to-end throughput of every candidate route as well as the existing flows by our model. For example, for flow $n$ the route indicated by dash line may have further better end-to-end throughput. Evaluation of our modeling-based route selection by simulation is shown in Section VI.

Based on this modeling-based route selection algorithm, we clarify that when there are multiple flows in the topology, as the route selection is always done by selecting the best route with the maximal end-to-end throughput for the current flow at the present, the system achieves optimal performance in greedy manner from the point of view of end-to-end throughput.

## 5. Simulation for Modeling

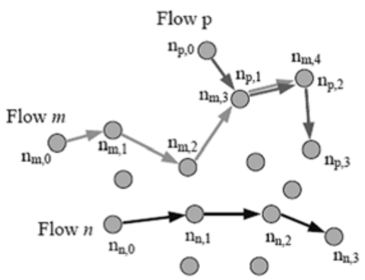
### 5.1 Simulation Parameters

We use QualNet 4.0$^{TM}$ as our simulation platform. Because there is no significant behavioral difference between IEEE 802.11a and 802.11b, the calculations and simulations exactly follow the specification of IEEE802.11a standard. Also, since there will not be essential changes in the modeling procedure in the presence of multiple bit rates from 6Mbps to 54Mbps, we only consider the basic rate, 6Mbps. The transmission range is adjusted to 380 meters and it equals the CS range. All the adjacent nodes are 380 meters apart. The interference range, which means the range of physical HNP, is around 500 meters, about 1.3 times of the CS distance. The UDP datagrams following a Poisson arrival pattern is utilized to validate our probabilistic analysis. The basic DCF scheme without RTS/CTS is tested, as RTS/CTS won't matter the modeling and the performance significantly.

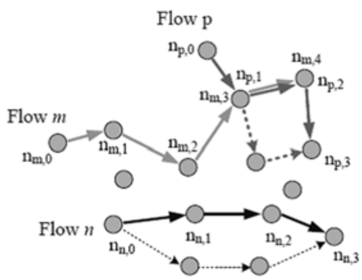
As shown in Fig. 5, the throughput before the threshold (called sustainable throughput) is the same as input traffic load. After the input load exceeds the threshold, the flow will have a high packet loss rate. In the analytical curve, the upper boundary is calculated by our model, and then end-to-end throughput is approximated by the line shown in right figure. In the following we will show the comparison between the simulation results with our analytical results.

### 5.2 Scenarios with a single flow

The simplest scenario is with one single straight flow. The topology is shown as Fig. 6(a), and the hop count varies from 3 hops to 20 hops. Also, we tested one zigzag flow which will experience more intra-flow channel competition and HNPs than straight flows, as shown in Fig. 6(b). The histogram demonstrates the boundaries that we



(a) Normal Routing Paths



(b) Modeling Candidate Routes

Fig. 4 Example of Modeling-based Route Selection

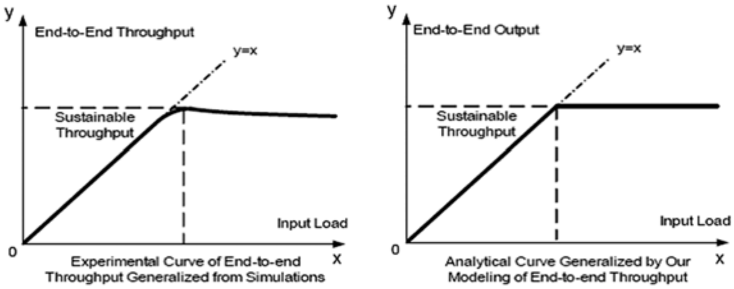



Fig. 5 End-to-end Throughput of Flows (Simulation v.s. Modeling)

