Loss Differentiated Rate Adaptation in Wireless Networks

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***Abstract*— Data rate adaptation aims to select the optimal data rates for current channel conditions leading to substantial performance improvement. This paper proposes a data rate adaptation technique that: (1) exploits the periodic IEEE 802.11 beacons; (2) discriminates between frame losses due to channel fading and those due to collisions and takes actions appropriate for each type of loss; and (3) recommends and justifies the use of the lowest data rate for the very first retransmission after a frame loss. The last feature - namely retransmitting at the lowest data rate - helps in diagnosing the real cause of a frame loss. Moreover, this work analytically shows that retransmitting at the lowest data rate is more efficient, especially in poor SNR environments or when there is no knowledge of the cause of a loss (channel degradation or transmission collision). This scheme, dubbed Loss Differentiated Rate Adaptation (LDRA), is extensively evaluated through simulations and shown to perform better especially when network traffic is heavy.**

Keyword: Rate Adaptation; Loss Differentiation; Beacon.

I. INTRODUCTION

The wireless medium is highly sensitive to environment disturbances (e.g., weather conditions, interference from other sources...). Such a sensitivity renders the wireless medium highly instable and results in fluctuations of wireless channel quality. This wireless channel instability suggests the use of data rate adaptation algorithms to dynamically select appropriate data rates (modulation scheme) for given levels of channel quality.

Traditional data rate adaptation strategies [1]–[7] have been proposed to estimate the data rate by analyzing either the signal-to-noise ratio (SNR) or the frame loss rate. However, the adopted data rate is not always the optimal one for current channel conditions because the adaptation does not closely fit channel fluctuations. A suboptimal data rate might lead to channel underutilization (data rate too low) or to higher frame losses (data rate too high). Moreover, factors other than channel conditions may degrade wireless frame transmissions: 1) further distance between nodes and 2) frame collisions for contention MAC protocols. The discrimination between channel degradation and collisions may yield better data rate adaptation. For channel degradation, a more robust modulation (with a lower data rate) can increase the signal-to-noise ratio (SNR) and counter degradation. But, for collisions, decreasing the data rate does *not* alleviate channel congestion. This work proposes a passive sender-based data rate adaptation strategy with loss differentiation without requiring the overhead of RTS/CTS control frames.

Three key contributions characterize this work. **First**, before transmitting, a station estimates the channel quality by monitoring the periodic *beacon* frame (mandatory in 802.11). **Second**, when the station experiences a frame loss *not* due to collisions, LDRA diagnoses it as such, recovers with adopting the *lowest data rate retransmission*, and freezes the binary exponential back-off (no collisions). For a loss due to collisions, the data rate is not unduly decreased as a lower data rate would increase radio reception range and thus may worsen congestion (increase collisions). As explained later, the use of the lowest data rate enables a technique to diagnose the real cause of a frame loss. **Finally**, we analytically demonstrate for 802.11 networks that retransmissions at the lowest data rate rather benefit network performance, especially in poor SNR environments.

The remaining of this paper is organized as follows: Section II describes the related work in data rate adaptation. Section III outlines the motivations. Section IV details the proposed scheme. We analytically justify the retransmissions at the lowest rate in Section V. The simulation results are presented in Section VI. Section VII concludes this paper.

II. RELATED WORK

Data rate adaptation schemes differ based on whether they are: 1) sender or receiver based; 2) driven by frame loss rate or by received signal strength indication (RSSI); 3) loss-collision discriminators or not.

Auto Rate Fallback (**ARF**) [3] implemented in the Lucent WaveLan-II product is the earliest proposed sender based scheme for data rate adaptation in WLAN. **ARF** is a loss rate driven scheme. In **ARF**, a sender starts transmitting at the lowest data rate. If the transmission succeeds for ten consecutive frames, the sender increases its transmission data rate. Otherwise, it decreases the data rate. With **ARF**, the data rate oscillates, and never converges to a stable data rate even under fairly steady channel conditions. This problem is illustrated by Figure 3: although the wireless channel steadily supports 5.5 Mbps, ARF fluctuates the selected rate between

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5.5 Mbps and 11 Mbps and induces a frame loss rate in excess of 16%.

