An Empirical Study of Analog Channel Feedback

Wei-Liang Shen†‡, Kate Ching-Ju Lin† and Ming-Syan Chen†‡
†Research Center for Information Technology Innovation, Academia Sinica, Taiwan
‡Department of Electrical Engineering, National Taiwan University, Taiwan

Abstract: Exchanging the channel state information (CSI) in a multiuser WLAN is considered an extremely expensive overhead. A possible solution to reduce the overhead is to notify the analog value of the CSI, which is also known as *analog channel feedback*. It however only allows nodes to overhear an imperfect channel information. While some previous studies have theoretically analyzed the performance of analog channel feedback, this work aims at addressing issues of realizing it in practice and empirically demonstrating its effectiveness. Our prototype implementation using USRP-N200 shows that analog channel feedback produces a small error comparable to that of estimating CSI using reciprocity, but however can be applied to more general scenarios.

Categories and Subject Descriptors C.2.2 [**Computer Systems Organization**]: Computer-Communications Networks

General Terms Experimentation, Measurement

Keywords Analog Channel Feedback, MIMO

1. INTRODUCTION

Exchanging the CSI in a multiuser WLAN is considered an extremely expensive overhead. A possible solution to overhead reduction for channel feedback is to leverage *channel reciprocity*, which is a property that the channels in the forward and reverse directions are the same. Consider a scenario where Alice is interested in knowing the channel between Alice and Bob, which is called the forward channel in this work. To obtain the perfect channel information, Bob should learn the channel from the preamble sent by Alice, and send it back to Alice. However, by leveraging reciprocity, we can ask Bob to send a preamble for Alice to learn the channel between Bob and Alice, called the reverse channel, and use it to estimate the forward channel without channel feedback.

Though learning the CSI using reciprocity has been empirically shown feasible in many practical systems, e.g., [1, 2], it however has two limitations. First, it requires *hardware calibration* [1], which incurs additional overhead and could be performed imperfectly, affecting accuracy of channel estimation. Second, and more importantly, reciprocity is only applicable to the above Alice and Bob example, where a node wants to feedback the forward channel to its own source, i.e., Alice. It however cannot be applied to a general scenario where Bob needs to feedback its forward channel to a node other than its source, say Chris. This scenario is actually quite common and necessary for many applications, e.g., interference alignment and MU-MIMO rate adaptation.

To address the above issues, an alternative solution is to notify the analog value of the CSI without modulation and coding, also known as *analog channel feedback* [3], which requires significantly less overhead than traditional quantized (digital) channel feedback. Any node that overhears the analog information can recover the imperfect but accurate enough CSI. While some previous theoretical works [3] have analyzed the performance of analog channel feedback, this work aims at addressing issues of realizing it in practice and empirically demonstrate its benefit and limitation. Our prototype implementation using USRP-N200 shows that analog channel feedback produces a small error comparable to the error of learning CSI using reciprocity, but however can be applied to more real applications.

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2. ANALOG CHANNEL FEEDBACK

In this section, we first introduce analog channel feedback, and discuss how to apply it in a MIMO system. We finally investigate practical issues of realizing it in practice.

Analog channel feedback in a SISO system: The high level idea of *analog channel feedback* is that, unlike the traditional approach, which represents data as digital (discrete) values, *analog channel feedback* represents the CSI as analog (continuous) values, and transmits these analog values directly without modulation and coding. Any node that overhears the information can simply decode the received signal and get the channel information without demodulation and the CRC check. The main difference is that the traditional digital channel feedback ensures a node to receive exactly the same channel information with what the notifier learned if it passes the CRC check, while a node receiving analog channel feedback could recover imperfect channel information with additive channel noise.

Lets consider again the Alice and Bob example. Assume that Bob wants to announce the channel between Alice and Bob $h_{AB} = a + bi$. The traditional digital channel feedback requires Bob to convert the real part of h_{AB} to the binary number, e.g., $(a)_{10} = (001 \cdots 0)_2$, and convert the image part to another binary number. It hence costs two floating points to represent h_{AB}. Analog channel feedback differs from the traditional approach in that Bob directly transmits the complex number of the channel information $h_{AB} = a + bi$ without any binary quantization and modulation, and hence costs only one sample to send h_{AB}. Any neighboring node, say Chris, overhears the analog feedback $y = h' * h_{AB} + n$, where h' is the channel between Bob and Chris and n is the additive channel noise. Chris can hence

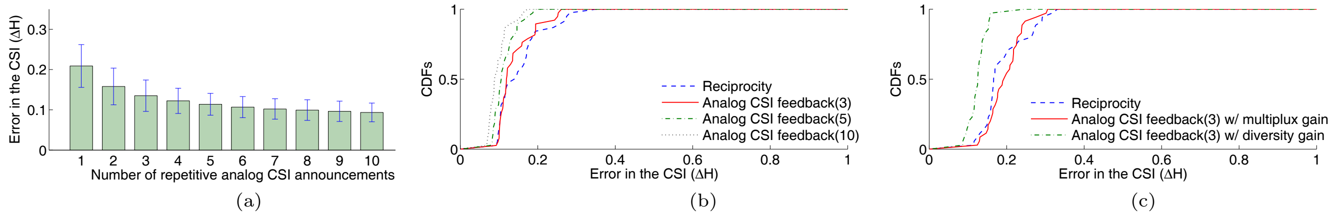

Figure 1: (a) Error in analog channel feedback, (b) Accuracy comparison for 1x1 link, (c) Accuracy comparison for 2x2 link

recover h_{AB} by decoding y, i.e., $\tilde{h}_{AB} = y/h' = h_{AB} + n/h'$. Accuracy of such imperfect channel information depends on the error n/h'. To apply analog channel feedback in OFDM channels, where each subcarrier has a distinct channel information, Bob can simply use each subcarrier to send the analog channel information of that subcarrier, and hence require only one OFDM symbol for channel feedback.

