An Innovative Rate Adaptation Algorithm for Multicast Transmissions in Wireless LANs

Stefano Paris* and Nicolò Facchi† and Francesco Gringoli† and Antonio Capone‡

* LIPADE
Paris Descartes University
stefano.paris@parisdescartes.fr

† Department of Information Engineering
CNIT - University of Brescia
firstname.lastname@ing.unibs.it

‡ DEI
Politecnico di Milano
capone@elet.polimi.it

***Abstract*—Rate adaptation represents a key functionality of the 802.11 MAC protocol for performance enhancement. Several solutions have been proposed for improving the transmission rate of unicast communications using frame receptions/losses, BER (Bit Error Rate) and SNR (Signal to Noise Ratio) measurements. Nevertheless, rate adaptation for multicast transmissions represents a more challenging tasks due to the complexity of estimating the reception correlation of wireless links.**

This paper presents a novel scheme for selecting the best transmission rate for multicast communications using the packet reception correlation of the links established among the nodes of the multicast group with the access point.

The proposed algorithm has been evaluated on a real-life testbed using commercial wireless cards. The results show that our solution accurately estimates the reception correlation of wireless links, thus considerably increasing the performance of multicast transmissions up to 3x and 5x in terms of throughput and delay, respectively.

Keywords-Multicast Rate Adaptation, Multimedia Communication, Wireless Networks.

I. Introduction

The time-varying nature of the wireless channel due to effects like signal attenuation, fading, scattering and external interference causes transmission errors and frame losses that, in turn, make hard to model accurately the quality of the wireless link. To overcome these problems and improve the throughput of radio communications, several technologies, including IEEE 802.11, adopt rate adaptation techniques, which dynamically adjust the transmission rate of the sending node according to the channel conditions.

Rate adaptation algorithms based on frame losses have been firstly designed for unicast communications, since the ARQ mechanism implemented by the IEEE 802.11 MAC protocol provides the necessary information to control effectively the data rate. These rate adaptation algorithms differ mainly for the type of information used to estimate the link quality. In particular, they can be broadly divided into three main categories: frame reception/loss rate [1], [2], BER (Bit Error Rate) [3] and SNR (Signal to Noise Ratio) [4].

Some preliminary solutions have been also proposed to dynamically adapt the transmission rate of multicast communications [5], [6]. All these algorithms define a feedback mechanisms both to notify the AP when some of the multicast group stations does not receive successfully a data frame and to collect the necessary information to select the transmission rate. However, due to the complexity of collecting information related to the reception correlation of all multicast stations, most of the IEEE 802.11 commercial cards use the lowest available data rate for multicast/broadcast transmissions. Nevertheless several multimedia applications that exploit broadcast data transmissions at the MAC layer, like video streaming, would benefit from the utilization of higher transmission rates.

In order to assess the reception correlation of the stations that belong to the multicast group, we design an adaptive mechanism to estimate the joint reception probability using a novel feedback protocol that can be seamlessly integrated with the IEEE 802.11 PCF (Point Coordination Function) to minimize the signaling overhead. The estimated joint reception probability is then used to select the data rate that minimizes the transmission time necessary to deliver reliably a single data frame to all station of the multicast group; thus improving the overall goodput.

Our work makes the following contributions:

- We propose an innovative algorithm to adjust the transmission rate of multicast frames in order to jointly improve the throughput and the delay of multicast communications in wireless LANs.
- We design an adaptive approach to compute the inter-link reception correlation in wireless networks.
- We integrate both algorithms within the Linux mac80211 middleware and evaluate their performance on a real-life testbed composed of off-the-shelf nodes based on Broadcom 802.11g Wireless NICs.
- We perform a thorough evaluation of the proposed mechanism in realistic network scenarios.

Experimental results show that the proposed rate adaptation algorithm improves the network performance with respect to fixed rate solutions currently implemented by standard wireless drivers. In particular, our solution achieves a gain ranging from 2x to 3x in terms of throughput experienced by multimedia applications, while reducing the transmission delay up to 5 times.

The paper is structured as follows: Section II discusses related work. Section III presents the rate adaptation algorithm we propose for multicast transmissions and the mechanism used to estimate the correlation affecting the links of the multicast group. Section IV illustrates the results which show the validity of our approach. Finally, concluding remarks are discussed in Section V.

II. Related Work

In recent years, several rate adaptation algorithms for unicast communications over IEEE 802.11 wireless channels have been proposed to improve the throughput experienced by upper layer protocols and applications.

