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ON THROUGPUT OF MULTIPATH DATA TRANSMISSION OVER MULTIHOP AD HOC NETWORKS

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ABSTRACT

Data transmission in ad hoc networks involves interactions between MAC-layer protocol and data forwarding along network-layer paths. These interactions have been shown to have significant effect on system performance. In this paper, their impact on the multipath data transmission system over multihop IEEE 802.11 MAC-based ad hoc networks is studied. An analytical model is developed to demonstrate the mechanism of multipath multihop transmission system. Two methods are proposed to estimate the effect of 802.11 DCF backoff scheme on packet service time in such system. The system throughput is evaluated and its bounds are obtained based on these estimation methods. The model is validated by means of simulation at various scenarios.

KEY WORDS

Multipath transmission, performance analysis, 802.11 MAC protocols, and ad hoc networks

1. Introduction

The IEEE 802.11 [1] standard is the most commonly used MAC layer when multihop ad hoc networks are utilized. The ad hoc operation is supported by its Distributed Coordination Function (DCF) based on the Carrier Sense Medium Access with Collision Avoidance (CSMA/CA) random access scheme. A large part of the existing work on modeling and analysis IEEE 802.11 MAC performance in wireless networks has focused on its throughput, capacity, and delay in WLANs and at single-hop scenarios in ad hoc networks [2-4]. Recently, a growing number of studies on proposing analytical models for evaluating 802.11 characteristics under multihop conditions have been conducted [5-9].

The literature also contains some studies on interactions between 802.11 MAC protocols and network paths in ad hoc networks. The effect of different MAC layer protocols to network routing algorithms is investigated in [10]. The impact of the interactions on the achievable capacity of the MANET is examined in [11]. The path coupling involving these interactions is analyzed in [12]. These studies show that data transmission in ad hoc networks involves the cross-layer interactions between MAC-layer channel access and network-layer data forwarding, and these interactions have significant impact on energy efficiency, throughput and delay in system.

Multipath data transmission has been studied to provide load balance, support multimedia applications, and secure data transmission in ad hoc networks [13-15]. It is the combination of multipath routing and Multiple Description Coding (MDC). Multiple paths are found using multipath routing algorithms and selected according to specified criteria. The source traffic stream composed of data and added fault-recovering redundancy is divided into a number of packetized sub-streams, each of which is transmitted through a different path. A partial reception of any M out of N transmitted packets at receiver can lead to the successful reconstruction of original message. Studies in this area have focused on developing multipath routing algorithms [16] and developing coding schemes for multipath topologies [17].

Recently, the performance analysis of multipath data transmission over multihop ad hoc networks has generated more interest. An analytical modeling framework investigating issues related to multipath transmission in ad hoc networks has been proposed in [18]. However, this work only focuses on the impact of multipath routing on system performance. It does not consider the effect of MAC layer protocols. Some simulation studies on multipath transmission in 802.11-based ad hoc networks have been done from a multi-layer network perspective [19, 14]. Their results show that, although it can guarantee the provided service under some specific conditions, multipath data transmission does not outperform single path transmission and does not necessarily improve quality of applications in 802.11-based wireless networks for most cases.

This paper focuses on throughput evaluation of multipath data transmission system over multihop 802.11 MAC-based multihop ad hoc networks. A model is developed to reflect the impact of 802.11-based multipath transmission on frame service time. Two methods are proposed to quantify this impact. The bounds of throughput are derived. The presented results suggest that the 802.11 MAC affects the performance of such system remarkably.

This study is conducted from a network perspective rather than only focusing on the operation and performance analysis of 802.11 MAC at one single node. To analyze the interactions between MAC layer and network multipath forwarding, the effect of both 802.11 MAC protocols and network layer paths needs to be taken into consideration in system modeling.

This paper has been organized as follows. In Section 2, the multipath transmission system is defined. The analysis model of multipath data transmission system throughput is provided in Section 3. Section 4 validates the model by means of simulation. Concluding remarks are provided in Section 5.