Pang and Liew [8] extended Auto Rate Fallback (ARF) with a loss-differentiating MAC layer technique they developed in [9]: this differentiation technique assumes that the frame header is short and thus resilient to wireless channel fading. Therefore, if the frame header can be decoded while the payload is corrupted, Pang and Liew attribute the frame loss to wireless channel degradation. Otherwise (i.e, the complete frame is lost), they diagnose the frame loss as a collision. In Pang and Liew work [8],“the data rate is reduced only when a loss of a data packet is caused by link errors”. However, the authors do not suggest how to react to frame losses due to collisions and how to deal with retransmissions after a frame loss.

Holland, Vaidya, and Bahl proposed a Receiver Based Rate Adaptation scheme (dubbed **RBRA**) [10]. Based on channel conditions sensed through the reception of RTS, the receiver determines the most appropriate data rate that the channel can support and feeds it back in the CTS frame. The sender uses this estimated rate for data exchange. **RBRA** works for both WLAN and multi-hop ad hoc networks, but it requires control (probe) frames such as RTS/CTS. **RBRA** assumes that channel conditions do not vary much between the time RTS is received and the time the data frame is sent.

While this work was in progress, two proposals taking into account loss differentiation in IEEE 802.11 networks were published. The first is called Robust Rate Adaptation Algorithm (dubbed **RRAA**) by Wong, *et al.* [11]. **RRAA** is a loss rate driven scheme. It keeps short term frame loss rates, and adapts the transmission rate accordingly. Beyond that, the authors also proposed “Adaptive RTS Filter” to assess new channel conditions. With this scheme, RTS/CTS are usually turned off, but when a certain number of frames are lost, the RTS frame is turned on to probe channel quality. The authors argue that “Adaptive RTS Filter” is helpful to “prevent collision losses from triggering rate decrease”. The other strategy is proposed by Kim, *et al.* [12], named **CARA**. **CARA** also requires RTS/CTS probing. If a data frame fails without RTS, RTS probing is turned on. **CARA** assumes that all RTS frames at basic rate are resilient to channel fading and concludes that RTS/CTS transmission failures are caused by collision. On the other hand, if RTS is transmitted successfully, but the transmission of the following data frame at higher rate fails then this failure is attributed to channel degradation, and **CARA** decreases the data rate as in **ARF**. **CARA** does not consider the scenario where an RTS frame could be lost due to a receiver node moving out of radio range.

Table I summarizes the characteristics of our proposed **LDRA** and other data rate adaptation algorithms reviewed above.

Scheme	Based	Driven	RTS/CTS Required	Loss Differentiation
ARF	Sender	Loss rate		
Pang	Sender	Loss rate		✓
RBRA	Receiver	RSSI	✓	
RRAA	Sender	Loss rate	✓	✓
CARA	Sender	Loss rate	✓	✓
LDRA	Sender	RSSI		✓

TABLE I
RATE ADAPTION SCHEMES

III. MOTIVATION

A. Motivation ♯1: Initial Rate Estimation

In IEEE 802.11, a periodic *beacon* frame is used for multiple functions [13]:

- Synchronization between wireless stations or between a wireless station and an access point
- Power management
- Broadcast of available data rates.

The beacon, periodically broadcast, is an essential component in infrastructure (WLAN) or infrastructureless networks (Ad-Hoc). Sender based schemes might suffer from their inability to appropriately select a data rate for the very first frame(e.g., at the beginning or just after some long inactivity on the channel). After inactivity, channel conditions may have degraded and a sender may inefficiently send the first frame multiple times at an inappropriate data rate. The mandatory periodic beacon frame provides an opportunity to estimate the optimal data rate for that first frame without the overhead of RTS/CTS control frames.

