Using Rate Balancing to Improve Throughput in a Wireless Multi-hop Chain Topology

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Abstract— **A well-known problem in wireless multi-hop communication is the significant degradation of throughput when the number of hops increases. Previous research shows that in a chain topology, nodes using IEEE 802.11 can at best achieve 1/4, but in practice only 1/7, much smaller than the ideal 1/3 of the throughput of single-hop transmission. In order to improve performance in multi-hop cases, we introduce a rate balance scheme and tune the sensing range at physical layer and contention window at MAC layer. Our simulation results show that the throughput ratio close to 1/4 is achievable when the number of hops is as high as 12; better ratios of 1/3.4 and 1/3.6 are achieved when number of hops is 5 and 8, respectively.**

I. INTRODUCTION

Multi-hop wireless communication is a flexible paradigm to rapidly deploy and to extend the coverage of dynamic networks such as ad hoc wireless networks, mesh networks and sensor networks. In multi-hop wireless networks, a source node may not be able to directly communicate with its destination, therefore it may rely on intermediate nodes, which act as routers, to transmit data. To share the common wireless channel, nodes may use the random medium access control (MAC) protocols, such as IEEE 802.11 [1], to contend for the opportunity to access the channel. Random MAC protocols are robust due to their distributed nature, however their mechanisms often result in significant wastage of resources in a multi-hop environment. When the number of hops increases, throughput considerably decreases [2-4], hence limiting the applicability of these networks.

A. Related works

The capacity of multi-hop wireless networks has been studied by both theoretical [2, 3] and simulation-based analyses [4, 5]. In [2], per node end-to-end throughput is estimated to be $O(1/\sqrt{n})$, where n is the total number of nodes. In [3], authors have pointed out that the capacity can be O(log n) with a specific traffic pattern, namely relay traffic pattern. This result is applied to ad hoc networks with relay transmission and can be extended to sensor networks. In [4], the capacity was studied for configurations of single cell, chain of nodes and lattice networks with different traffic scenarios. Specifically, in the case of a forwarding chain, the ideal throughput of an n-hop chain is 1/3 of that of a single-hop, and typically, this ratio is 1/7. These analyses show that in multi-hop transmission, nodes using random MAC protocols (e.g. IEEE 802.11) experience a large number of collisions and spend a lot of time to resolve these collisions, resulting in performance degradation.

Proposals to improve throughput are extensively studied and they can be classified into those that control transmission rate [6-9], and those that tune control parameters such as contention window [10, 11] or sensing range [12].

Rate control schemes regulate traffic entering the network, thus they reduce the collisions. Explicit rate control schemes are introduced in [8, 9] where the optimal load is estimated using a traffic model or feedback information. Implicit rate control schemes typically introduce a delay at sources, thus effectively reducing input traffic. The amount of delay can be pre-determined [13], or be computed using a traffic model [6]. Other indirect techniques suggest to favour the next hop to contend for the common channel [7, 8]. Source nodes then have fewer chances to send data, i.e. their rates are reduced. These schemes successfully reduce collisions, however, they inadequately addressed to other factors such as backoff time or sensing range, which also have impact on performance.

Improvement of throughput can also be achieved by tuning contention window (CW) and sensing range, which have significant impact on MAC performance. In [10], the authors developed an analytical model using p-persistent backoff algorithm to derive the average size of CW that would maximize the theoretical throughput limit of the protocol. This model requires as an input the number of nodes, which is not always available in a real network. In [11], a slow CW decrease scheme is proposed. CW is kept large to avoid possible collisions in the case a node is overloaded. This scheme may be inefficient if overload and congestion occur at only a few points in the network. Physical carrier sensing range also significantly affects the performance as pointed out in [14, 15]. A large sensing range may considerably reduce collisions, but at the same time, it also causes more unnecessary backoff time. Most studies [4, 9, 15] assume sensing range has a fixed value as it depends on the radio sensitivity of wireless interface, thus its impacts are indirectly examined by arranging the distance between nodes. In [12], the authors suggest to tune the carrier sensing range so that a cost function is maximized. Unfortunately, the question of estimation of the optimal sensing range is still left unanswered.

