Modeling End-to-End Throughput of Multiple Flows in Wireless Mesh Networks

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***Abstract*—Wireless Mesh Networks (WMNs) have gained a lot of attention recently. Due to the characteristics as an infrastructure, many efforts are made in order to improve or guarantee throughput in WMNs. In this paper, we propose a general modeling methodology to analyze the end-to-end throughput of multiple concurrent flows. We take into account the carrier sensing behaviors, interference and the IEEE 802.11 Distributed Coordination Function mechanism. By probabilistically calculating the average service time for each successful transmission at each node, we analyze the bottleneck throughput of each flow, and hence obtain the achievable end-to-end throughput. We carry out simulation experiments with various traffic patterns of multiple flows in WMNs to validate our modeling.**

***Index Terms*—Multi-Flow, End-to-End Throughput, Wireless Mesh Network**

I. Introduction

Recently, Wireless Mesh Network (WMN) systems based on the IEEE 802.11 WLAN technology [1] have been proliferated rapidly. The 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 their clients. Routers are intermediate mesh nodes that relay data to the gateway, which is connected to the Internet.

The performance of a WMN system is significantly limited by the broadcast nature of the wireless medium. A node has to compete with others within its carrier sensing (CS) range for data transmission. This operation is called channel competition. In IEEE 802.11a/b/g 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), exposed node problem and so on. HNP is mainly caused by the ignorance of the transmissions outside the CS range. There are two kinds of he HNPs: (1) protocol level HNP and (2) physical level HNP. 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. The protocol level and physical level HNPs are detailed later.

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. But in realistic scenarios, analyzing throughput of multiple concurrently ongoing flows is viable to evaluate the topology design, routing strategy, and resource allocation. Our contribution is to model the end-to-end throughput of multiple communication flows in WMN systems.

The rest of this paper is organized as follows: In Section II, we will briefly introduce the constraints of throughput in WMNs. In Section III, we will explain preliminary definitions and the proposed modeling procedure in detail. In Section IV, we carry out comprehensive simulation experiments in order to evaluate our modeling. In Section V, our work will be concluded and future work will be briefly mentioned.

II. Background

A. Fundamental Constraints of WMNs

WMN systems mainly suffer from three fundamental constraints: channel competition by the CS mechanism, protocol level HNP that RTS/CTS can solve, and physical level HNP that cannot be handled by RTS/CTS.

1) Channel Competition: In WMN systems, a node has to compete to occupy the channel to transmit a packet. In IEEE 802.11a/b/g, the Distributed Coordination Function (DCF) based on CSMA/CA is used for nodes to share the common channel. 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 or signaling cost/hazards.

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 a receiver but not in the CS range of a sender. People developed the RTS/CTS mechanism in order 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 [8].

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 signal 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. Capture Effect [6] 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.

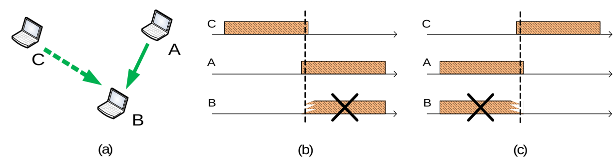

Fig. 1. Interference Relationship

We demonstrate interference and capture effect in our modeling as shown in Figure.1 , where our focus is on the packet from A 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 (both protocol level HNP and physical level HNP). With the above the simple 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.

B. Current Related Work

Realistic modeling of WMN systems is crucial for further WMN resource management, such as channel allocation, dynamic routing, load balancing, adjustment of topology and so on. Bianchi [3] initially proposed the basic analysis on DCF for saturated traffic case in infrastructure mode WLANs. Ken Duffy's Model [2] 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 [5] 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 [4] presented the probabilistic analysis of the link throughput. It considers multiple flows from the perspective of links, not of nodes. 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.

III. Modeling and Analysis

A. Preliminaries

In our analysis and modeling, a homogeneous WMN with one channel is assumed. Static routing is used, since we consider the throughput analysis of the predefined paths. If there are concurrently multiple interferers, our model considers interference signals one by one, not the cumulative interference.

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. If we adjust the input traffic load to be equal to the capacity of the bottleneck node, the maximum end-to-end throughput of this flow can be obtained.

In a WMN, there are total N concurrently ongoing flows, denoted by $F_i, i \in \{1, 2, \ldots, N\}$. 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, $j \in \{0, 1, \ldots, M_i\}$. $n_{i,0}$ 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 [7]).

We first focus on the analysis and modeling of one single flow in the WMN. Suppose a flow F_x spans over M_x hops, and hence 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 ρ_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,

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

where λ_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:

$$E\left[T_i\right] = T_s + E\left[TBackoff_i\right] + E\left[TU_i\right] + E\left[TC_i\right] \tag{2}$$

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 or not.