The beacon based rate estimation would benefit receiver based strategies by estimating the most appropriate data rate for the required RTS/CTS frames. Usually, it is recommended to transmit RTS/CTS frames at the lowest data rate so that they can reliably be received by each station in transmission range. Li *et al.* (Full Auto Rate) [6] showed that higher throughput can be achieved if the RTS/CTS frames are transmitted at a higher estimated data rate based on channel conditions.

B. Motivation ♯2: Benefit of Loss Differentiation

In traditional data rate adaptation schemes, a frame loss is generally (and unduly) interpreted as an indication of wireless channel degradation. Thus they decrease the rate for data frame. However, a frame loss due to collisions does not warrant a data rate decrease. On the contrary, a lower data rate may worsen medium congestion in case of collisions and will incur under-utilization of the medium. On the other hand, a frame loss due to channel degradation should not trigger exponential binary back off (no collision occurred). Loss differentiation is needed to take appropriate actions for each type of loss (congestion or channel degradation).

C. Motivation ♯3: Need for Sender-based Schemes

The RTS/CTS control frames are *optional* in the IEEE 802.11 standard. For small data frames, as is the case for real time applications like VoIP, the use of RTS/CTS dramatically increases the relative overhead. Based on an analysis by Garg and Kappes [14], the use of RTS/CTS control frames yields an efficiency as low as 12% when a unique station is transmitting VoIP traffic with a 160 byte payload. So, RTS/CTS control frames should be used only when data frame size is over some threshold. Receiver based data rate adaptation schemes require RTS/CTS control frames.

A beacon based scheme can also be used to estimate the data rate for the optional RTS/CTS control frames. The benefit of such operation is shown by Li *et al.* (Full Auto Rate) [6].

D. Motivation ♯4: Retransmission Cost Reduction

In state-of-the-art data rate adaptation algorithms, the retransmission after a frame loss is normally performed at the at the most recent data rate (that led to a loss). Such a strategy is not adequate and essentially inefficient when the frame loss occurred due to channel degradation. In such a case, transmissions at the most recent rate only result in repeated frame losses and waste the network bandwidth. If the retransmission is performed at the lowest data rate, it succeeds if the receiver station is still in radio range, although the channel conditions degraded. Therefore, retransmissions cost and efficiency are improved.

IV. Loss Differentiation Rate Adaptation

The proposed scheme, dubbed LDRA in this work, mainly consists of three components: (1) data rate estimation for initial and ongoing transmissions using received signal strength (RSS) from the beacon, (2) data rate selection for retransmissions after a frame loss, and (3) frame loss differentiation with appropriate actions for each type of frame loss. Note that LDRA works for IEEE 802.11 in infrastructure mode as well as in infrastructureless (ad hoc) mode.

A. Rate Estimation:

In IEEE 802.11 infrastructure network, a station that is associated and synchronized with its access point knows the beacon interval. Each station periodically listens for a beacon frame that can be used to measure the channel conditions through the signal-to-noise ratio (SNR), the received signal strength (RSS), the frame loss rate, or the error bit rate. Based on such collected information, the station estimates the most appropriate data rate to communicate with the source of the beacon. The smaller is the beacon interval, the more accurate is the estimation as channel conditions would less drastically change. This is particularly true for low speed mobile nodes or stationary nodes like mesh networks. Even if the beacon interval is comparably large, this estimated rate is still more appropriate than a randomly selected or "guessed" *initial* data rate at the beginning of the transmission.

A supplement to the beacon estimation is to take all communication frames into consideration for adaptive data rate adaptation after two stations start their communication. Such a strategy can provide more accurate estimation if there are multiple transmissions within a beacon interval.

When RSS is collected from the physical layer, LDRA adjusts the data rate R_n such that $R_n = \alpha * R_{n-1} + (1-\alpha) * r$ where r is the instantaneous rate estimated from the received signal strength (RSS). When α is a constant, this equation is similar to Pavon and Chois [5]. We use an adaptive α such that $\alpha = \beta * \frac{R_n - R_{low}}{R_{high} - R_{low}}$ and β is a constant from 0 to 1. R_{low} is the RSS low threshold for a given data rate (e.g. 5.5 Mbps); and R_{high} is the RSS high threshold for the same data rate.