The Collision Aware Rate Adaptation scheme (CARA) proposed in [2] combines information obtained both from the RTS/CTS frame exchange and the CCA-based backoff to evaluate the channel status and select accordingly the transmission rate In [1] the authors improve the stability of frame losses based schemes through the design of Robust Rate Adaptation Algorithm (RRAA) that uses a transmission rate as long as rate switching does not lead to goodput enhancements. The work [7] further extends RRAA considering past transmission outcomes to avoid the selection of those data rates that offered low performance.

SNR-triggered schemes select the highest transmission rate that permits to obtain a target frame delivery rate using SNR-BER relationships. To improve the accuracy of the prediction mechanism in the presence of external interference, which affects the SNR-BER relationship, Zang *et al.* propose the SGRA (SNR-Guided Rate Adaptation) [4].

BER-based solutions like SoftRate [3] and AccuRate [8] estimates respectively the bit error rate (BER) and the error vectors of every PHY symbol to predict the expected frame delivery rate achievable using a given transmission rate.

Conversely, multicast transmissions have received less attention due to the complexity of implementing an efficient feedback mechanism to collect the information used by the rate selection routine. For example, multicast rate adaptation schemes like [5], [6] adjust the data rate according to the lowest SNR among those perceived by the stations of the multicast group. However, the rate control based on the worst SNR does not guarantee necessarily the same delivery probability to all stations of the multicast group, since the joint reception probability may differ.

Unlike previous solutions, *rate-less* mechanisms like Strider [9] exploits forward error correction schemes to improve the throughput of wireless communications.

Our proposed solution falls in the category of mechanisms based on the frame delivery probability estimation. Nonetheless, to the best of our knowledge, our mechanism is the first algorithm which measures adaptively the joint reception probability of multicast members.

III. Rate Adaptation for Multicast Transmissions

This section presents the algorithm that we propose to adapt the transmission rate according to the joint reception correlation of the wireless links established between the AP and the stations of a multicast group.

A. Rate Adaptation Algorithm

The algorithm executed by the AP probes adjacent transmission rates and collect information from the stations of the multicast group to assess whether the rate change may lead to goodput improvements.

In order to inform the AP about the multicast frames received correctly, we designed a feedback mechanism coordinated by the AP. Specifically, we define a temporal super-frame composed of two periods which defines two different operating modes, namely the transmission and polling periods.

The super-frame, which is illustrated in Figure 1, starts always with a transmission period during which all nodes that belong to the same Basic Service Set (BSS) operate using the standard CSMA medium access mechanism to transmits their data traffic. In particular, during this period, the AP sends multicast frames to the stations using the transmission rate selected by the proposed algorithm according to the measurements collected in the previous round. Stations collect the sequence numbers extracted from the Sequence Control field of the received frames to build the information that they will feedback to the AP during the polling period. During the polling period the AP polls stations to obtain the necessary information to compute the reception correlation of the different wireless links and select the best transmission rate that maximize the throughput of the receiving stations. The AP sends a single poll frame at the same multicast group and then waits for the feedbacks that each station transmits as a unicast data frame. If some feedback frame is lost, the AP retransmits the poll after a short timeout for a maximum of n_a attempts.

In the experiments, we set the timeout considering propagation delays, transmission times of the poll and the successive response at the lowest bit-rate, whereas n_a has been fixed to 7 attempts.

Note that, the implementation of the poll procedure using the ACK piggyback algorithm proposed in [10] can further reduce the overhead caused by the feedback mechanism.

The proposed rate adaptation mechanism is summarized in Algorithm 1. It receives as input the set of stations that belong to the multicast group, and it outputs the data rate which should be used in the successive transmission phase to improve the goodput of multicast communications.

The algorithm proceeds in 3 steps. After the AP has transmitted K consecutive multicast frames, it starts the polling phase (step 1) and collects the information used in step 2 to compute the joint reception probability of the wireless links connecting the AP with the stations involved in multicast communications. Finally, in step 3, the AP computes the best data rate to be used for the successive multicast transmissions in order to improve the goodput, as illustrated in Section III-C.

B. Estimation of the Frame Reception Correlation

The proposed rate adaption algorithm resorts on a slightly modified version of the adaptive scheme proposed in [11] for estimating the correlation of frame receptions and losses of different wireless links. Hereafter, we summarize the mechanism, which has been tailored for the single hop scenario considered in this work, and we illustrate how it can be integrated within the 802.11 MAC protocol.