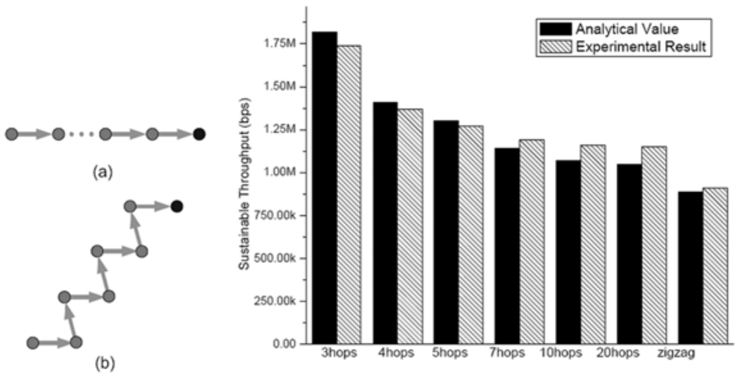



Fig. 6 Topology and Simulation Results of Single Flow

calculated by theoretical modeling fit the turning points of the simulation curves.

### 5.3 Scenarios with two flows

Diverse traffic patterns of two flows are evaluated in this part. Firstly there are two flows going concurrently and we adjust the distances between intermediate nodes of the two flows, in order to make one or two pairs of nodes be located in each other's interference range and CS range, respectively. Fig. 7(a,b,c,d) show those topologies. Note that in each topology, a dot line indicates interference, and a round circle is the transmission range as well as the CS range. As we can see from the comparison the modeling method can provide very accurate analytical value compared with practical simulation results in these scenarios.

Traffic patterns of parallel flows are likely to be common in WMNs. Four different topologies with parallel flows in Fig. 7 are evaluated. Firstly, the distance between two parallel flows is adjusted to be

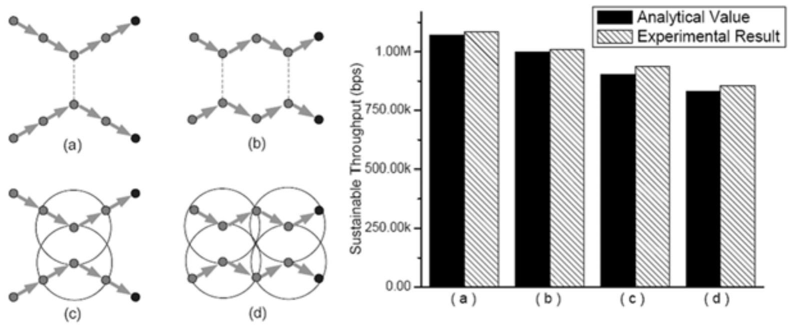



Fig. 7 Topology and Simulation Results of Two Flows

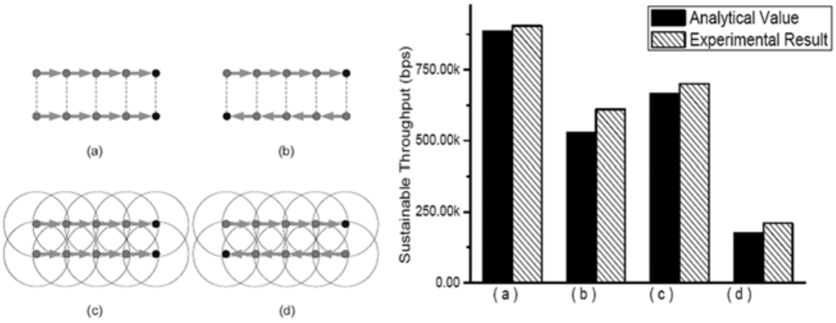



Fig. 8 Topology and Simulation Results of Parallel Flows

equal to the interference range. And the flows in same and opposite directions are tested. Then the distance between the two flows is adjusted to be the same as the CS range, which means nodes will suffer channel competition instead of interference.

Finally we found that the parallel traffic flows achieve poor throughput in WMNs, since there are many hidden nodes. And the situation becomes worse if two flows are going in opposite direction. The reason is that the last node of one flow suffers from the first node of the other flow, which is always trying to make transmissions. We should avoid this kind of topology in traffic engineering.