B. Frame Loss Differentiation:

Since no data rate adaptation scheme is perfect, the sender may transmit at a too high data rate, leading to frame losses. A frame can also be lost from transmission collision. A frame loss may hint to decrease the data rate. In **ARF** [3] and other frame loss based rate adaptation schemes, the number of lost frames or the frame loss rate determine the data rate. **ARF** decreases the data rate whenever two consecutive frames get lost, no matter what caused the frame loss. However, a lower rate would unduly hurt performance if the frame loss was due to a collision. Thus, it is critical to determine the cause of a frame loss and take appropriate actions for data rate adaptation.

LDRA exploits the retransmission (after a loss) at the lowest rate retransmission as a tool to accurately diagnose the cause of a frame loss (collision or channel degradation). When a frame loss occurs for the very first time, the sender retransmits the frame at the lowest data rate, instead of the same rate. Such retransmission at the lowest data rate allows the discrimination based on the following cases:

- If the receiver is still within the radio range, then the receiver would most likely receive this retransmitted data frame because of the lowest data rate. Thus the sender can receive the acknowledgement and correctly infer that the loss is due to channel degradation.
- If the retransmitted frame is lost, *and* no beacon is received during the latest *N* beacon periods, the sender can correctly infer that the receiver is *out of range*(for the current channel quality).
- If the retransmission at the lowest data rate is lost, but a beacon frame has been received in the latest *N* beacon periods, then the sender can infer that the loss is rather due to collisions.

After diagnosing the loss, LDRA will take the appropriate actions for each type of loss as explained in the next section.

C. Reactions to Frame Loss:

After a frame is lost, three reactions are proposed to improve network performance upon different loss causes.

Frame loss due to channel degradation: Since the loss is not due to a collision, then the sender should *not* double its contention window as stipulated in IEEE 802.11 [13]. Moreover, based on the last frame exchange at the lowest rate, the sender will estimate the new appropriate data rate.

Frame loss due to out of range receiver: The sender will immediately pause its transmissions until it detects a new beacon frame. This results in two benefits: 1) it eliminates unnecessary network traffic and therefore reduces collisions (or hidden/exposed terminal problems), and 2) it saves power.

For the frame loss identified from a collision: As usual, the sender will invoke, for good reason, the binary exponential backoff mechanism, but will not decrease the data rate: a lower data rate does not remedy or alleviate collisions. On

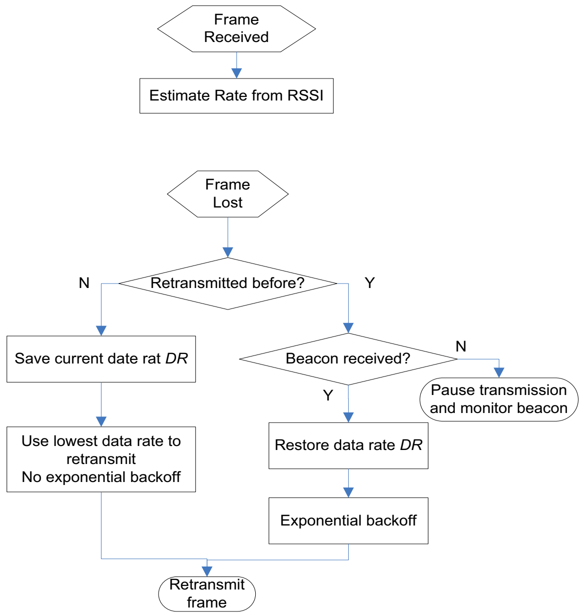

Fig. 1. LDRA Algorithm Flow Chart

the contrary, a lower data rate increases radio coverage and thus may *worsen* interference and collisions. Therefore, the sender should maintain the current data rate after a collision. This is a critical difference from traditional data rate adaptation algorithms without loss differentiation.