B. Our contributions

Given that throughput is heavily reduced by data collisions and unnecessary backoff time, we propose to apply our scheme of rate balance and to adjust sensing range and CW according to the level of interference. The rate balance scheme appropriately regulates traffic such that intermediate nodes can forward data efficiently. Throughput is improved while data collisions and backoff time are reduced. As data collisions are alleviated, the sensing range and CW can be adjusted to further reduce the backoff period. We verify the proposal by simulations in a chain topology, and demonstrate that the ratio of throughput of multi-hop and single-hop transmissions is 1/3.4, 1/3.6, and 1/4.1 for the number of hops of 5, 8 and 12, respectively. These ratios are higher than the expected best ratio of 1/4 and the typical ratio of 1/7 derived in [4]. Our approach shows that it is possible to get closer to the theoretical limit ratio of 1/3 when the number of hops increases. In addition, we point out that future study on optimizing sensing range should take into account the impact of traffic characteristics, which may change with different traffic regulation schemes.

C. Overview of the paper

The rest of this paper is organised as follows. In Section II, we review the IEEE 802.11 RTS/CTS protocol and our motivation in improving throughput in multi-hop transmission. In Section III, we propose our scheme of rate balance to regulate traffic at nodes and adjustment of sensing range and CW according to interference condition. We then evaluate our approach in multiple scenarios in Section IV. Finally, we present conclusions and ideas for future work in Section V.

II. PRELIMINARIES AND MOTIVATION

In this section, we briefly explain the IEEE 802.11 RTS/CTS scheme [1], which we assume is the baseline protocol used for multi-hop wireless networks[1]. We then explain the problem of throughput degradation in multi-hop transmission and our motivation to improve the performance.

A. IEEE 802.11 with RTS/CTS

The IEEE 802.11 MAC protocol [1] specifies how nodes share access to a common wireless medium. The protocol is based on Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA). Two access schemes are defined: the basic access scheme with acknowledgement of data frames; and the Request-To-Send/Clear-To-Send (RTS/CTS) scheme, which introduces an additional two-way handshake between sender and receiver before the data transmission.

In the RTS/CTS scheme (Fig. 1), a node having a frame ready to transmit senses the status of the channel. If the channel is idle for a period of time equal to the DCF Inter-Frame Space (DIFS), then the node starts a random backoff (BO) period and continues to monitor the channel status. Providing the channel remains idle, a RTS frame is first sent to the intended destination. If the intended destination is available to receive the DATA frame (it may not be if the channel is busy or another node has reserved the channel using RTS/CTS), it waits a Short Inter-Frame Space (SIFS) and responds with a CTS frame. Upon receipt of the CTS the source then sends the DATA frame. The destination node then responds with the ACK frame. If the source node does not receive an ACK within ACK-Timeout period, it shall retransmit the DATA frame. Both RTS and CTS play in important role of reserving the channel and contain the time required to complete the DATA and ACK transmission. Any other nodes that receives a RTS or CTS will assume the channel is busy for the indicated time and defer access. The RTS/CTS scheme reduces collisions of large DATA frames at expense of possible collisions of small RTS frames and additional small overheads. The RTS/CTS scheme is also useful for reducing the number of hidden terminals [16], which may lead to significant performance loss in a multi-hop wireless networks.

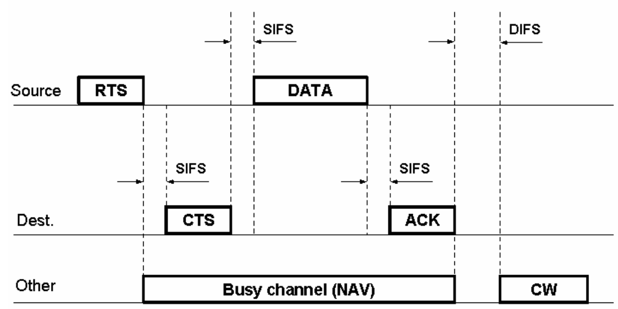

Fig. 1: IEEE 802.11 RTS/CTS scheme

The BO period is randomly selected between *(0, CW -1)*, where *CW* is the current size of contention window. Initial value of *CW* is set to the minimum contention window, *CWmin*. *CW* is doubled every time a packet transmission fails until it reaches a maximum contention window, *CWmax*. The BO period decreases when the channel is idle, suspended when the channel is determined busy, and finishes (allowing a frame to be sent) when the period reaches zero. The random BO period minimises the probability of packet collision when nodes try to repeatedly send data at the same time.

