Performance Evaluation of a Unified IEEE 802.11 DCF Model in NS-3

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Abstract. The IEEE 802.11 Distributed Coordination Function (DCF) is a basic component in the medium access control (MAC) protocol of Wireless Local Area Networks (WLANS). Recently, a unified analytical framework has been proposed [1] to capture the fundamental features of IEEE 802.11 DCF networks, which provides various accurate performance predication in NS-2 simulations. In the past a few years, NS-3 is widely considered an emerging and promising network simulator for researchers and engineers to validate their analytical models based on simulation experiments. Similar to NS-2, NS-3 provides a thorough 802.11 PHY and MAC protocol stack, the accuracy of which is, nevertheless, not yet been fully investigated. In this paper, we conduct a performance evaluation study of the unified IEEE 802.11 DCF analytical model in [1] with NS-3. Various network scenarios (distinct conditions, varying system parameters, different access modes and network topologies.) are conducted. The performance evaluation study shows that the theoretical predication closely matches with NS-3 simulation results. This case study implies that not only the theoretical model is a credible model for homogeneous IEEE 802.11 DCF networks but also NS-3 WiFi module can provide 802.11 network simulations as well as NS-2.

Keywords: Performance evaluation · NS-3 · IEEE 802.11 DCF

1 Introduction

Recently, a unified analytical framework has been proposed for IEEE 802.11 DCF networks in [1]. Different from the classic Bianchi's model in [2], the behavior of each Head-of-Line (HOL) packet, including backoff collision, successful transmission, has been captured based on a discrete-time Markov renewal process. This analytical framework has been evaluated using NS-2 simulation experiments, which demonstrates that it is a simple yet accurate model for IEEE 802.11 DCF networks.

Network simulation is a commonly-used methodology for properly producing the behavior of a real system, which plays an indispensable role in communication systems and computer networks owing to its scalability, stability and repeatability. Recently, NS-3 is recognized as an emerging and promising discrete-event

H. Song et al. (Eds.): SIMUtools 2019, LNICST 295, pp. 395–406, 2019.
https://doi.org/10.1007/978-3-030-32216-8_38

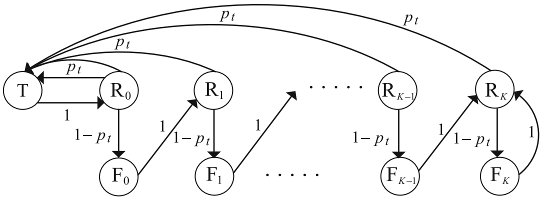


Fig. 1. An embedded Markov chain $\{X_j\}$ of the state transition process of an individual HOL packet in IEEE 802.11 DCF networks [1].

network simulator for students, researchers and developers. Different from the antiquated simulator NS-2, NS-3 has a modular core written in C++, and a Python scripting interface (similar to OTcl in NS-2), which better mimics real systems and supports software integration and updatable models [3]. Based on these excellent features, NS-3 has been achieving momentum in research and education.

NS-3 is instrumented with a detailed model of the MAC layer for the WiFi module, however, there exist very few studies to validate the NS-3 MAC layer model due to its complexity. A number of studies have been conducted to validate of the physical layer and the channel model in NS-3 [4–8]. Patidar et al. reported a preliminary validation study of the MAC layer of NS-3 by varying the number of nodes [9]. Baldo et al. [10] validated the NS-3 MAC model using a testbed. In this paper, we provide a performance evaluation study of the aforementioned unified IEEE 802.11 DCF analytical model proposed in [1] with NS-3. This work can also serve as a validation of the NS-3 MAC implementation for IEEE 802.11 DCF networks from an analytical perspective.

The remainder of this paper is organized as follows. Section 2 describes the major analytical results of the unified framework. Simulation setup is outlined in Sect. 3. Section 4 presents the simulation results including how to tune the NS-3 simulator and discusses the validation between simulation and theoretical analysis. Finally, we conclude the paper in Sect. 5.

2 Validation Setup

In this section, we present the unified analytical framework for IEEE 802.11 DCF networks [1] and outline the expressions of the network sum rate $\hat{D}$ for both unsaturated and saturated network, both the basic access and RTS/CTS modes. We aim to evaluate the accuracy of the NS-3 MAC layer model based on the analytical results obtained based on this model, which has been validated by the well-known NS-2 in [1].