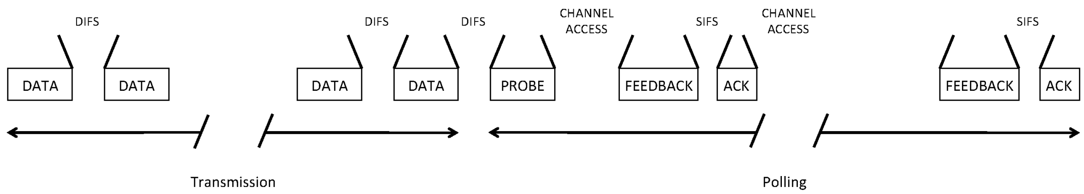


Fig. 1: Super-frame used by the multicast rate adaptation algorithm executed by the AP to estimate the joint delivery probability.

Algorithm 1: Multicast Rate Adaptation

Input : $\mathcal{N}$
Output: r
if $phase = polling$ **then**
  foreach $i \in \mathcal{N}$ **do**
    $(bm_i(e), s_i(e)) \Leftarrow$ poll_station(i);
  end
  $p_{e-1} \Leftarrow$ joint_rx_prob($\mathbf{bm}(e), \mathbf{s}(e), \mathbf{s}(e-1), f^{tx}$) ;
  if $e \geq 2$ **then**
    $r_e \Leftarrow$ tx_rate($r_{e-2}, p_{e-2}, r_{e-1}, p_{e-1}$) ;
  end
end

Upon receiving the poll frame from the AP, each station sends back within the feedback frame the information related to the multicast frames correctly received in the last transmission period. The feedback accommodates the sequence number of the last received multicast data frame, s_i, and a bitmap of size K bits, b_i, whose k^{th} bit represents the reception ($b_{ik} = 1$) or the loss ($b_{ik} = 0$) of the data frame identified by sequence number $\lfloor s_i/K \rfloor \cdot K + k$.

Upon collecting all information from the stations of the multicast group, namely sequence numbers and bitmaps, the AP computes the joint reception probability $P^{(t)}_{1,2,\ldots,n}(\mathbf{1})$ that the destination nodes of links $(t,1)$, $(t,2)$, ..., (t,n) received the same packet from t, according to (1). In this equation, the function $\zeta(bm)$ counts the number of '1' in the bitmap bm, whereas f^{tx} is the number of multicast data frames considered for the computation of $P^{(t)}_{1,2,\ldots,n}(\mathbf{1})$.

$$P^{(t)}_{1,2,\ldots,n}(\mathbf{1}) = \frac{\zeta(\wedge_{i \in \mathcal{N}} bm_i)}{f^{tx}} \tag{1}$$

As illustrated in the example network scenario of Figure 2, each station $i \in \{1,2,3\}$ sends in the feedback frame the tuple containing the bitmaps and the sequence number corresponding to the multicast data frames received from the AP t. Since the poll is done synchronously by the AP at the end of a transmission period, all received feedbacks should report information about the same set of transmitted multicast frames. To this end, the AP uses the minimum $s_i(e)$ among all received sequence numbers of the period e, $s_{i,min}(e)$, to remove the unnecessary bits that represent frames received only by a subset of the multicast group.

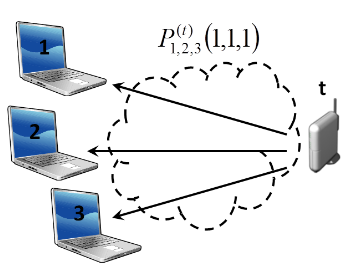


Fig. 2: Network topology.

Note that when $s_{i,min}(e)$ is lower than the sequence number of the first multicast frame transmitted in the previous round, then some stations have not received any frame. In this case, we assume that the station has left the multicast group, and the algorithm proceeds using only the information obtained by the remaining stations. Indeed, if a station does not receive the polls, which are transmitted by the AP at the lowest bit-rate, it cannot receive even data frames.

On the contrary, when $s_{i,min}(e)$ is greater than the sequence number of the first multicast frame transmitted in the previous round, all received bitmaps can be used to compute the joint reception probability. Indeed, the ratio between the number of '1', resulting from the logical AND of all bitmaps and the number of K data frames transmitted in the last transmission period, represents the joint reception probability of the links established by the AP with all stations of the multicast group.