The LDRA core algorithm is illustrated by the flow chart in Figure 1.

V. Justification for Retransmissions at the Lowest Rate

In IEEE 802.11b [15], there are four modulation schemes: BPSK (1Mbps), QPSK (2Mbps), CCK5.5 (5.5Mbps), CCK11 (11Mbps). We analyze the expected time required to successfully transmit a frame for each modulation in different signal-to-noise ratio (SNR) environments. In IEEE 802.11, the FER (Frame Error Rate) is associated with a frame length of 1024 bytes. If the bit error rate (BER) p is very small and losses are independent, then the corresponding FER can be approximated as $p*1024*8$. The expected number of required transmissions for a frame to be successfully transmitted is $\frac{1}{1-FER}$. The expected transmission time at *frame rate bw* is $\frac{1}{(1-FER)*bw}$. Based on the bit error rate data reported by Wu [16], Figure 2 illustrates the relationship between expected transmission time and SNR for different modulations. The x-axis represents the signal-to-noise ratio (SNR), and the y-axis is the expected transmission time. Bianchi *et al.* [17] observed that the signal-to-noise ratio in outdoor environment is usually less than 6 db for 802.11b/g. From Figure 2, it can be observed that, if a frame is transmitted at 5.5 Mbps or 11 Mbps in an environment with signal-to-noise ratio less than 6 db, it has to be retransmitted so many times that transmissions are unlikely to succeed. But for the lowest rate of 1 Mpbs or 2 Mbps, a frame will successfully be transmitted almost every time in

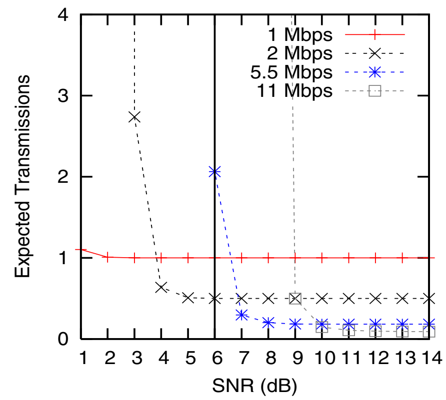

Fig. 2. Expected Transmission

low SNR. Thus, in traditional retransmission schemes, even if a frame is lost from channel fading with a very low SNR, CSMA/CA always assumes the loss to be due to collision. It backs off and retransmits the frame at the same high data rate again for several times. As illustrated by Figure 2, this retransmission strategy is wasteful and doomed for frame loss resulting from channel fading. Thus, it is important to retransmit at the lowest data rate and differentiate the reason of a frame loss.

VI. Experiments and Simulations

In this section, we mainly evaluate the network performance improvement by **LDRA** over other existing algorithms with frame loss from wireless transmission collision and channel fading.

Simulation Configuration: LDRA is simulated in IEEE 802.11b WLAN and ad hoc modes with ns-2 [18] (version 2.29). Three data rates are used: 11 Mbps, 5.5 Mbps and 2 Mbps. The proposed scheme is compared with ARF [3] and Adaptive Auto Rate [5] through simulations of a single flow and then multiple competing flows. All wireless stations are within a 500mx500m area that is covered by the signal of the access point located at the center. For mobile nodes, the velocities are from 2 m/s to 14 m/s.

We simulate the channel fading with the two-ray ground fading model. The two-ray ground fading model [19] is a large scale fading model. According to this model, the signal received is composed of two components: the line-of-sight through the direct path and the wave reflected by ground. In general, the power of the received signal at a location is proportional to the exponent of the transmission distance, which follows:

$$P_r = P_t \Gamma \frac{1}{d^4} \tag{1}$$

where P_t is the power of the signal at the transmitter; Γ represents the antenna factors, such as the heights, the antenna gains; and the d is the transmission. With the two-ray ground fading, the signal-to-noise ratio is constant at the receiver if both the receiver and the transmitter are static at some locations.