2.1 Analytical Framework for IEEE 802.11 DCF Networks

A unified analytical framework for IEEE 802.11 DCF networks is established to model the behavior of each HOL packet as a discrete-time Markov renewal process in [1]. Figure 1 shows the embedded Markov chain X_i, which denotes the state of a HOL packet at the ith transition including the state of successful transmission T, the state of waiting for request R_i and the state of collision F_i.

In an IEEE 802.11 DCF network, we consider there are n nodes with packet transmissions over a noiseless channel, where each node has an infinite buffer and each head-of-line (HOL) packet has an infinite maximum number of retransmission attempts. Suppose that each node has identical backoff parameters, including the initial backoff window size W and the cutoff phase K. Assume that each node is equipped with a traffic arrival rate of λ. For an unsaturated network in [1], the normalized throughput $\hat{\lambda}_{out}$, which is defined as the percentage of time for successful transmissions, is given by

$$\hat{\lambda}_{out} = n\lambda. \tag{1}$$

In a saturated network, each node always has a packet ready for transmission. As shown in [1], the normalized throughput $\hat{\lambda}_{out}$ is derived as

$$\hat{\lambda}_{out} = \frac{-\tau_T p_A \ln p_A}{1 + \tau_F - \tau_F p_A - (\tau_T - \tau_F) p_A \ln p_A}, \tag{2}$$

where τ_T and τ_F denote the holding times of HOL packets in successful transmission and collision states (in unit of time slots), respectively, and p_A is the non-zero root of the fixed-point equation of the steady-state probability of successful transmission of HOL packets given that the channel is idle, p:

$$p = \exp\left\{ -\frac{2n}{W \cdot \left(\frac{p}{2p-1} + \left(1 - \frac{p}{2p-1}\right) (2(1-p))^K \right)} \right\}. \tag{3}$$

where n is the number of nodes, W is the initial backoff window size, K is the cutoff phase ($K = \log_2(\frac{CW_{\max}}{CW_{\min}})$).

Note that the normalized throughput $\hat{\lambda}_{out}$ evaluates how efficient the time is used for successful transmissions. It, however, does not reflect how much information can be transmitted in terms of bits per second. Therefore, in this paper, we focus on the network sum rates, which is defined as the number of information bits that are successfully transmitted per second. Thus, in an unsaturated network, the network sum rate $\hat{D}$ can be written as

$$\hat{D} = \hat{\lambda}_{out} \cdot \frac{\frac{8PL}{R_D \sigma}}{\tau_T} \cdot R_D = \frac{8PL \cdot n\lambda}{\sigma \tau_T}. \tag{4}$$

from (1), where PL denotes the packet payload length (in the unit of bytes).

For a saturated network, its network sum rate $\hat{D}$ is determined by (1) the normalized throughput $\hat{\lambda}_{out}$, (2) the fraction of time that is used for packet payload transmission in each successful transmission, and (3) the transmission rate R_D. It can then be written from (2)

$$\hat{D} = \hat{\lambda}_{out} \cdot \frac{\frac{8PL}{R_D \sigma}}{\tau_T} \cdot R_D = \frac{-8PL \cdot p_A \ln p_A}{\sigma \left(1 + \tau_F - \tau_F p_A - (\tau_T - \tau_F) p_A \ln p_A\right)}. \tag{5}$$

In the parameter settings of NS-3, when a node encounters a collision, the node will go through a period of ACK time-out or CTS time-out. Therefore, the holding times of successful transmission and collision states of basic access mechanism can be written as

$$\tau_T^{ba} = \frac{(\frac{8PL}{R_D} + \frac{8\text{MH}}{R_D} + 2\text{PH} + \frac{8\text{ACK}}{R_B} + \text{SIFS} + \text{DIFS})}{\sigma} \tag{6}$$

and

$$\tau_F^{ba} = \frac{\frac{8PL}{R_D} + \frac{8\text{MH}}{R_D} + \text{PH} + \text{ACKTimeout} + \text{DIFS}}{\sigma} \tag{7}$$

respectively. R_B denotes the basic rate (in the unit of Mbps). MAC header (MH) and ACK frames are in the unit of bytes. PHY header (PH), DCF interframe space (DIFS) and short interframe space (SIFS) are in the unit of μs.