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.

$$\begin{array}{ll} T_s^{Basic} & = MAC + PHY + Payload + \\ & \quad SIFS + ACK + DIFS \\ T_s^{RTS/CTS} & = RTS + SIFS + CTS + SIFS \\ & \quad + MAC + PHY + Payload \\ & \quad + SIFS + ACK + DIFS \end{array} \tag{3}$$

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

$$E\left[TBackoff_i\right] = \sum_{n=0}^{m} \left(\frac{CW_n}{2}\sigma\right) \beta_i^n \tag{4}$$

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}. σ is the time slot duration specified by IEEE802.11 standard (e.g. IEEE802.11a, it is 9μs). Therefore, if we define ψ_i as the fraction of time that node i spent in backoff between two successive successful transmissions. It can be calculated as

$$\psi_i = \frac{E\left[TBackoff_i\right]}{Max_{j<i}\left(E\left[T_i\right]\right)} \tag{5}$$

3) $E[TU_i]$: From Bianchi's modeling, given the collision probability β_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 τ'',

$$\tau_i'' = \frac{2\left(1-2\beta_i\right)}{W\left(1-2\beta_i\right) + \beta_i\left(W+1\right)\left(1-\left(2\beta_i\right)^L\right)} \tag{6}$$

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 τ' to denote a relative probability that a packet transmission is not affected by the hidden nodes and α' is the overall probability of node n_{i+1} expecting a transmission from node n_i.

$$\alpha_i' = \rho_i \tau_i' = \rho_i \left(1-\theta_i\right) \tau_i'' \tag{7}$$

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

$$\theta_i = \frac{1 - \prod_{k \in S_{cs}(n_i) \cap \overline{S_{cs}(n_{i+1})^+}} \left(1-\alpha_k\right)}{1 - \prod_{k \in S_{cs}(n_i)^+} \left(1-\alpha_k\right)} \left(1-\psi_i\right) \tag{8}$$

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

$$\begin{array}{l} 1-\beta_i = \left(1-\delta_i\right) \prod_{k \in S_{cs}(n_{i+1})^+ \cap S_{cs}(n_i)} \left(1-\alpha_k\right) \\ \qquad \prod_{j \in S_{cs}(n_{i+1}) \cap \overline{S_{cs}(n_i)^+}} \left(1-\alpha_j\right)^{\psi_i V^{Basic}} \\ \qquad \prod_{h \in S_I(n_i) \cap \overline{S_{cs}(n_{i+1})^+}} \left(1-\alpha_h\right)^{\psi_i V^{ACK}} \end{array} \tag{9}$$

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 can be categorized as

$$\begin{array}{l} V^{Basic} = TS \\ V^{RTS/CTS} = RTS + SIFS \\ V^{ACK} = ACK \end{array} \tag{10}$$

δ_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 as similar to θ_i

$$\delta_i = \frac{1 - \prod_{k \in S_{cs}(n_{i+1}) \cap \overline{S_{cs}(n_i)^+}} \left(1-\tau_k\right)}{1 - \prod_{k \in S_{cs}(n_{i+1})^+} \left(1-\tau_k\right)} \left(1-\psi_i\right) \tag{11}$$

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

$$\tau_i = \left(1-\beta_i\right) \tau_i' = \left(1-\theta_i\right)\left(1-\beta_i\right) \tau_i'' \tag{12}$$

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

$$\alpha_i = \rho_i \tau_i = \rho_i \left(1-\beta_i\right) \tau_i' = \rho_i \left(1-\theta_i\right)\left(1-\beta_i\right) \tau_i'' \tag{13}$$

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

$$\gamma_i = \frac{\tau_i}{\left(\sum_{k \in S_{cs}(n_i)} \alpha_k\right) + \tau_i} \tag{14}$$

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 successful transmissions by n_i. Then,

$$E\left[TU_i\right] = E\left[\sum_{k=0}^{A_i} t_{k,i}\right] = E\left[A_i\right] E\left[t_{k,i}\right] \tag{15}$$

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

$$E\left[A_i\right] = \frac{1-\gamma_i}{\gamma_i} = \frac{1}{\gamma_i} - 1 = \frac{\sum\limits_{k\in S_{cs}(i)} \alpha_k}{\tau_i} \tag{16}$$

And

$$E\left[t_{k,i}\right] = \sum_{j\in S_{cs}(n_i)} \left(\frac{\alpha_j}{\sum\limits_{k\in S_{cs}(n_i)} \alpha_k} Ts \right) \tag{17}$$