B. Improving performance of multi-hop transmission

We consider a chain of nodes (Fig. 2) as it is the basic multi-hop transmission scenario. We point out a big gap between actual and achievable throughput performance. A set of nodes using 802.11 RTS/CTS is distributed along a line such that adjacent nodes separate each other by a distance approximately to their transmission range. We examine how a packet is forwarded in that chain to derive the trivial limit of throughput performance in n-hop transmission.

Assume that source node 0 sends data to destination node

[1] Although there are many alternate MAC protocols for multi-hop wireless networks, it is reasonable to assume 802.11 RTS/CTS or its variances will be used in those networks due to its simplicity and widespread deployment.

12. After transmitting a packet to node 1, source 0 should defer access to let node 1 forward the packet to node 2. Source 0 should also defer access until node 2 has forwarded the packet to node 3 in order to avoid collision at node 1 when both nodes 0 and 2 simultaneously transmit data. Node 0 can resume its transmission when node 3 forwards the packet. Thus, source node 0 can access the channel at most 1/3 of the available time.

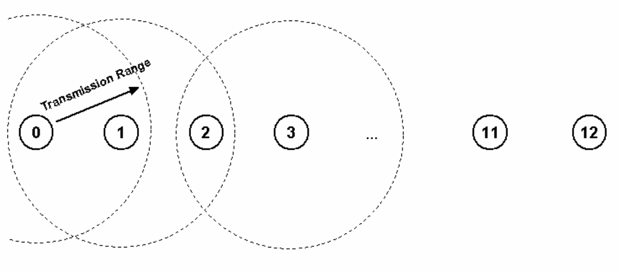

Fig. 2: Chain of 12 hops

Denoting k_i the ratio of achievable throughput in a chain of i hops ($i+1$ nodes) and achievable throughput in a chain of single hop, we have $k_i \leq 1/3$ with $i \geq 3$. This ratio can be achieved only with a perfect global scheduler in the chain. Assuming 802.11 RTS/CTS with parameters specified in Table 1, achievable throughput of single-hop chain is about 1.7Mb/s (out of channel capacity of 2Mb/s). Furthermore, the best ratio of 1/4 is expected in [4] and a ratio of 1/5 is derived in [9]. Simulation results reported in [4] also show that 802.11 RTS/CTS can achieve only the ratio of 1/7, much smaller than the ideal ratio of 1/3.

We illustrate the previous analysis by conducting simulations using Glomosim [17]. This discrete-event simulator provides models of various physical, MAC, routing and application layer protocols, and is tailored towards multi-hop wireless networks. Table 1 lists the parameter values used in the simulation. We measure the performance of chains of 5, 8 and 12 hops, and present the results in Fig. 3.

Parameter	*Value*
Distance between nodes	350 m
Path loss model	Two-ray ground
Rx threshold	-10.0 dBm
Rx sensitivity	-91.0 dBm
Tx power	15 dBm
Rx antenna gain	0 dB
Data rate	2 Mb/s
Slot, DIFS, SIFS	50, 28, 128 µs
PLCP header	24 bytes
RTS, CTS, ACK	20, 14, 14 bytes
DATA payload	1460 bytes
CWmin, CWmax	15, 1023
Application	CBR/UDP

Table 1: IEEE 802.11 model parameters

Fig. 3 shows the throughput performance is well below 1/4 single-hop throughput, and far below the theoretical limit of 1/3. When offered load increases, throughput decreases from a peak to saturated throughput. Main reason of the degradation is the increase of data collisions and backoff time, which consume the scarce wireless resources. In order to increase the throughput, a rate control scheme is necessary to regulate traffic so that throughput should be closer to the peak level. Further tuning can also be applied to improve the performance.