With the RTS/CTS mode, the holding times in successful transmission and collision states can be written as

$$\tau_T^{rts} = \frac{\frac{8PL}{R_D} + \frac{8\text{MH}}{R_D} + 4\text{PH} + \frac{8(\text{RTS} + \text{CTS} + \text{ACK})}{R_B} + 3\text{SIFS} + \text{DIFS}}{\sigma} \tag{8}$$

and

$$\tau_F^{rts} = \frac{\frac{8RTS}{R_B} + \text{PH} + \text{CTSTimeout} + \text{DIFS}}{\sigma} \tag{9}$$

respectively, where RTS and CTS are in the unit of bytes.

2.2 Comparison Between Dai's Unified Model and the Classic Bianchi's Model

A widely adopted model of IEEE 802.11 DCF networks was proposed by Bianchi in [2], where a classic two-dimensional Markov chain established for the backoff process of each saturated node. The differences between Bianchi's classic model and Dai's unified models are:

(1) In Bianchi's model, it only considers the case where the network is saturated. However, in Dai's model, the performance of both unsaturated and saturated network conditions are studied.
(2) In Bianchi's model, it only focuses on throughput, while a unified analysis of stability, throughput, and delay performance are fully studied in Dai's model. The results of both models are shown to be consistent in the saturated throughput.
(3) Performance analysis of Bianchi' model and a series of its follow-up studies is based on numerical calculation, which, nevertheless, renders difficulties for performance optimization. However, due to the explicit nature of Dai's model, explicit expressions of maximum network throughput and the optimal backoff parameters are derived in both homogeneous and heterogeneous IEEE 802.11 DCF networks in [1,11–14].

(4) Dai's model for homogeneous IEEE 802.11 DCF networks is further extended to various heterogeneous IEEE 802.11 DCF networks in [12–15].

As Bianchi's model is limited to the analysis of saturated network throughput, we introduce Dai's model to fully validate the NS-3 WiFi module. In turn, with the accuracy of Dai's model has been verified in NS-2, we further increase the credibility of Dai's model by the simulations with the NS-3 WiFi module.

3 NS-3 Simulation Setup

In this section, we will first describe the overall architecture of NS-3 WiFi module, and then we will introduce the details of simulation setup.

3.1 NS-3 WiFi Module

An overview of NS-3 WiFi module architecture is shown in Fig. 2. In NS-3 WiFi networks, nodes contain a WifiNetDevice object to hold together WifiChannel, WifiPhy, WifiMac, and WifiRemoteStationManager. When an application initiates transmission, the WifiNetDevice interface sends the packet to WifiMac class which handles high MAC level functions such as different MAC types, beacon, association, and so forth. DcaTxop handles the request access to the channel from DcfManager. When access is granted, DcaTxop pushes the packet to MacLow for initiating data transmission. WifiPhy class is mainly designed to receive packet and tracking energy consumption. WifiChannel is designed to interconnect with the WifiPhy so that packets can be received through the channel.