The mechanism used by the AP to estimate iteratively the joint reception probability at the end of a transmission period e is listed in Algorithm 2. The function $LeftShift\_0(mask, n)$ shifts the bits of the bitmap $mask$, which has been initialized with K '1', by n positions on the left. The auxiliary bitmap $mask$ is therefore used to consider only the data frames that might be received by all stations of the multicast group. To illustrate how the joint reception probability is evaluated at the end of the polling interval e (i.e., before the transmission period $e+1$), let us refer to the example scenario shown in Figure 3, which depicts the bitmaps and the sequence numbers collected by the AP t from the three stations of Figure 2. Since all bitmaps, whose length is $K = 64$ bits, are perfectly aligned and $s_{i,min} = 509$, the algorithm will compute the joint

---

Algorithm 2: Joint Reception Probability Estimation

input : $\mathbf{bm}(e), \mathbf{s}(e), \mathbf{s}(e-1), f^{tx}, f^{rx}$
output: $P^{(t)}_{1,2,\ldots,n}(\mathbf{1})$
$s_{i,min} = \min\{\mathbf{s}(e)\}$;
$mask = \mathbf{1}_k$;
$mask = LeftShift\_0(mask, K - (s_i(e)\%K) - 1)$;
$f^{rx} = \zeta(\wedge_{i \in \mathcal{N}} bm'_i \wedge mask)$;
$P^{(t)}_{1,2,\ldots,n}(\mathbf{1}) = \frac{f^{rx}}{K}$;

---

probability using only the frames lying in the range $[448; 509]$, which correspond to bits within the range $[0; 61]$.

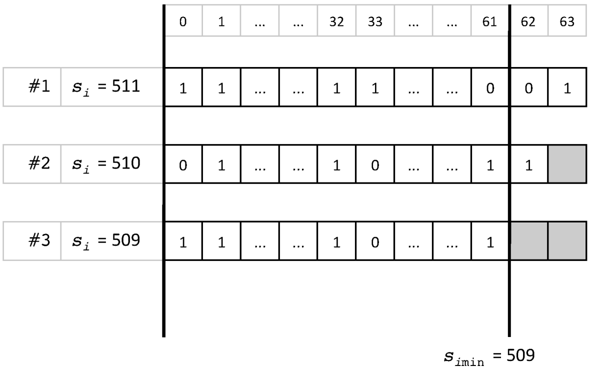


Fig. 3: Joint reception probability estimation. The sequence number of the last transmitted data frame is $s_i(e) = 511$ and $K = 64$. However, only station 1 received the frame 511. The last frame received by stations 2 and 3 was respectively 510 and 509.

C. Selection of the Transmission Rate

The function selecting the transmission rate r_e used in round e (i.e., $tx\_rate(P^{(t)}_{1,2,\ldots,n}(\mathbf{1}))$ in Algorithm 1) is performed using the information collected in the previous last two rounds. Specifically, let us define p_{e-1} and p_{e-2} as the joint reception probabilities $P^{(t)}_{1,2,\ldots,n}(\mathbf{1})$ measured at the end of the previous two transmission rounds. Furthermore, let r_{e-1} and r_{e-2} be the transmission rates used in these periods. Then, the average number of transmissions that should be performed by the AP to successfully deliver a data frame to all members of the multicast group during the round $e-1$ can be computed as follow:

$$N(p_{e-1}, r_{e-1}) = \sum_{i=1}^{\infty} i \cdot p_{e-1} \cdot (1 - p_{e-1})^{i-1} = \frac{1}{p_{e-1}}. \tag{2}$$

Assuming the same size L for all multicast frames, the average time necessary to deliver reliably a data frame to all members of the multicast group using the transmission rate r_{e-1} during the round $e-1$ is equal to Equation (3):

$$T(p_{e-1}, r_{e-1}) = N(p_{e-1}, r_{e-1}) \cdot \frac{L}{r_{e-1}} = \frac{L}{r_{e-1} \cdot p_{e-1}}. \tag{3}$$

Similarly, the average number of transmissions and the time necessary to deliver successfully a data frame to all members of the multicast group during the round $e-2$ are $N(p_{e-2}, r_{e-2} = {}^{1}\!/_{p_{e-2}}$ and $T(p_{e-2}, r_{e-2}) = \frac{L}{r_{e-2} \cdot p_{e-2}}$, respectively.