The crossing flows can frequently happen in reality. We test 3 crossing traffic patterns, as shown in Fig. 9. Topology in Fig. 9(a) shows that two flows rendezvous at the gateway, and Fig. 9(b) and (c) show two flows merge at an intermediate router and have common sub-path to the same gateway. The nodes near the rendezvous point in Fig. 9(b) are hidden to each other, and the ones near the rendezvous point in Fig. 9(c) are within the CS range each other.

Obviously topology in Fig. 9(b) performs much better than that in Fig. 9(c). Since the joining nodes are in each other's CS range, the joining communication can be organically made. If joining nodes in each flow are hidden to each other, the performance at the joint will be seriously bad. Therefore, in topology and routing design, we should avoid joint, however, if we have to make joint path for flows, we'd better make the nodes near to the joint nodes in each other's CS range.

### 5.4 Scenario with multiple flows and multiple gateways

We investigate very large scale WMNs with multiple gateways and multiple flows. Fig. 10 shows one simulation with 5 flows and 2 gateways. Thin dot line means relationship of interference and thick dot line means relationship of CS.

After observation and calculations of highly combined 25 equations, we compute the values: the boundaries of the end-to-end throughput of flows match the experimental curves well as shown in Fig. 11.

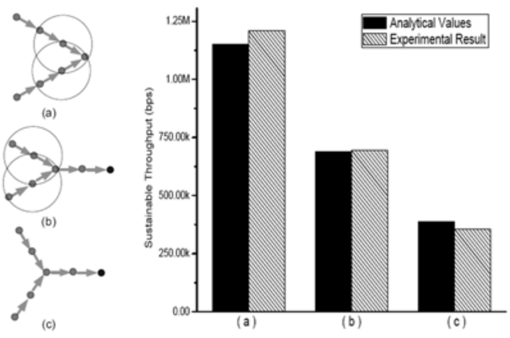



Fig. 9 Topology and Simulation Results of Joint Flows

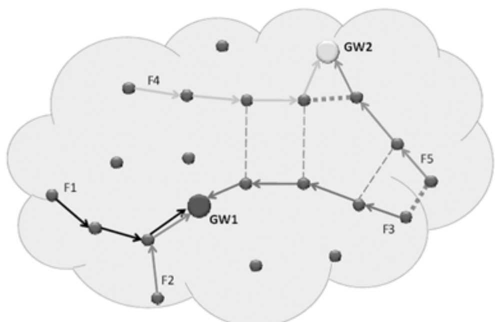



Fig. 10 Scenarios with Multiple Flows and Multiple Gateways

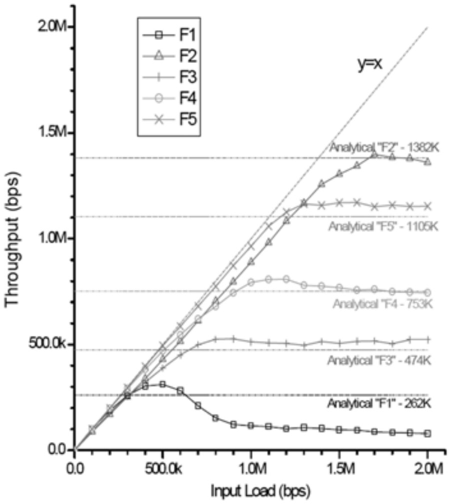



Fig. 11 Results of Scenario with Multiple Flows and Multiple Gateways

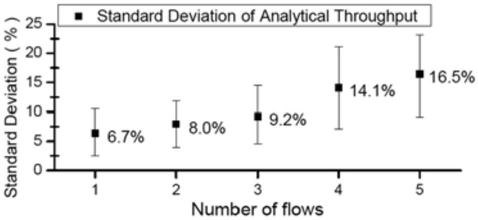



Fig. 12 Standard Deviation of Analytical Throughput on Multiple Flows

Plenty of various scenarios of random topology with 1 to 5 flows are tested in order to calculate the standard deviation of the analytical end-to-end throughput to the experimental results, which is showed in Fig. 12. We use the percentage of standard deviation to the realistic results then we see the modeling calculation can accurately represent the achievable end-to-end throughput of multiple flows. As the amount of flows increases, the standard deviation increase too, since there are more and more interference and huge amount of equations induce unstable roots. In the situations with 5 flows, it is around 16.5% which is still acceptable.