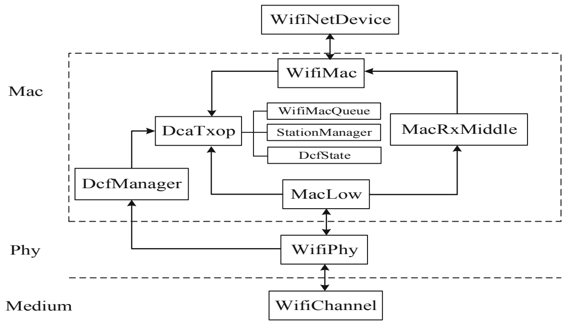


Fig. 2. WiFi module architecture of NS-3 simulator

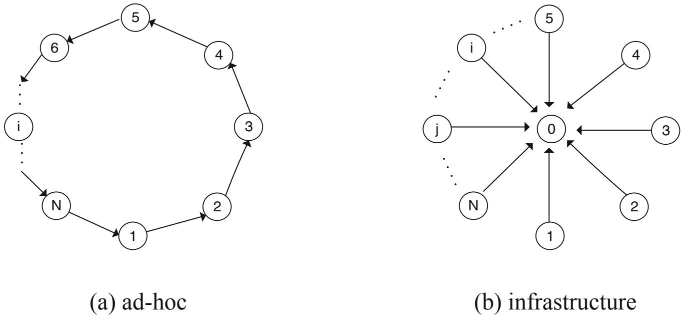


Fig. 3. Network topology

3.2 Simulation Setup

We consider both the ad-hoc mode and the infrastructure mode with varying system parameters to implement detailed comparisons between simulation results and the mathematical model of IEEE 802.11 DCF networks shown in Fig. 3, it is well known that in the infrastructure networks, the access point (AP) needs to continuously transmit a beacon frame to inform the node of the fundamental information in the network and the association between nodes and AP is also necessary. In an ad-hoc network, on the other hand, the additional channel activity due to association (beacon transmission, active scanning etc.) are avoided. Note that we focus only on packet payload transmissions and ignore the association effect in the mathematical model. Therefore, it can be expected that we can obtain simulation results closer to our mathematical analysis in the ad-hoc node.

In the ad-hoc network, the number of nodes is set to increase by 5 each time in the range of 5 to 50. Each node sends a packet to an adjacent node with date rate of 54 Mbps. Each node serves as both a transmitter and a receiver. Therefore, the aggregated network sum rate is the sum of the date rate of each node.

Table 1. System parameter settings [17].

PHY header (PH)	20 µs	ACKTimeout	69 µs
MAC header (MH)	36 bytes	CTSTimeout	69 µs
ACK	14 bytes	DIFS	34 µs
RTS	20 bytes	SIFS	16 µs
CTS	14 bytes	Slot Time σ	9 µs
$CW_{\min}$	15	$CW_{\max}$	1023

In the simulation experiments, we utilize the default WiFi channel and the physical layer from the YANS model [16], and choose the AdhocWifiMac as

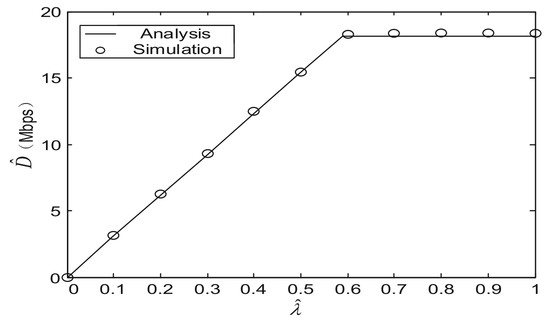


Fig. 4. Network sum rate $\hat{D}$ versus aggregate input rate $\hat{\lambda}$ in IEEE 802.11 DCF network with basic access mechanism. $PL = 1023$ bytes. $n = 50$. $W = 16$. $K = 6$. $R_D = 54$ Mbps. $R_B = 6$ Mbps.

the type of the MAC layer. Currently, NS-3 has supported several IEEE 802.11 standards, and we select the 802.11a standard as the WiFi standard with date rate and basic rate from 6, 9, 12, 18, 24, 36, 48 to 54 Mbps. The value of system parameters are summarized in Table 1.

4 Performance Evaluation

In this section, we will present a series of designed DCF simulations in NS-3, and demonstrate the comparison between analytical results with Dai's model and simulation results with NS-3 WiFi module. In particular, to evaluate the performance of Dai's model in the NS-3 WiFi module, we first increase the traffic arrival rate to load the network from unsaturated to saturated modes, and then set varying number of nodes n, the initial backoff window size W and the cutoff phase K to obtain the simulation results.

4.1 Network Performance versus Traffic: Unsaturated to Saturated

In NS-3, we increase the aggregate input rate $\hat{\lambda} = n\lambda$ to load the network states from unsaturated to saturated, and λ is the probability to generate a new packet every τ_T time slots. By steadily increasing $\hat{\lambda}$, the network transits from the unsaturated to saturated states.

Figure 4 shows that network sum rate $\hat{D}$ increases and eventually saturates as the aggregate input rate $\hat{\lambda}$ grows. In fact, the network is unsaturated when each node has a low $\hat{\lambda}$, where $\hat{D}$ linely increases with $\hat{\lambda}$, each HOL packet can be successfully transmitted. As $\hat{\lambda}$ increases, each node always has a packet to transmit and the network becomes saturated. In this case, the network sum rate $\hat{D}$ not longer increases with $\hat{\lambda}$, and is determined by the system backoff parameters.