The selection of the transmission rate to be used in round e, r_e, is performed comparing the transmission times of two previous rounds according to the following rule:

$$j = index\_of(\mathbf{R}, r_{e-1}),$$
$$r_e = \begin{cases} \mathbf{R}[j+1] & \frac{T_{e-1}}{t_{e-2}} \leq 1 \\ \mathbf{R}[j-2] & \frac{T_{e-1}}{t_{e-2}} > 1. \end{cases} \tag{4}$$

In Equation (4), $\mathbf{R}$ represents the list of available transmission rates, while the function $index\_of(\mathbf{R}, r_{e-1})$ returns the index of rate r_{e-1} (i.e., the data rate used for the round $e-1$) within the list $\mathbf{R}$. We assume that when $j \leq 2$, $\mathbf{R}[j-2]$ is simply equal to the lowest transmission rate of the list.

Given the set of transmission rates available with the IEEE 802.11 a/g standards, the rule defined in Equation (4) approximates a linear-increase/multiplicative-decrease adaptive rule. When the transmission time between two consecutive rounds decreases or remains constant, the adaptation algorithm attempts to further reduce the transmission time by increasing the data rate that will be used in the successive round. Indeed, assuming that the joint reception probability does not vary sharply between two consecutive transmission rates, the rate increase would reduce the overall transmission time, thus increasing the goodput perceived by the stations of the multicast group. On the contrary, when the transmission time increases, the adaptation algorithm halves the data rate to recover quickly from an unreliable operating state. In this case, the increase of the transmission time is caused by the degradation of the joint reception probability, which would require more transmissions to deliver successfully a single data frame to all stations.

Note that the transmission rate is increased even when there is no performance improvement between two consecutive rounds, to prevent the utilization of a suboptimal transmission rate. Indeed, as long as the joint reception probability does not decreases is always better off using higher transmission rates to improve the network performance.

IV. Experimental Results

We discuss in this section the experimental results achieved by the proposed multicast rate adaptation algorithm in a real-life wireless network. We first introduce the experimental methodology and we later illustrate the performance improvements that we measured with respect to the standard fixed rate implementation.

A. Experimental Methodology

We evaluated our solution in a real-life network scenario composed of one Access Point (AP) and 4 Stations (STAs) inside the Department of Information Engineering at the University of Brescia: the AP and three stations, which are located inside the same lab, are desktop computers, whereas the fourth station is an Alix D2D node connected to a battery and free to move. All nodes are equipped with a Broadcom 4318 wireless NICs. As can be seen from Figure 4, at the beginning of the experiment, all stations are lined up 10 meters on the right of the AP. We moved the mobile node farther away from the AP towards its right, alongside the corridor with steps of five meters, for testing the behavior of the proposed technique with increasing attenuation and fading effects over the received signal. The massive presence of floor-to-ceiling walls and solid steel glass doors, in fact, makes the corridor adverse to the propagation of the signal, thus leading to different delivery probabilities at the four receiving stations. For each position at which we placed the mobile node in the corridor, the AP performs three tests with fixed transmission rate and three with the rate selected by the technique proposed in the previous

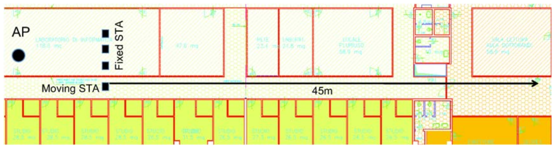


Fig. 4: Testbed with three fixed stations and one mobile node.

Section. During each test the AP works as a greedy CBR source generating 150000 multicast packets that saturate the channel, which is interference free with respect to surrounding BSS. The packet payload size is fixed to 1470 bytes, which is equal to the value used by several video streaming applications based on the Real Time Protocol (RTP).

We consider as performance metrics the *Average Goodput*, namely the average bandwidth actually used for successful transmission of useful data (the application-layer payload), and the *Average Delay* of the multicast transmissions measured by the four STAs.

B. Network Performance Analysis

Figure 5(a) shows the average goodput as a function of the distance between STA 4 and the AP, which is the device hosting the CBR source.

It can be observed that in all experimental scenarios, the proposed multicast rate adaptation algorithm outperforms the fixed rate solution implemented by commercial APs. In particular, we obtain a performance increase ranging from 230% to 330%, when STA 4 is moved away from 10 to 55 meters from the AP. The reason for the uneven variation of the throughput with distance is the highly irregular geometry of the environment which makes multipath effect important: a small movement of the mobile node may have a dramatic effects as can be seen when moving from 25 to 30 meters, the throughput shows a sharp increase and then starts decreasing again (same effect when moving from 45 to 50 meters).