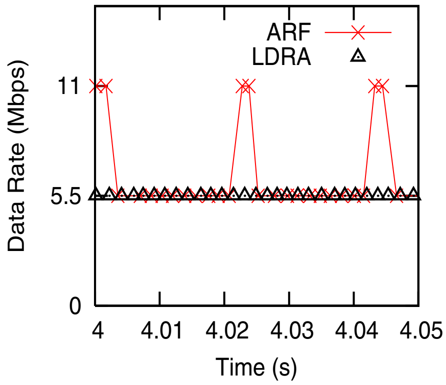

Fig. 3. Rate Adaptation Comparison

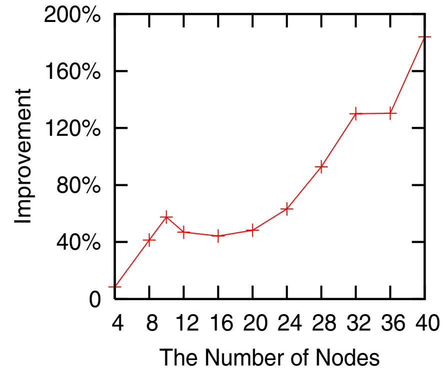

Fig. 5. Improvement with Network Density

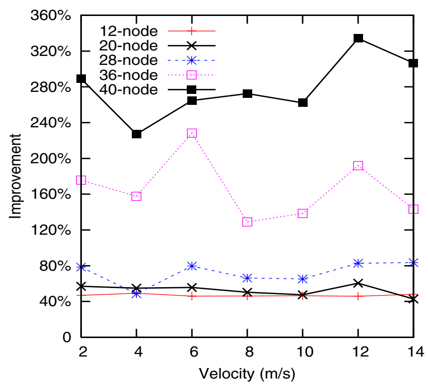

Fig. 4. Throughput Improvement at Different Velocity

Data Rate Adaptation: First, LDRA is compared with ARF to show LDRA's ability to converge to a steady data rate. The first experiment consists of one mobile client node and one access point. The client node randomly moves at speeds from 1 m/s to 10 m/s within an area such that 5.5 Mbps is the most appropriate data rate. Figure 3 plots the results: the x-axis represents the time and the y-axis is the data rate. Figure 3 shows, as expected, that ARF frequently changes the data rate because it blindly makes adjustments regardless of wireless channel conditions. Under the same conditions, the proposed scheme, LDRA, remains steady at the appropriate data rate of 5.5 Mbps.

Throughput Improvement: We define throughput improvement of LDRA over some scheme X as $\frac{Throughput_{LDRA} - Throughput_X}{Throughput_X}$. UDP CBR is used as the traffic in most experiments, except the last case testing TCP flows.

Figure 4 plots the throughput improvement in an experiment for different network densities by varying the number of mobile nodes at different velocities from 2 m/s to 14 m/s in a WLAN network. The x-axis is for velocity and the y-axis represents the network throughput improvement with different node densities. The different curves in the figure represent results for different numbers of mobile nodes. As shown on the figure, although the velocity impacts throughput, it does not significantly impact the *improvement*. The improvement sharply increases with nodes density. This is due to LDRA's ability to correctly distinguish a frame loss due to collisions and from one due to wireless channel fading. As collisions increase in denser networks, LDRA exploits its ability to correctly diagnose collision losses and to maintain the original data rate. With ARF, the node unduly decreases the data rate. As collisions increase, LDRA performs better than ARF, leading to a better throughput improvement.

The relationship between throughput improvement and network density is even stronger from the simulation results depicted in Figure 5. In this scenario, the mobile nodes move at random velocity in an ad hoc network. The x-axis and y-axis respectively represent the number of mobile nodes in network and the throughput improvement.

We also compare the throughput improvement from LDRA with that from work by Pavon and Choi [5] in ad hoc network. In this simulation setting, we vary the network density by increasing the number of nodes moving within one flat area. Figure 6 illustrates the results. Note that the benefits from LDRA are more remarkable as the network density increases. In low network density, the adaptive scheme [5] performs better than LDRA, because it adapts the data rate more frequently than the beacon frequency imposed on LDRA. But in a high node density environment, LDRA outperforms it, due to the ability to differentiate losses.