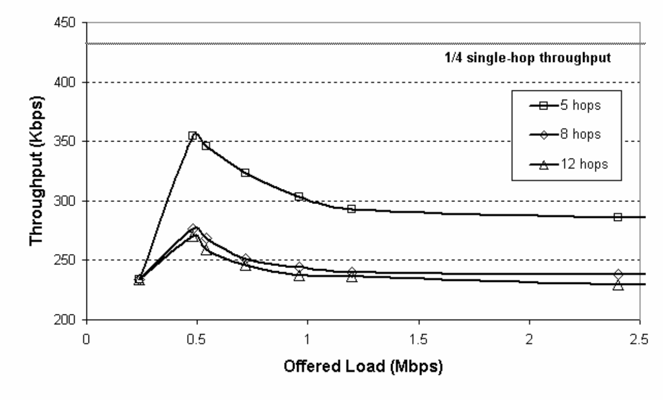

Fig. 3: Throughput performance of CBR sessions over 5, 8 & 12 hops

III. IMPROVING THROUGHPUT IN CHAIN TOPOLOGY

In this section we describe our solution to improve the performance of multi-hop transmission in a chain of nodes. First, it is necessary to control traffic from source nodes to destination nodes at a level that intermediate nodes can best forward data. Consequently, the transmission collisions will be alleviated. Secondly, once the traffic control scheme is successful in mitigating the collisions, performance can be further improved by reducing the unnecessary backoff time.

A. Rate balance scheme

When traffic load increases, usage of channel bandwidth in multi-hop transmission is significantly inefficient as number of data collisions and backoff period grows, leading to severe throughput degradation. Analysis of contending activities of nodes in multi-hop transmission has led to our proposal of rate balance scheme [18], which differs from other proposed rate control schemes [6, 8, 9] in the following features:

- **Rate balance scheme is applied at every intermediate node**: We argue that not only the source node must eventually reduce its transmission rate, but also intermediate nodes should independently control their traffic. A rate control scheme applied at sources must rely on the estimation of network traffic or on the feedback information from other nodes. Unfortunately, it is extremely difficult to exactly model traffic in a dynamic environment. Also, the feedback information may not timely reflect network status as it must travel over multiple wireless hops. Our scheme allows every intermediate node to control the traffic relaying through it, and provides implicit hop-by-hop feedback to the source node.

- **Traffic is regulated according to the rate balance condition**: The reasoning behind the balance scheme is an intermediate node can at most forward all packets it receives. Therefore, by maintaining the balance between receiving and forwarding activities, an intermediate node can perform at its best, efficiently contend for the channel, and resolve the congestion that may occur at the node. The best performance is achieved as the relay node forwards all packets that arrive. Contention is efficient in the sense that the channel is equally divided for receiving and forwarding packets. Congestion does not exist since the balance condition ensures that data queue at an intermediate node does not increase.

- **Rate balance scheme requires cross-layer information**: Implementation of the rate balance scheme is simple at the MAC layer: a node checks the balance condition before responding to a RTS. However, in order to detect relaying traffic, information about initial source and final destination are required from the network layer.

By monitoring the rate balance condition, our scheme can significantly improve the throughput, as well as reduce collisions and unnecessary backoff time. Further details and simulation results on our scheme can be found in [18].

B. *Interference and sensing range*

A node can correctly receive a frame if the received signal power is strong enough to overcome the noise power, i.e. signal to noise (SNR) ratio should be above a certain threshold. If the noise power is too high, the frame cannot be successfully decoded, i.e. a collision occurs. Besides successfully receiving frames, a node also uses channel sensing for the MAC to determine if the medium is busy or idle. If the node receives any signal above a certain power threshold, then the medium is assumed busy. Note this threshold is different to the threshold for successfully receiving a frame, i.e. a node may not be able to successfully receive a frame transmission, but may be able to sense that a transmission is ongoing.

As an abstraction of the power levels, one can define the following ranges to determine whether or not two nodes can transmit to, interfere with or sense (hear) each other:

- **Transmission Range (R_t)**: maximum distance at which a node can successfully receive a frame from a sender. This is normally computed based on a propagation path-loss model [19]. For example, using the two-way ground model in our simulations (Table 1), R_t is 367m.