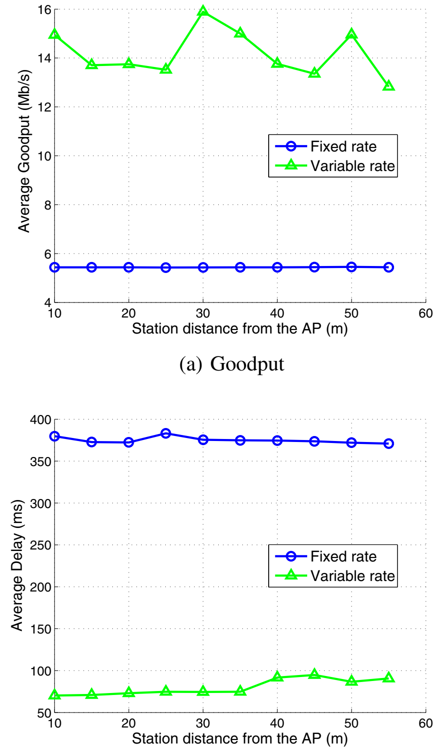
To provide a more in-depth comparison, we also measured the Average Delay incurred by the broadcast data transmissions of the CBR application. The corresponding results are illustrated in Figure 5(b). It can be observed that the proposed algorithm permits to reduce the one-way delay up to 5 times with respect to the standard solution adopted by commercial WiFi cards.

V. Conclusion

This paper proposed an innovative scheme that uses the frame reception correlation of wireless links for adapting the data rate of multicast transmissions in wireless LANs based on the 802.11 MAC protocol.

The proposed solution has been implemented in the mac80211 middleware of the Linux kernel and its performance has been evaluated on a real-life testbed.

Experimental results show that the proposed rate adaptation algorithm improves the throughput of multicast communications up to 300% with respect to fixed rate solutions, while reducing the transmission delay up to 5 times, thus representing a promising solution to enhance the performance of multicast transmissions.



(a) Goodput

(b) Delay

Fig. 5: Average Goodput, and Delay as a function of the distance of STA 4 from the AP.

Acknowledgment

This work was supported by the European Commission through the FP7 FLAVIA Project.

References

[1] S.H.Y. Wong, H. Yang, S. Lu, and V. Bharghavan. Robust Rate Adaptation for 802.11 Wireless Networks. *ACM MobiCom*, pages 146–157, 2006.

[2] J. Kim, S. Kim, S. Choi, and D. Qiao. CARA: Collision-aware Rate Adaptation for IEEE 802.11 WLANs. *IEEE INFOCOM*, 6:1–11, 2006.

[3] M. Vutukuru, H. Balakrishnan, and K. Jamieson. Cross-Layer Wireless Bit Rate Adaptation. *ACM SIGCOMM*, 39(4):3–14, 2009.

[4] J. Zhang, K. Tan, J. Zhao, H. Wu, and Y. Zhang. A Practical SNR-guided Rate Adaptation. *IEEE INFOCOM 2008*, pages 2083–2091, 2008.

[5] J. Villalón, P. Cuenca, L. Orozco-Barbosa, Y. Seok, and T. Turletti. Cross-layer Architecture for Adaptive Video Multicast Streaming over Multirate Wireless LANs. *IEEE Journal on Selected Areas in Communications*, 25(4):699–711, 2007.

[6] A. Basalamah, H. Sugimoto, and T. Sato. Rate Adaptive Reliable Multicast MAC Protocol for WLANs. *IEEE Vehicular Technology Conference*, 3:1216–1220, 2006.

[7] I. Pefkianakis, S.H.Y. Wong, H. Yang, S.B. Lee, and S. Lu. Towards History-Aware Robust 802.11 Rate Adaptation. *IEEE Transactions on Mobile Computing*, 99, 2012.

[8] S. Sen, N. Santhapuri, R.R. Choudhury, and S. Nelakuditi. AccuRate: Constellation Based Rate Estimation in Wireless Networks. *USENIX NSDI*, pages 12–12, 2010.

[9] A. Gudipati and S. Katti. Strider: Automatic rate adaptation and collision handling. *ACM SIGCOMM*, 41(4):158, 2011.

[10] P. Salvador, F. Gringoli, V. Mancuso, P. Serrano, A. Mannocci, and A. Banchs. VoIPiggy: Implementation and Evaluation of a Mechanism to Boost Voice Capacity in 802.11 WLANs. *IEEE INFOCOM*, 2012.

[11] S. Paris and A. Capone. Correlation of Wireless Link Quality: A Distributed Approach for Computing the Reception Correlation. *Communications Letters, IEEE*, (99):1–3, 2011.