2. System Definition

In this section, the multipath data transmission system is defined and a brief description of the backoff scheme in 802.11 DCF is presented.

It is assumed that the transmission rate of the wireless link is *C* bits/sec. The frames of size D_{size} are assumed to arrive at source with average interval $1/\lambda$. Thus, according to MDC, given *K* paths between a pair of nodes, the source encoder generates packets of size D_{size}/K for *K* flows with average interval $1/(K\lambda)$. The packet service time at source is from the time instant that the packet starts to contend for channel to the time instant that it is either acknowledged for correct reception by intended receiver or dropped after reaching a maximum retransmit limit.

In the RTS/CTS mode of 802.11 MAC protocols, the time one data packet successfully transmitted over one hop is

$$T_{suc} = RTS + CTS + T_d / K + ACK + 3SIFS + DIFS \cdot \tag{1}$$

where T_d corresponds to the transmission time of a data packet with size D_{size}. $T_d = D_{size} / C \cdot$

In a network with 802.11 MAC protocols, if a node desiring to initiate transfer of packet senses the channel as busy, it defers transmission until the end of the ongoing transmission and then initializes its backoff timer, which is decremented everytime the channel is sensed idle. The backoff timer is set to a random interval using the formula

$$T_{BO}(k) = Ramdom(k) \times SlotTime \tag{2}$$

where the Slottime is the system time slot set by the physical layer and *Random(k)* is a pseudo-random integer drawn from a uniform distribution over the interval [0, *CW(k)*]. *Random(k)* is calculated from

$$Ramdom(k) = \mathrm{int}(rnd() \cdot CW(k)) \cdot \tag{3}$$

CW(k) represents the size of contention window for *k-th* transmission attempt. It is an integer within the ranger of CW_{min} and CW_{max}, which are the minimum and maximum contention window sizes respectively. At the *k-th* attempt, *CW(k)* is

$$CW(k) = \min[CW_{\max}, 2^{k-1}(CW_{\min} + 1) - 1] \qquad k \geq 1 \cdot \tag{4}$$

Let *S* represent the backoff stage, the maximum backoff stage is

$$S_m = \log_2[(CW_{\max} + 1)/(CW_{\min} + 1)] + 1 \cdot \tag{5}$$

In the case of a collision, the contending nodes update their backoff timer according to the exponential backoff scheme in 802.11 DCF. The channel then stays busy for a duration T_{col} before the contending nodes start decreasing their backoff timer again.

$$T_{col} = RTS + DIFS \tag{6}$$

In this paper, as the steady-state system throughput is concerned, the long-term characteristics like average service time, instead of the instant characteristics like service time distribution, are investigated. Thus, the backoff timer $T_{BO}(k)$ is represented by its statistic expectation value T_{BO}^{k}, which is obtained from the formula

$$T_{BO}^{k} = \frac{CW(k)}{2} \times SlotTime \cdot \tag{7}$$

The expectation value of backoff time corresponding to the initial contention window CW_{min} is notes as T_{BO}, i.e. $T_{BO} = T_{BO}^{1}$.

The 802.11 standard regulates an insertion of an additional backoff interval after the *CW* value reverts to CW_{min} following a successful transmission even if no additional transmission is currently queued. This assures that the transmitted packets from a user are always separated by at least one backoff interval. This additional backoff time is called *tailing backoff* in [4]. The statistic expectation value of a tailing backoff is T_{BO}.

In the following analysis model, issues of node mobility and multipath routing are not considered. This is primarily because the interest here is to characterize the impact of interactions between MAC and network layers on multipath multihop data transmission system. As long as a set of nodes are within range of each other, their mobility pattern will not change the selected paths. And selecting multiple paths between a pair of nodes is not within the scope of this paper. To concentrate on the multipath multihop system, it is also assumed that no other source station is within the range of the considered source station.

3. Multihop Multipath Modeling

In this section, we develop the model to evaluate throughput of multipath transmission system in 802.11-based multihop wireless networks.