Another set of experiments were carried with TCP flows. Different numbers of TCP flows are tested for LDRA and ARF. The first scenario measures the improvement of the total network throughput of all TCP flows. We increase TCP flows by adding more mobile nodes, each node with one TCP flow to the access point. The simulation results are plotted in Figure 7. The x-axis represents the number of TCP flows. The y-axis represents the overall network throughput improvement of LDRA over ARF. This figure shows a dramatic improvement up to almost 100% for different scenarios.

Delay Jitter Improvement: Figure 8 shows a significant improvement of delay jitter in WLAN by LDRA over ARF. Delay jitter is defined as the time difference in delay between two successive frames. We collect the maximum delay jitter

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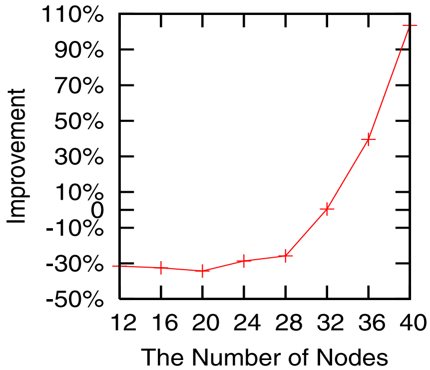

Fig. 6. Improvement with LDRA vs Adaptive

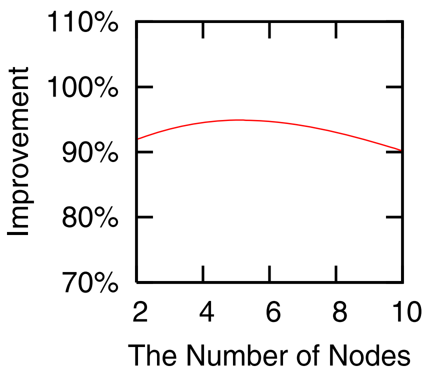

Fig. 7. Throughput Improvement in TCP

for each scheme to compute the delay jitter improvement as $\frac{DelayJitter_{ARF}-DelayJitter_{LDRA}}{DelayJitter_{LDRA}}$. The experiment involves one mobile client node and its access point with a UDP flow. The x-axis and y-axis respectively represent the velocity and the delay jitter improvement. Retransmissions at the lowest data rate substantially contribute to this improvement because the number of retransmissions is minimized by LDRA. LDRA, with the lowest data rate retransmission, induces less variability of delay after a frame loss and therefore yields a lower delay jitter than ARF.

VII. Conclusion

This work presents a Loss Differentiated Rate Adaptation (LDRA) scheme to dynamically adjust the data rate in a wireless network. LDRA measures channel conditions through the periodic beacons and determines the most appropriate data rate. By retransmitting at the lowest data rate after a loss, LDRA is able to correctly diagnose the real cause of a frame loss and to take appropriate actions. For losses not related to collisions, the mobile node does not double its contention window. For losses due to collisions, LDRA does not decrease its data rate. This ability of loss differentiation significantly improves throughput. Additionally, retransmissions at the lowest data rate minimize the expected number of retransmissions after a loss and reduce both the delay and the delay jitter.

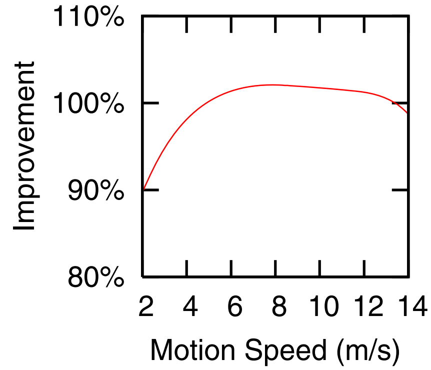

Fig. 8. Delay Jitter Improvement

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