- **Interference Range (R_i)**: maximum distance at which a nodes transmission can interfere at a receiver. This is dependant the propagation model, the distance between sender and receiver ($d \le R_t$) and the SNR threshold. From Table 1:

$$R_i = \sqrt[4]{SNR\_THREHOLD} * d = 1.78*d \le 1.78*R_t$$

- **Sensing Range (R_s)**: maximum distance at which a node will determine the medium busy if another node is transmitting. It should be large enough so that a transmitter is able to detect on-going radio activities it should neither interfere with nor be interfered by. In most studies, this range is fixed around $2.2R_t$.

These ranges impact on the number of hidden and exposed nodes in the network, and consequently the number of collisions or wastage of transmission opportunities. Therefore, varying these relative ranges can potentially lead to performance gains.

Prior studies on ad hoc networks and multi-hop transmissions [14, 15] have pointed out that sensing range may have important impact on performance. Reported analyses on capacity of multi-hop transmissions usually assume a fixed sensing range (R_s) based on the transmission range (R_t). The interference range (R_i) depends on the distance between receiver and interfering nodes.

Clearly, a large R_s would successfully eliminate possible collisions. However, we argue that although the selection of R_s depends on the sensitivity of physical device (e.g. antenna), it can be adjusted by changing the threshold that differentiates the idle and busy states of the channel. Furthermore, R_s should be adjusted according to the interference level of other nodes. Obviously, if interference level is high, collisions are more likely to happen and vice versa. Therefore, if the degradation of performance is mainly contributed by collisions, a large R_s is useful to eliminate these collisions. However, if the problem of collisions is mitigated, a large R_s would be inefficient as it would introduce unnecessary backoff time.

Our suggestion to adapt the sensing range to the amount of interference also relies on the fact that there is a direct relation between traffic characteristics and interference level. Even in the simple chain topology, traffic characteristics of a single session between two nodes may greatly vary with different scheduling or traffic regulation schemes. Variation in traffic characteristics would result in a different interference level. Most studies on the impact of sensing range on performance fail to address this relation: they generally focus only on the nodes' relative distances, which are the main parameters in estimating received power and SNR ratio.

Detail analyses of interference condition and determining optimal sensing range are not trivial and are out of scope of this paper. For the sake of simplicity, we adjust R_s at only two levels of $1.78R_t$ and $2.2R_t$ in order to show the importance of determining sensing range based on interference level. Our simulation results (Section IV) confirm that adjusting R_s can reduce unnecessary backoff time, resulting in improvement of throughput performance. Furthermore, different R_s would be best suited for different traffic conditions.

C. *Collision and contention window*

The IEEE 802.11 MAC uses a binary exponential backoff period to avoid multiple nodes that our coming out of deference to transmit at the same time (hence possibly causing a collision). The scheme is reported to be inefficient in numerous papers [10, 11], which proposed various techniques to improve the scheme. The selection of backoff period depends on a contention window (Section II.A): the larger the CW, the less chance nodes will select the same backoff period. However, the larger the CW, the more time a node defers its transmission even when the channel may be available to send data, resulting in inefficient channel usage.

In our study, we apply a simple estimation of CW based on the number of interfering nodes within a two-hop range. This information can be extracted from overhearing RTS/CTS frames, which contain required address information. In the chain topology considered in this paper, a node contends for the channel against at most four others. Therefore, the default value of *CWmin* of 15 [1] is large enough to guarantee a low probability of collisions. With an appropriate small CW, the backoff time is reduced while not increasing data collisions, leading to throughput improvement.

IV. EVALUATION AND SIMULATION RESULTS

In Section III we identified the main impacts on the inefficiency of 802.11 MAC protocol in multi-hop transmission, and proposed methods to improve the performance. The rate balance scheme will appropriately regulate traffic at nodes and reduce data collisions. Once data collisions are insignificant, reducing sensing range and contention window can be considered to decrease unnecessary backoff time. In this section we use simulations to evaluate our proposed solution in terms of throughput performance.