It has been shown in [11] that, ideally, the RTS/CTS-based 802.11 protocols could achieve chain utilization as high as ⅓. If the radios of stations that are not neighbors do not interfere with each other, only stations at least *3* hops away can send out packets at the same time. It can be concluded that a new packet transmission can occur no earlier than the completion of the first *3* hops of previous transmissions [12]. Hence, the minimum time necessary for a data packet of size D_{size}/K to transmit over a multihop path i of hop length $Nhop_i$ is

$$T_{i,m} = \min(3, Nhop_i)T_{suc} \cdot \tag{8}$$

For multiple multihop paths disjoint except for the source and destination, although the transmissions on different paths can occur simultaneously, a transmission along one path within *2* hops from source prevents the source from sending out packets to all paths. Accordingly, it can be concluded that a packet for one path could be transmitted from the source no earlier than the first *3*-hop completion of the previous transmissions on other paths. Hence, given K paths between the source and destination, the hop length of transmission pipeline for a data frame, which is divided into K packets for K flows, is $\sum_{i=1}^{K}\min(3, Nhop_i) \cdot$ The minimum time necessary for a complete frame transmission through all these paths is

$$\sum_{i=1}^{K} T_{i,m} = \sum_{i=1}^{K}\min(3, Nhop_i)T_{suc} \cdot \tag{9}$$

The throughput of multipath multihop system is related to packet service time and traffic load. In the considered model, the packet transmission time is $T_{i,m}$ and the traffic load is represented by the average packet arrival interval $1/(K\lambda)$. Based on their relationship, the system throughput can be analyzed under the following two conditions.

3.1 Under Condition $(T_{i,m} + T_{BO}) < 1/(K\lambda)$

When $(T_{i,m} + T_{BO}) < 1/(K\lambda)$, in which T_{BO} is a tailing backoff, the packet generation rate at source is smaller than the packet transmission rate in system. No packet is dropped due to multiple unsuccessful transmission attempts. Every generated packet is sent out and received successfully. The system throughput is the actual traffic load.

3.2 Under Condition $(T_{i,m} + T_{BO}) \geq 1/(K\lambda)$

Under this condition, the factors such as interference between different paths and packet service time increment due to the 802.11 DCF backoff scheme need to be considered.

As stated above, in an 802.11 RTS/CTS-based multipath multihop system, any transmission at the first 2 intermediate nodes along one path makes the source defer the transmission of next packet and initialize its backoff timer. The packet service time increment along the path i due to the 802.11 DCF backoff scheme is denoted by $T_{BO,i}$.

As two nodes connected with destination D on two different paths are hidden nodes to each other, they cannot forward packets to D simultaneously. This incurs delay at least T_{suc} at one such intermediate node. The total interference delay for K paths is at least $(K-1)T_{suc}$.

Therefore, the total time necessary to transmit a frame over K paths is:

$$T_{frame} = \sum_{i=1}^{K}[\min(3, Nhop_i)T_{suc} + T_{BO,i}] + (K-1)T_{suc} \cdot \tag{10}$$

Within the observation time T_{total}, after the last pipeline cycle and before finish of all work, there is some tail time

$$T_{tail} = \max_{i=1}^{K}(0, Nhop_i - 3)T_{suc} \cdot \tag{11}$$

Therefore, the number of data frames received within T_{total} is

$$D_{rcv} = \frac{T_{total} - T_{tail}}{T_{frame}}, \tag{12}$$

and the system throughput is

$$Throughput = \frac{D_{rcv} \times D_{size}}{T_{total}} bits/\sec \cdot \tag{13}$$

The model shows that the throughput in a multihop multipath transmission system depends on the observation time, the number of paths, the length of each path, and the size of transmitted frames.

The packet service time increment $T_{BO,i}$ is a very important parameter for the model performance. It is related to the number of paths and packet arrival rate in system. In the following, we proposed two methods to estimate its value.