## 6. Evaluation of Routing Paths Selection

We simulated the discussed scenario of modeling-based route selection from Section VI. In Fig. 13, we compare the original throughput of the flows without applying our modeling selection method, analytical calculated throughput of our modeling on the other route candidate, and the throughput of simulation after our modeling selection method. The Fig. 14 shows the comparison, where we can see that, by modeling-based route selection, more efficient route paths, $n_{n,0}$, $n_{n,1}$, $n_{n,2}$, $n_{n,3}$ for flow $F_n$, $n_{p,0}$, $n_{p,1}$, $n_{p,2}$, $n_{p,3}$ for flow $F_p$, are selected which can induce very significant improvement of end-to-end throughput of flows. Flow $n$ selects another route to avoid the CS relationship with flow $m$ at node $n_{m,2}$, then achieves 41% higher throughput. Flow $p$ also gain 16% improvement by changing its route from emerging with flow $m$ to just across with flow $m$. Even the existing flow $m$ can slightly raise its throughput. The modeling-based predication therefore is effective to select efficient routing paths for multiple flows.

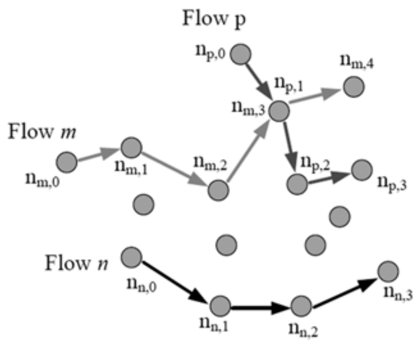



Fig. 13 Modeling-based Route Selection of Multiple Flows

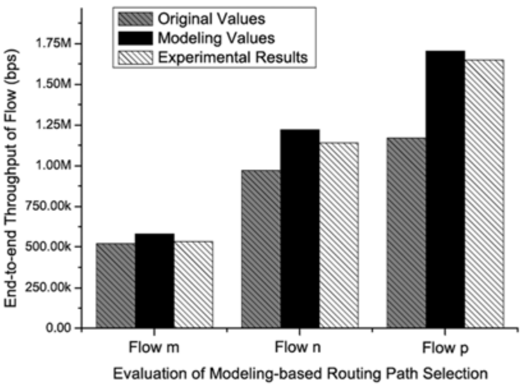



Fig. 14 Throughput Comparison of Modeling-based Route Selection Method

## 7. Conclusions and Future Work

In this paper, we proposed a method to select more efficient routing paths by modeling the end-to-end throughput of multiple candidate paths for flows. We analyze the average service time for successful transmission at each node to pinpoint the bottleneck nodes. After several candidate paths are created by general routing protocol, our proposed modeling method can be applied to get maximum end-to-end throughput of concurrently ongoing flows, then the most efficient routing path can be recommended to routing agent therefore improve the whole end-to-end throughput performance of the flows in WMS system. We carried out the simulations to validate the proposed modeling and routing path selection method, and the performance improvement is significant. In future, we will extend our methodology more effectively and accurately, consummate a routing protocol based on our method, and hopefully conduct test bed experiments.

## References

[1] Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Specification, IEEE Std. 802.11, 1999.

[2] S. Ray and D. Starobinski, "On False Blocking in RTS/CTS-Based Mul-tihop Wireless Networks," *IEEE Transactions on Vehicular Technology*, vol.56, no.2, March 2007.