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

$$\begin{aligned} E\left[TU_i\right] &= \frac{\sum\limits_{k\in S_{cs}(i)} \alpha_k}{\tau_i} \cdot \sum_{j\in S_{cs}(n_i)} \left(\frac{\alpha_j}{\sum\limits_{k\in S_{cs}(n_i)} \alpha_k} Ts \right) \\ &= \frac{1}{\tau_i} \sum_{j\in S_{cs}(n_i)} \left(\alpha_j Ts\right) \end{aligned} \tag{18}$$

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,

$$x_i = \frac{\tau_i}{1-(1-\tau_i') \prod\limits_{k\in S_{cs}(n_i)} (1-\alpha_k')} \tag{19}$$

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,

$$y_i = 1 - \frac{\left(\sum\limits_{k\in S_{cs}(n_i)} \alpha_k\right) + \tau_i}{1-(1-\tau_i') \prod\limits_{k\in S_{cs}(n_i)} (1-\alpha_k')} \tag{20}$$

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,

$$\begin{aligned} E\left[TC_i\right] &= \frac{y_i}{x_i} Tc \\ &= \frac{1-\tau_i-\left(\sum\limits_{k\in S_{cs}(i)} \alpha_k\right)-(1-\tau_i') \prod\limits_{k\in S_{cs}(i)} \left(1-\alpha_k'\right)}{\tau_i} Tc \end{aligned} \tag{21}$$

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:

$$\begin{aligned} T_c^{Basic} &= PHY + MAC + Payload + DIFS \\ T_c^{RTS/CTS} &= RTS + DIFS \end{aligned} \tag{22}$$

After analysis, we get the same number of equations as the number of nodes in all the flows, and equations are numerical solvable. This modeling can adapt to multi-channel WMNs easily. During the analysis of the sets of CS and HNPs, we can just put related nodes within the range of the node in the same channel into its related set, and then calculate in the same manner.

5) Calculation for Multiple Flows: The calculation for multiple flows follows the same procedure as single flow. What we need to do is accurately analyze the CS neighbor nodes and interference neighbor nodes of each node, including not only the nodes in the same flow, but also the the nodes in other flows, if they are in related range. From the example in the Figure.2, between two flows, the red line means CS relationship, and the dash lines means nodes are 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 same modeling procedure, and calculation of massive equations, throughput of each flow can be obtained finally.

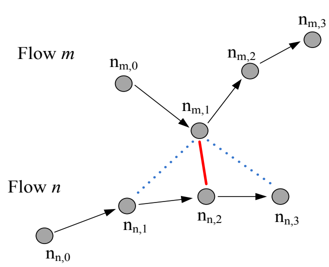

Fig. 2. A Example of Calculation on Multiple Flows)

IV. Simulation and Evaluation

A. 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.

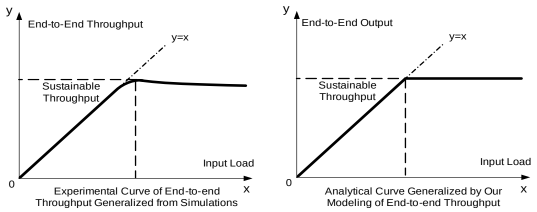

Fig. 3. Average Throughput of All Flows (Simulation on the left and Modeling on the right)

As shown in Figure.3, 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, 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.

B. Scenarios with a single flow

The simplest scenario is with one single straight flow. The topology is shown as Figure.4(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 Figure.4(b).

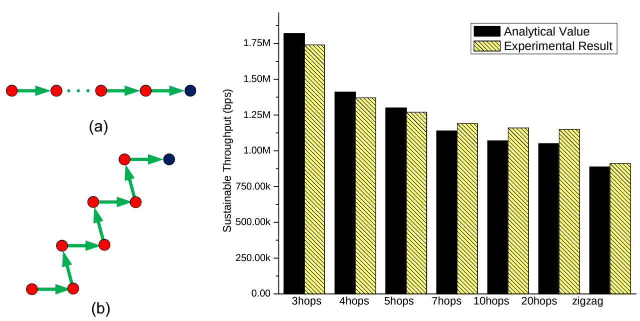

Fig. 4. Topology and Single flow results.

The histogram demonstrates the boundaries that we calculated by theoretical modeling fit the values of the turning points of the simulation results.