3.2.1 Method1

For a given one-path packet transmission time $T_{i,m}$, a smaller $1/(K\lambda)$, i.e. more packet generated within a time duration, implies more contention for the channel among source and intermediate nodes. Let $Diff_i = T_{i,m} - 1/(K\lambda)$. A larger $Diff_i$ corresponds to more collisions, a larger backoff stage at source and larger packet service time increment $T_{BO,i}$. Thus, $T_{BO,i}$ can be demonstrated by a backoff stage S, which is derived directly from and corresponds to the difference $Diff_i$.

For a path *i*, let s_i^{**} be the maximum backoff stage that makes $\sum_{j=1}^{s_i^{**}} T_{BO}^{j} < Diff_i, \quad 1 \le s_i^{**} \le S_m$, and s_i^{*} be the minimum backoff stage that makes $\sum_{j=1}^{s_i^{*}} T_{BO}^{j} > Diff_i, \quad 1 \le s_i^{*} \le S_m$. As $s_i^{*} = s_i^{**} + 1$, $\sum_{j=1}^{s_i^{*}} T_{BO}^{j} = \sum_{j=1}^{s_i^{**}} T_{BO}^{j} + T_{BO}^{s_i^{*}}$. Then

$$T_{BO,i} = \begin{cases} T_{BO}^{S_i^{**}} & if \quad Diff_i < \sum_{j=1}^{s_i^{**}} T_{BO}^{j} + \dfrac{T_{BO}^{s_i^{*}}}{2} \\ T_{BO}^{S_i^{*}} & if \quad Diff_i > \sum_{j=1}^{s_i^{**}} T_{BO}^{j} + \dfrac{T_{BO}^{s_i^{*}}}{2} \end{cases} . \qquad (14)$$

In this method, $T_{BO,i}$ is approximated by $T_{BO}{}^{k}$, the statistic expectation value of a backoff timer $T_{BO}(k)$. It needs to be mentioned that this estimation does not demonstrate the actual operation of 802.11 backoff scheme and the backoff stage derived from (14) is not the actual backoff stage at source. Actually, the source backoff timer stops decreasing when the channel is sensed busy in 802.11 MAC,

3.2.2 Method2

$T_{BO,i}$ is analyzed according to the operation of 802.11 MAC backoff scheme at source in this method. Based on the relationship between $1/(K\lambda)$ and the packet transmission time, the following four cases are considered.

1. If $(T_{suc}+T_{BO}) \ge 1/(K\lambda)$, i.e. the average packet arrival interval is smaller than the one-hop packet transmission time plus a tailing backoff time, the source needs to contend with $[min(3, Nhop_i) - 1]$ intermediate nodes along path *i* for the channel. The maximum time increment appears when each contention leads to a collision at source. It is

$$T_{BO,i} = T_{add,1} = [\min(3, Nhop_i) - 1]T_{col} + \sum\nolimits_{j=1}^{\min(3,Nhop_i)} T_{BO}^{j} . \qquad (15)$$

2. If $(T_{suc}+T_{BO}) < 1/(K\lambda) < T_{i,m}$, i.e. $1/(K\lambda)$ is larger than the packet transmission time over one hop while smaller than that over one multihop path, the source needs to contend with $[min(3, Nhop_i) - 2]$ intermediate nodes along path *i* for the channel. When $K = 1$. The maximum $T_{BO,i}$ is

$$T_{BO,i} = [\min(3, Nhop_i) - 2]T_{col} + \sum\nolimits_{j=1}^{\min(3,Nhop_i)-1} T_{BO}^{j} \qquad Nhop_i \ge 2 \;. \qquad (16)$$

For $K > 1$, as the source contends with fewer intermediate nodes along path *i*, the interference from the $[min(3, Nhop_i) - 2]$ intermediate nodes along other paths should be considered. The maximum time increment is

$$\begin{aligned} T_{BO,i} = \min\{&T_{add,1}, \\ &T_{BO} + \sum\nolimits_{j=1}^{K} [\min(3, Nhop_j) - 2](T_{col} + T_{BO}^{2})\} \qquad Nhop_j \ge 2 \end{aligned} \qquad (17)$$