A. Simulation Setup

The aim of our simulations is to compare the throughput performance when applying our scheme and that of 802.11 MAC protocol derived in [4]. We setup the simulation as follows:

- Each simulation has duration of 60 seconds.
- Unless otherwise noted, the parameter in Table 1 are used.
- The chain length is set to 5, 8, and 12 to study how throughput performance depends on the number of hops
- The radio sensitivity is set to -91.0 dBm and -94.7 dBm, thus the sensing ranges are $1.78R_t$ and $2.2R_t$ respectively.
- Maximum contention window *CWmax* is set to 15, equal to *CWmin*, thus nodes always contend with *CWmin.*

B. Reducing data collision by using rate balance scheme

In order to show that the rate balance scheme can efficiently reduce data collisions, we count the number of ACK-timeouts as an indication of DATA frame collisions. A sender experiences ACK-timeout if DATA is lost or corrupted, thus no ACK is returned, or if DATA is correctly received, but returning ACK is corrupted. In all these cases, DATA frames are considered as being collided, and they are retransmitted.

We use a sensing range of $1.78R_t$, for the cases where (i) only basic 802.11 MAC protocol (basic) is applied; (ii) rate balance scheme (RB) is turned on; (iii) RB is on and sensing range and CW (all) are adjusted. Total number of collided DATA frames at all nodes is counted over simulation period.

The total number of data collisions is summarized in Fig. 4(a) for the cases of offered load are set to 0.72Mb/s, 0.96Mb/s, and 1.2Mb/s. The results show that the rate balance scheme efficiently mitigates the problem of data collision when reducing the sensing range. For example, for the chain of 8 hops, number of collisions of nearly 80 is reduced to 0 when turning on rate balance scheme. When reducing the sensing range and CW, the number of data collisions increases: the short sensing range fails to detect collisions and small CW increases the probability of collisions. However, these impacts are compensated by their contribution in reducing unnecessary backoff time (Section IV.C), thus in overall, they improve throughput. We also note that if sensing range is $2.2R_t$ (results not shown) it would eliminate data collisions, hence we will not see the impact of rate balance scheme.

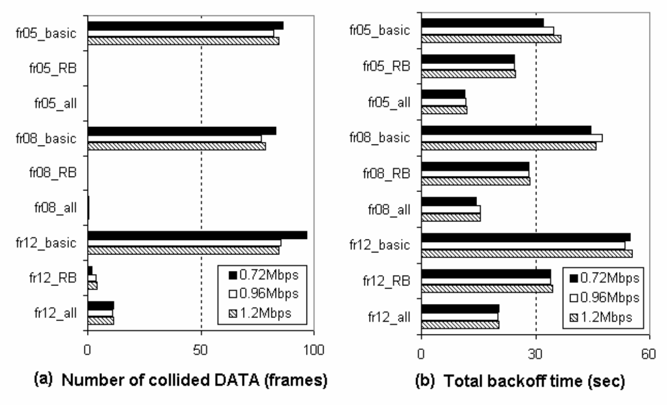

Fig. 4: (a) Rate balance significantly reduces collision of DATA frame and (b) Adjusting sensing range and CW reduce backoff time

C. Reducing BO time by adjusting sensing range and CW

Given that collisions are alleviated by the rate balance scheme, it is reasonable to consider tuning the sensing range and contention window to reduce unnecessary backoff time. We measure total BO time at all nodes over the simulation period when (i) applying basic 802.11 scheme with sensing range of $2.2R_t$ (basic), then (ii) turning on rate balance scheme (RB), and finally (iii) turning RB on and setting sensing range to $1.78R_t$ and CWmax to 15 (all).

The total backoff time is summarized in Fig. 4(b). The results show that our scheme can efficiently reduce the collisions, and as a consequence, BO time is reduced, compared with the basic scheme. Adjusting to a shorter sensing range and smaller CW can further reduce the BO time. For instance, in a chain of 12 nodes working in basic scheme, total BO time is about 55s, which is reduced to near 35s with our scheme and further decreased to about 20s with adjustments of sensing range and CW.

D. Adjusting sensing range according to interference level

In order to show that sensing range should be tuned according to interference level, i.e. traffic characteristics, we plot the throughput of a chain of 8 nodes with different sensing ranges of $1.78R_t$ (solid lines) and $2.2R_t$ (dashed lines), and when rate balance (rate_balance) scheme is turned on.