C. 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. Figures.5(a), 5(b), 5(c), and 5(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

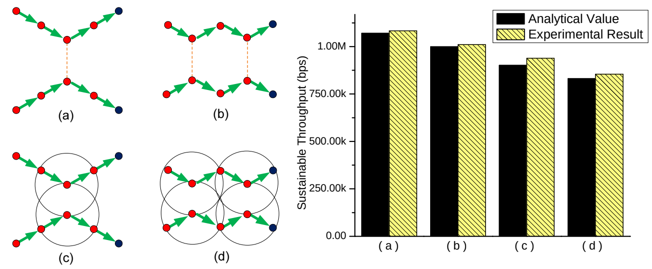

Fig. 5. Topology and Two flow results.

provide very accurate analytical value compared with practical simulation results in these scenarios.

Traffic patterns of parallel flows is likely to be common in WMNs. Four different topologies with parallel flows in Figure.6 are evaluated. Firstly, the distance between two parallel flows is adjusted to be 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.

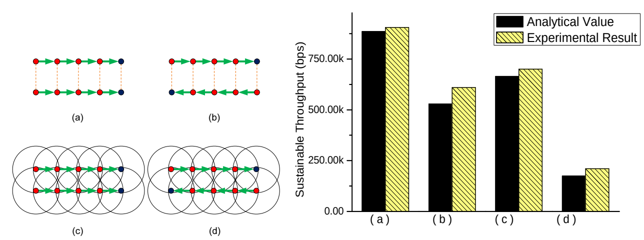

Fig. 6. Topology and simulation results.

The crossing flows can frequently happen in reality. We test 3 crossing traffic patterns, as shown in Figure.7. Topology in Figure.7(a) shows that two flows rendezvous at the gateway, and Figure.7(b) and 7(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 Figure.7(b) are hidden to each other, and the ones near the rendezvous point in Figure.7(c) are within the CS range each other.

From Figure.7, (b) performs much better than (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.

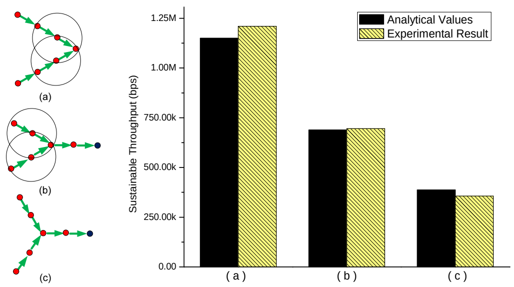

Fig. 7. Topology and simulation results.

D. *Scenario with multiple flows and multiple gateways*

We investigate very large scale WMNs with multiple gateways and multiple flows. Figure.8 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

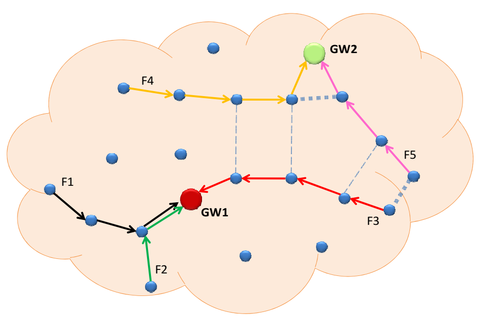

Fig. 8. Scenarios with Multi-Flows and Multi-Gateway

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 Figure.9.

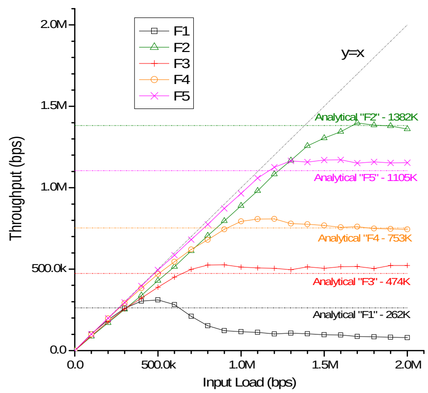

Fig. 9. Results of Scenario with Multi-Flows and Multi-Gateway

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 Figure.10. 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.

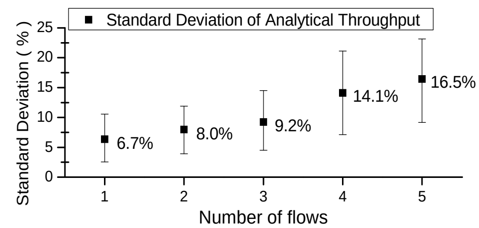

Fig. 10. Standard Deviation of Analytical Throughput on Multiple Flows

V. Conclusions and Future Work

We have presented an analytical methodology to calculate end-to-end throughput of multiple flows in WMNs. We analyze the average service time for successful transmission at each node to pinpoint the bottleneck link. For those purposes, we take into account the collision probability, the CS relationship, and both protocol and physical HNPs. We also carry out the simulations to validate the proposed modeling. In future, we will extend the modeling methodology by considering the capture effect and conduct the testbed experiments to verify the modeling.

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