3. If $|T_{i,m} - 1/(K\lambda)| \le T_{BO}$, in which T_{BO} is a tailing backoff, the maximum time increment is a tailing backoff following the previous transmission plus an initial contend backoff T_{BO} because of busy channel. It is

$$T_{BO,i} = 2T_{BO} . \qquad (18)$$

4. When the throughput on one path reaches the maximum chain utilization, i.e. the system capacity, all contending nodes are equal. The packet transmission is deferred at source and all intermediate nodes. Then, none of the previous three equations is suitable for getting the time increment. It becomes to be

$$\begin{aligned} T_{BO,i} = &\sum\nolimits_{j=1}^{\min(3,Nhop_i)} [\min(3, Nhop_i) - j](jT_{col} + \sum_{n=2}^{j+1} T_{BO}^{n}) . \\ &+ \min(3, Nhop_i)T_{BO} \end{aligned} \qquad (19)$$

4. Simulation Results and Performance Analysis

The GloMoSim [20] library-based simulator was used to validate the analytically developed system throughput model. In the simulation, each node has a radio power range of *376* meters. The throughput of multipath multihop system is obtained under steady state at different scenarios. The frame arrival interval time $1/\lambda$ is fixed and the frame size D_{size} is changed according to the traffic load. The buffer size at each node is *100*. *10* simulations with different random seeds are implemented. Each simulation runs for *100* seconds to get the steady-state statistic results. The simulation parameters are summarized in Table 1.

Table 1. Simulation Parameters of the 802.11 MAC Protocols.

Parameter	Value
Channel bit rate	2Mb/s
PHY preamble/header	192µs
MAC header	224µs
Packet payload size	128, 256, 512, 1024, 2048bytes
DIFS	50µs
SIFS	10µs
Slot time	20µs
RTS	282µs
CTS	258µs
ACK	298µs
Initial backoff window	31
Maximum backoff stage	5
Short retry limit	7
Long retry limit	4

The considered *20*-node system, shown in Fig. 1, consists of *5* multihop node-disjointed paths from source 0 to destination 1. The hop length of the primary path is *3*. The length of all the other paths is *5*. The system traffic load is varied from *0.1024*Mb/s to *1.6384*Mb/s.

Fig. 2 and Fig. 3 show the system throughputs for different number of paths with $T_{BO,i}$ estimated using Method1 and Method2. The comparisons show that the model gives a precise evaluation of the throughput of 802.11-based multipath multihop system. The statements in the proposed model have been proven to be true by the simulation results. The variances of simulation results obtained using different random seeds are very insignificant.

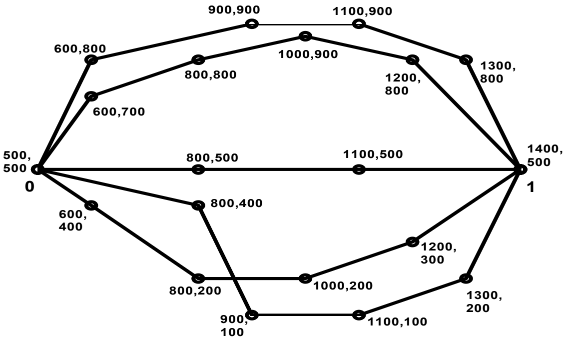
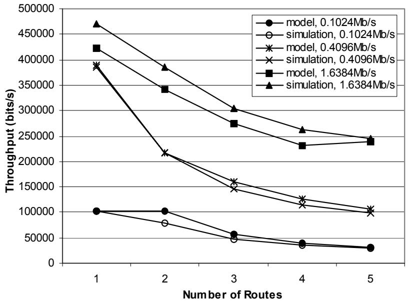
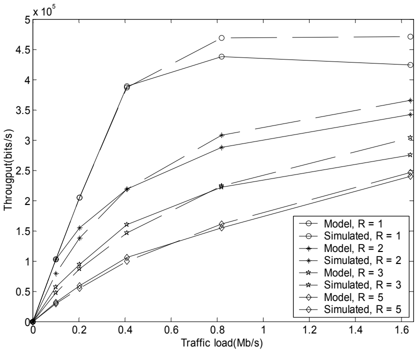


Fig. 1. Topology for multihop multipath model.