The simulation results (Fig. 5) show that large sensing range increases throughput in basic scheme, but not in the case where rate balance scheme is turned on. The reason is with basic scheme, throughput degradation is mainly contributed by collisions of data frames (Section IV.B). Increasing the sensing range reduces these collisions, resulting in the improvement. However, as data collisions are mitigated (by our scheme), large sensing range causes unnecessary BO time, thus it reduces throughput. Therefore, a good sensing range should be selected based on not only the relative distance between nodes, but also the traffic characteristics. Most research on optimising sensing range fail to address this issue.

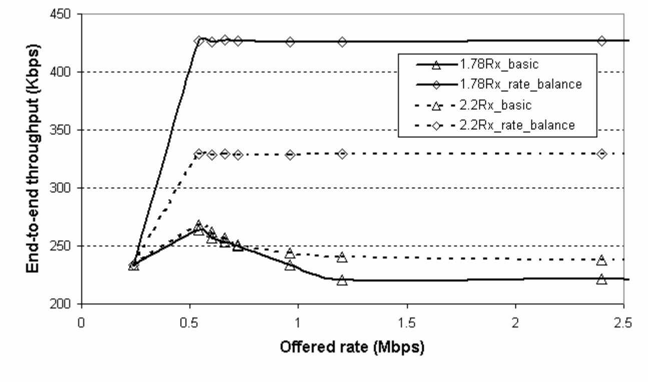

Fig. 5: Selection of sensing range depends on traffic characteristics

E. Near throughput limit in the chain topology

We measure and compare throughput performance in the cases (i) only basic 802.11 RTS/CTS is applied (basic, dashed lines) and (ii) the rate balance scheme is turned on and sensing range and CW are adjusted (all, solid lines).

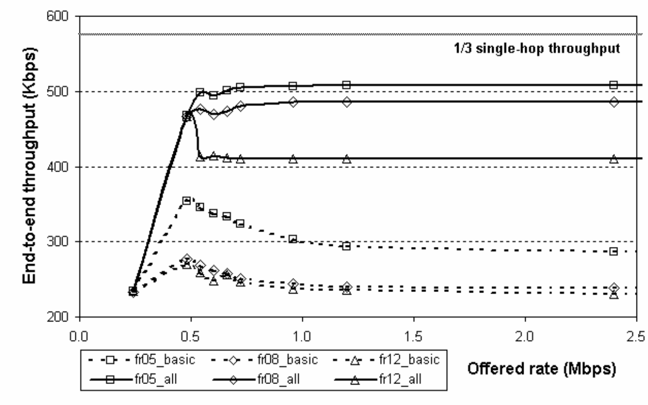

Fig. 6: Improvement of end-to-end throughput in chain topology

As shown in Fig. 6, throughput is considerably improved by applying rate balance scheme, which regulates the traffic at intermediate nodes and alleviates data collisions, and adjusting of sensing range and CW, which reduce unnecessary backoff time. In the cases of 5 and 8 hops, k_5 and k_8 are 1/3.4 and 1/3.6, respectively. Those ratios exceed the best ratio of 1/4 [4] for basic IEEE 802.11, and are closer to the theoretical limit ratio of 1/3. Even with a number of hops as high as 12, throughput ratio k_{12} is 1/4.1, very close to the ratio of 1/4.

V. CONCLUSIONS

Poor performance of multi-hop transmission when increasing number of hops hinders the extension of the coverage of wireless ad hoc networks. When using a random MAC protocol such as 802.11 RTS/CTS, nodes randomly access the channel, thus they experience large number of data collisions and unnecessarily high backoff time when traffic load is high. Consequently, scarce bandwidth is wasted and throughput performance degrades.

In this paper we propose to apply a rate balance scheme and to adjust the sensing range and the CW according to interference level. Analyses in chain topologies show that our scheme provides significant throughput enhancement, which surpass the best throughput performance of the baseline IEEE 802.11 protocol. This result is promising for multi-hop transmission as high throughput is maintained with high number of hops.

Future work is needed in extending the analysis to other network configurations with more realistic traffic scenarios. With background traffic introduced, traffic characteristics and interference level will change, thus the current simplified schemes of adjustment of control parameters need to be enhanced. Also further study of our scheme taking into account fairness and delay is needed.

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