4.2 Saturated Throughput versus Key System Parameters

For a saturated IEEE 802.11 DCF network, it can be seen that network sum rate $\hat{D}$ depends on the number of nodes, the initial backoff window size and the cutoff phase from Eqs. (3) and (5). In this section, we compare the network sum rate of the simulation and theoretical results by tuning distinct system parameters.

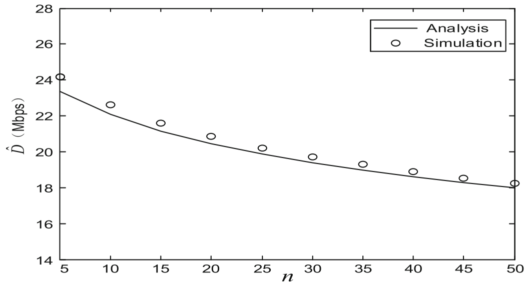
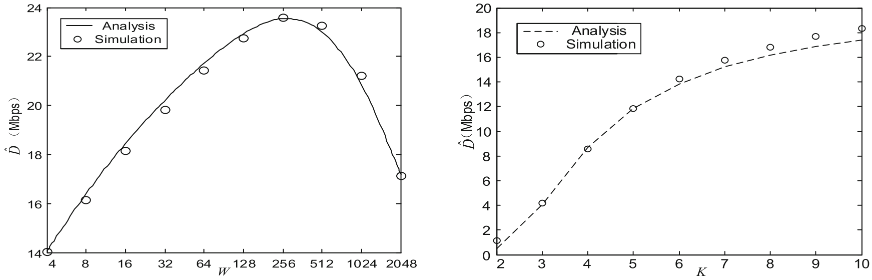


Fig. 5. Network sum rate $\hat{D}$ versus the number of nodes n in a saturated IEEE 802.11 DCF network with basic access mechanism. $PL = 1023$ bytes. $W = 16$. $K = 6$. $R_D = 54$ Mbps. $R_B = 6$ Mbps

Figure 5 compares network sum rate $\hat{D}$ obtained in NS-3 with the theoretical results by varying the number of nodes n. As shown in Fig. 5, the NS-3 simulation results are close to the theoretical curve except when n takes a small value such as $n = 5$. The reason is that $\hat{D}$ is determined by the limiting probability of the successful transmission of HOL packets p in the mathematical model and p is obtained under an implicit assumption that n is sufficiently large. Therefore, when $n < 5$, the theoretical network sum rate may slightly deviate from the simulation results.

In Fig. 6a, it can be observed that network sum rate $\hat{D}$ obtained in NS-3 and theoretical analysis are well matched by tuning the initial backoff window size W. The network sum rate $\hat{D}$ increases first and then decreases as W increments. When W increases, each node achieves a larger backoff window size to avoid collision and thus the network achieves higher network sum rate due to fewer collisions. However, when W continues to increase, each node may have a longer backoff duration so that the channel can be idle for a long time. In this case, the utilization of channel will be reduced, leading to a decreased network sum rate.

As shown in Fig. 6b, network sum rate $\hat{D}$ of theoretical model is close to the NS-3 simulation results. When the cutoff phase K increases, $\hat{D}$ is monotonically increasing. With a larger K, the maximum backoff window size will increase. In this case, each node has a higher probability of choosing a different backoff window size to avoid collisions and thus the network has higher network sum rate due to fewer collisions.



(a) (b)

Fig. 6. Network sum rate $\hat{D}$ versus backoff parameters in a saturated IEEE 802.11 DCF network with basic access mechanism. (a) $\hat{D}$ versus the initial backoff window size W. (b) $\hat{D}$ versus the cutoff phase K. With $PL = 1023$ bytes. $n = 50$. $R_D = 54$ Mbps. $R_B = 6$ Mbps.

4.3 Basic vs. RTS/CTS Access Modes

In the IEEE 802.11 standard, the DCF protocol is equipped with two access modes, including the default basic access mechanism and the optional RTS/CTS mechanism. With the basic access, the node first sends a packet after the DIFS duration if it senses the channel idle. Otherwise, the node chooses a backoff window size for the backoff process. If the node receives the ACK frame, it confirms that its packet is successfully received by the destination. Otherwise, if the node does not receive the ACK frame after the ACK time-out period, the node restarts the backoff process.