[3] J.K. Lee, W.H. Kim, S.J. Lee, D.H. Jo, J.H. Ryu, T.K. Kwon and Y.H. Choi, "An Experimental Study on the Capture Effect in 802.11 Networks," *in Proc. of WinTECH*, 2007.

[4] G. Bianchi, "Performance Analysis of the IEEE 802.11 Distributed Coordination Function," *IEEE Journal On Selected Areas In Communications*, vol.18, no.3, March 2000.

[5] K. Duffy, D. Malone, and D. J. Leith, "Modeling the 802.11 Distributed Coordination Function in Non-saturated Conditions," *IEEE Communications Letters*, vol.9, no.8, pp.715-717, 2005.

[6] Mukesh M. Hira, F.A. Tobagi, "Throughput Analysis of a Path in an IEEE 802.11 Multihop Wireless Network," in *Proc. Of IEEE WCNC*, 2007.

[7] Y. Gao, D.M. Chiu, John C.S. Lui, "Determining the End-to-end Throughput Capacity in MultiHop Networks: Methodology and Applications," in *Proc. Of ACM SIGMETRICS*, pp. 39-50, 2006.

[8] T. Salonidis, M. Garetto, A. Saha and E. Knightly, "Identifying High Throughput Paths in 802.11 Mesh Networks: a Model-based Approach," *IEEE International Conference on Network Protocol, ICNP2007*, pp.21-30, 2007.

[9] M. Timmers, S. Pollin, A. Dejonghe, L. Van der Perre, F. Catthoor, "Throughput Modeling of Large-Scale 802.11 Networks," *IEEE Global Telecommunications Conference, GLOBECOM 2008*, pp.1-6, 2008.

[10] B. Wang, F. Song, S.D. Zhang, H.K. Zhang, "Throughput Modeling Analysis of IEEE 802.11 DCF Mechanism in Multi-Hop Non-Saturated Wireless Ad-Hoc Networks," in *Proc. Of International Conference on Communications Circuits and Systems, ICCCAS 2008*, pp.383-387, 2008.

[11] X.H. Ge, D. Yan, Y.T. Zhu, "Throughput Model of IEEE 802.11 Networks with Capture Effect," in *Proc. Of International Conference on Wireless Communications, Networking and Mobile Computing, WiCOM 2006*, pp.1-4, 2006.

[12] R. Khalaf, I. Rubin, J. Hsu, "Throughput and Delay Analysis of Multihop IEEE 802.11 Networks with Capture," in *Proc.of IEEE International Conference on Communications, ICC2007*, pp.3787-3792, 2007.

[13] J.K. Lee, S.J. Lee, W.H. Kim, D.H. Jo, T.K. Kwon and Y.H. Choi, "RSS-based Carrier Sensing and Interference Estimation in 802.11 Wireless Networks," in *Proc. of the IEEE SECON*, 2007.

왕 효 비

2006년 화중과기대학교 컴퓨터학과 졸업 2008년 서울대학교 컴퓨터공학부 석사 2008년~현재 서울대학교 컴퓨터공학 박사. 관심분야는 무선 메쉬 네트워크 라우팅, 트래픽 분석, 미래 모마일 인터넷 서비스

권 태 경

1993년 서울대학교 컴퓨터공학과 졸업. 1995년 서울대학교 컴퓨터공학과 석사. 2000년 서울대학교 컴퓨터공학과 박사. 2002년~현재 서울대학교 전기컴퓨터공학부 교수. 관심분야는 센서 네트워크, 무선 메쉬, 유비쿼터스 컴퓨팅, 미래 인터넷

최 양 희

1975년 서울대학교 전자공학과 졸업. 1977년 한국과학기술원 전자공학과 석사. 1984년 프랑스 ENST 전산학 박사. 1991년~현재 서울대학교 전기컴퓨터공학부 교수 관심분야는 미래 인터넷,멀티미디어 통신