Analog channel feedback in a MIMO system: Consider now a MIMO example where Alice has M antennas and Bob has N antennas. Say Bob wants to announce its $M \times N \times K$ channel matrix between Alice and Bob, where K is the number of OFDM subcarriers. Due to space limit, we only discuss the case where Bob announces its CSI to a node with more than or equal to N antennas and thus being able to decode N concurrent streams. In this case, each of Bob's N antennas is in charge of transmitting $M \times 1 \times K$ channel information, which is the channels from Alice's M antennas to that corresponding antenna over K subcarriers. All of Bob's N antennas can transmit their channels concurrently. Analog channel feedback in this MIMO example hence requires M OFDM symbols.

Practical issues: We now discuss some practical issues. First, to eliminate the error, i.e., n/h', in analog channel feedback, we leverage the property that channel noise n is typically additive white Gaussian noise (AWGN), which follows a zero-mean normal distribution. In particular, a channel notifier, e.g., Bob in the above example, can announce the same analog CSI multiple times. Then, a node that overhears the feedback can average up multiple received analog channels and approximate the error to zero. We will evaluate in Sec. 3 how many repetitive announcements are sufficient to cancel out most of the noise. Second, each hardware has a *linearity range*, which is the range of input and output values for an amplifier to ensure the linear function of signals. Hence, the amplitude of analog channel feedback needs to be within the linearity range of hardware to ensure proper decoding. To achieve this goal, we allow a channel notifier to scale the analog channels by a coefficient and then transmit the scaled analog channels along with that coefficient. Consider again the same example. Instead of directly sending the channel of the k^{th} subcarrier h^k_{AB}, Bob can send $\alpha * h^k_{AB}$, where $\alpha = L/|h^{max}_{AB}|$, L is the hardware linearity range, and $|h^{max}_{AB}|$ is the maximum magnitude among the channels of all subcarriers. A node can hence recover the analog CSI by decoding $\tilde{h}^k_{AB} = y/h'/\alpha$.

3. EMPIRICAL EVALUATION

We implement analog channel feedback using the USRP-N200 radios equipped with an RFX2400 daughterboard. Our prototype implementation uses a 10MHz 802.11 OFDM channel, which includes 48 data subcarriers. We follow [1] and use $\Delta\mathbf{H} = \|\mathbf{H} - \tilde{\mathbf{H}}\|/\|\mathbf{H}\|$ to quantitatively examine accuracy of the CSI, where $\mathbf{H}$ is the true CSI learned by the channel notifier and $\tilde{\mathbf{H}}$ is the estimated CSI recovered by the node who is interested in this information, using either reciprocity or analog channel feedback.

Impact of number of repetitive announcement: We first check how many repetitive analog CSI feedback is sufficient to cancel out the error. We implement the example of Alice and Bob, both equipped with a single antenna, and repeat the experiment in randomly-selected locations in our testbed. Fig. 1(a) plots the average error ($\mathbf{\Delta H}$) over all the experiments when Bob announces the analog CSI from once to ten times. It verifies that Alice can get a more accurate channel information if it averages up more repetitive announcements of the analog channel information. The figure however shows that averaging three repetitive analog CSI is sufficient to reduce the error significantly.

Accuracy Comparison: We next compare accuracy of the CSI learned by analog channel feedback and using reciprocity. We consider again the single-antenna Alice and Bob example. Fig. 1(b) plots the CDFs of the error in the CSI learned by using reciprocity and analog channel feedback with 3, 5, and 10 repetitive announcements, respectively. The figure indicates that analog channel feedback with three repetitive announcements requires only a little bit more overhead, i.e., three OFDM symbols, than reciprocity, but can outperform reciprocity in most of cases because the channels might not be perfectly symmetric and the hardware might not be able to be calibrated perfectly. Fig. 1(c) compares accuracy of the recovered CSI for the 2×2 MIMO scenario. It shows that sending analog CSI using the multiplex gain achieves a performance comparable to reciprocity. We can further reduce the error by leveraging the diversity gain. Note that the overhead is still very small, i.e., few OFDM symbols, even if achieving the diversity gain requires double overhead.

4. CONCLUSION

In this work, we empirically evaluate the effectiveness of analog channel feedback using USRP-N200, and discuss some practical implementation issues. Our testbed results show that analog channel feedback reduces the overhead significantly, but can produce an acceptable small feedback error, comparable to that learned by using reciprocity. However, unlike using reciprocity, analog channel feedback allows a channel notifier to broadcast its CSI to a node other than its source, and hence can be applied in general scenarios.

5. REFERENCES

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