Different from the basic access, the node first sends a short RTS frame to reserve the channel in RTS/CTS access. If the RTS frame is successfully received by the destination, and the destination sends the CTS frame to all nodes so that other nodes will not contend for the channel and the node can successfully reserve the channel to send the packet. Then, the packet transmission starts and is confirmed to be successful by the ACK frame or starts the backoff process after the CTS time-out period.

Figure 7 demonstrates how the network sum rate $\hat{D}$ varies with the packet payload PL in both modes. In the simulation experiments, we set the date rate to 54 Mpbs and 24 Mbps, respectively with the same settings of $n = 50$, $W = 16$ and $K = 6$. As shown in Fig. 7, a good match can be observed between the theoretical analysis and simulation results, which provides a good indication that Dai's model can be served as a considerably credible model to validate the WiFi MAC layer in both NS-2 and NS-3.

4.4 Ad-Hoc vs. Infrastructure

A wireless ad-hoc network is a decentralised type of wireless network. Each node is both a sender and a receiver. It can transmit packets to other nodes and receive a packet from a sending node. However, an infrastructure network is generally centralized based on pre-defined network facilities, where a station must communicate with an access point (AP) first to access the network. The additional channel activity due to association (beacon transmission, active scanning etc.) is added compared to an ad-hoc network.

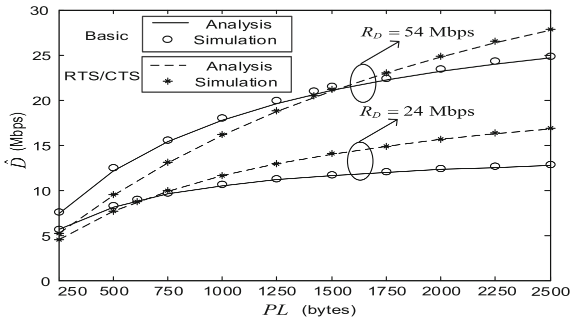


Fig. 7. Network sum rate $\hat{D}$ versus the packet payload PL in a saturated IEEE 802.11 DCF network with basic access and RTS/CTS. $n = 50$. $W = 16$. $K = 6$. $R_B = 6$ Mbps.

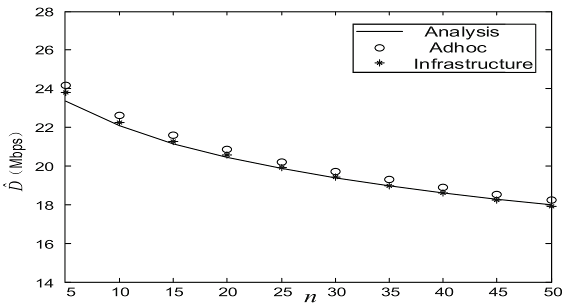


Fig. 8. Network sum rate $\hat{D}$ versus the number of nodes n in a saturated IEEE 802.11 DCF network with basic access in ad-hoc and infrastructure mode. $PL = 1023$ bytes. $n = 50$. $W = 16$. $K = 6$. $R_D = 54$ Mbps.

Figure 8 depicts the effect of the association activity in the infrastructure network on network sum rate performance. By comparing the relation between network sum rate $\hat{D}$ and the number of nodes n in the ad-hoc and infrastructure networks, the network sum rate $\hat{D}$ in the ad-hoc network is slightly higher than that in infrastructure network due to the extra time overhead of the association activities in the infrastructure mode.

5 Conclusion

In this paper, we conduct a performance evaluation study of the unified IEEE 802.11 DCF analytical model [1] against the IEEE 802.11 MAC simulation model in NS-3. We have instrumented the simulator with different scenarios including traffic conditions varying from unsaturated to saturated, system parameters including the number of nodes n, the initial backoff window size W and the cutoff phase K, and varying the packet payload PL in the basic access and RTS/CTS modes. Our study shows that the unified analytical framework proposed for homogeneous IEEE 802.11 DCF networks matches closely with the NS-3 MAC model. The work demonstrates that (1) NS-3 WiFi module can work accurately for 802.11 model validations; (2) the unified analytical framework proposed in [1] is a simple yet solid theoretical tool for performance evaluation of homogeneous IEEE 802.11 networks.

Acknowledgments. The authors thank Rohan Patidar for his help in our NS-3 experiments. This work was supported in part by the National Natural Science Foundation of China (No. 61402186, No. 61370231).

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