(a) Throughput versus number of routes.

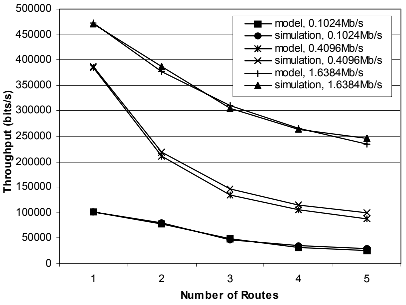


(b) Throughput versus traffic load.

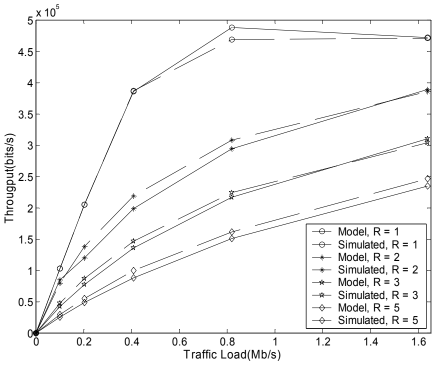
Fig. 2. Throughput using Method 1.

Given the number of paths *K*, the system throughput increases with the traffic load until attains the system capacity. The throughput decreases as *K* increases for a given traffic load. Hence, increasing the number of paths *K* has a negative effect on the throughput of 802.11-based multipath multihop system.

With $T_{BO,i}$ obtained using Method1, the model gives very close throughput estimation for large *K* or light traffic load in Fig. 2. However, since Method1 fails to demonstrate the increasing collisions and longer backoff time when the packet generation rate at source does not significantly exceed the packet transmission rate in system, the model over estimates the throughput. And, as the system utilizes the radio channel in a more efficient way than what Method1 demonstrates for small *K* and heavy traffic load, the model presents an under-estimation of the system throughput at these cases.



(a) Throughput versus number of routes.



(b) Throughput versus traffic load.

Fig. 3. Throughput using Method 2.

Compared to its performance in Fig. 2, the model gives out a better estimation of system throughput in Fig. 3 when $T_{BO,i}$ is obtained using Method2. As the 802.11 cannot discover the optimum transmission schedule on its own, the maximum achievable chain utilization of RTS/CTS-based 802.11 is less than the ideal ⅓ under our simulation setting. When *K=1* and the traffic load is *0.8192*Mb/s, the analytical value with $T_{BO,i}$ obtained from the first three cases is less than the ideal system capacity but has exceeded the actual maximum achievable system capacity. When *K=1* and the traffic load is *1.6384*Mb/s, as the model with $T_{BO,i}$ from (15) gives out a throughput close to the theoretical ⅓ chain utilization, $T_{BO,i}$ is then derived from (19) and the model gives out a throughput close to the simulation result.

The comparison between Fig. 2 and Fig. 3 shows that, while Method1 is simpler, Method2 gives out a better estimation of $T_{BO,i}$. Hence, there is a choice tradeoff between the complexity and the performance of $T_{BO,i}$ estimation.

5. Conclusion

In this paper, the combination of multipath routing and MDC in ad hoc networks has been examined based on IEEE 802.11 MAC protocols. Both analytical and simulation models have been developed to demonstrate the precise mechanism of multipath multihop system. The accuracy of the proposed model has been validated by means of simulations. The model shows that the throughput of multipath multihop system depends on the number of paths, size the frames and the system parameters of MAC protocol.

Multipath data transmission may not be the best way to improve the performance of current and near future ad hoc networks, as long as these networks are based on IEEE802.11 MAC protocols. However, a multipath scheme may be very useful for other purposes such as security and real-time application. To further enhance this study, it may be necessary to include the influence of background traffic.

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