MIMO Enabled Efficient Mapping of Data in WiMAX Networks

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Abstract. MIMO techniques supported by IEEE 802.16 networks improve either throughput or reliability in the network. But these MIMO techniques do not always perform optimally, especially in the presence of high mobility. In this paper, we propose a cross layered mapping technique that exploits multiple antenna available at each MS. An optional error correction mechanism is proposed at the receiver to correct erroneously received signal. Finally, using extensive simulations we show that the proposed technique achieves higher throughput compared to the existing techniques while providing the same reliability. We also show that the proposed technique can be a stand alone technique and adaptive switching of MIMO techniques is not required.

Keywords: WiMAX, IEEE 802.16, MIMO, Kalman Filter.

1 Introduction

Worldwide interoperability for Microwave Access (WiMAX) is the commercial version of the IEEE 802.16 standard [2] targeted to provide Wireless Broadband connectivity with data rates supported up to several hundred *Mbps* and covering distances up to several *kms*. WiMAX uses Orthogonal Frequency Division Multiple Access (OFDMA) technology at the physical layer in order to mitigate multi path interference. This improves the reliability of the transmitted data and the throughput of the network. WiMAX supports a variety of techniques such as Adaptive Modulation and Coding, Multiple Input Multiple Output (MIMO) to improve the achieved throughput of the network. WiMAX, in order to utilize the available MIMO techniques, supports up to 4 antenna at each Mobile Station (MS) and up to 8 antenna at the Base Station (BS). It also supports Adaptive MIMO techniques depending on the channel quality between an MS and the BS, and improves the quality of the data transmitted.

Some of the MIMO techniques that are comparable to the proposed technique are explained here. Spatial Multiplexing is a MIMO technique in which several streams of data (which is minimum of the number of antennas available at the transmitter and the receiver) can be transmitted simultaneously using multiple antennas. A 2×2 Spatial Multiplexing scheme is shown in Figure 1. For a fixed

L. Bononi et al. (Eds.): ICDCN 2012, LNCS 7129, pp. 397–408, 2012.

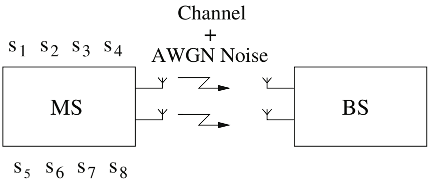

Fig. 1. MIMO Techniques: Spatial Multiplexing

number of allocated slots, the effective throughput achieved using multiple (two) antenna at an MS is theoretically twice the throughput achieved using a single antenna.

Spatial Diversity techniques are supported to improve reliability of the transmitted data. Transmit Diversity is a technique in which the same data (with different transmission characteristics) is transmitted on more than one antenna simultaneously. An example of Transmit Diversity technique (Alamouti Coding [1]) is shown in Figure 2. Receiver Diversity is a technique in which a signal is received across multiple antenna, and one of the receiver combining techniques among Maximum Ratio Combining, Selection Combining and Equal Gain Combining [3] is used to maximize the Signal to Noise Ratio (SNR) of the required transmitted signal. Since SNR of the required signal is maximized, errors in the signal are reduced. Thus the reliability of the transmitted data is improved by using multiple antenna at the receiver.

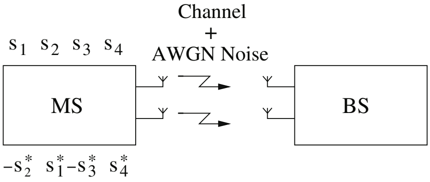

Fig. 2. MIMO Techniques: Spatial Diversity (Alamouti)

An interim concept, Path Diversity [7] is used to improve the loss resilience in Wireless Local Area Networks (WLANs) by enabling multiple Access Points (APs) to receive the data transmitted by a single client. A frame recombining scheme is used at each AP to recover original frame from a set of possibly erroneous frames, thus improving the reliability of the transmitted frame.

Currently, MAC Protocol Data Units (MPDU's) in WiMAX networks are scheduled for each frame based on the number of OFDM slots and the MIMO techniques allocated to each MS. These MIMO techniques are adaptively assigned to each MS depending on the channel quality. The reliability of the transmitted data and the achieved throughput of the network are highly dependent on the MIMO technique used. MIMO techniques are adaptively assigned to each MS based on the channel conditions, condition number and Quality of Service (QoS) requirements of each MS.

The problem that we study in this paper can be termed as 'Can we propose a MIMO technique that can maximize the achievable throughput with out compromising the reliability of transmitted data?' The reliability of transmitted data should be same as that of diversity techniques, but the throughput should be maximized. However, adaptive switching of existing MIMO techniques [12] is a completely different problem, and is not studied in this paper. Due to high variations in the channel, adaptive MIMO switching does not always provide optimal performance in high mobility regions. In this scenario, providing a MIMO technique that is always optimal is a challenge that we study in this paper.

In this paper, we design a transmission technique considering the channel conditions and improve the performance of the network. As this is a time invariant MIMO technique that guarantees reliability value equal to that of diversity techniques and throughput comparable to that of multiplexing techniques, the proposed technique need not be adaptive in nature. We achieve this by proposing an optional error correction mechanism at the receiver. The advantage of the proposed technique is that the choice of an appropriate MIMO technique to be used at each MS is reduced to the basic choice of whether to use multiple antenna or not for the transmission.

The rest of the paper is organized as follows. In Section 2 we provide the assumptions made and continue with description of the proposed technique in detail. The technique is evaluated in Section 3. We conclude the paper and provide drawbacks of the proposed technique in Section 4. In the Appendix, we provide a critical analysis of the assumptions made in the paper.

2 Proposed Technique

2.1 Assumptions

Following are the assumptions made in this work:

- The channel gain of the transmitted stream across an antenna remains constant for all the m OFDM slots in a single frame, between each MS and the BS. The transmission of signal through a channel can be represented mathematically as

  $$y = h * x + n \tag{1}$$

  where y is the received signal for the transmitted signal x with the channel gain as h and a constant Gaussian noise n of mean 0. Since the channel gain remains constant for a single frame between an MS and the BS, we assume that Equation 1 holds for all the OFDM slots transmitted at an MS i.e.,

  $$\forall i \in [1, m],\ y_{[i]} = h * x_{[i]} + n$$

  where i represents the OFDM slot. The value of h is independent of i, for all OFDM slots transmitted in a single frame. The channel gain is independent of the frequency at which data is transmitted, and the channel is assumed to be Additive White Gaussian in nature.

For each frame (typically of 5 ms duration), a typical WiMAX MS, feeds back the Channel Quality Indicator (CQI) attained in its previous frame to the BS. Since each MS uses several OFDM slots for transmission, and an MS transmits only one CQI value, we consider that all the OFDM slots in a single frame will have constant channel quality.

- When an MS transmits data across two antenna, each stream obtains different SNR values at the BS [8]. In a deployed cellular network, it can be deduced that the difference in the SNR values of the signals from two antenna will differ by at least 3 dB. The difference is also dependent on SNR levels. As the SNR values increase, so does the difference. When the SNR value of an MS is close to the accepted threshold value at the BS, it can be assumed that one stream of data is received with SNR$\geq$threshold (non-erroneous), and the other stream with SNR$<$threshold (erroneous). It is at this SNR region we propose the technique.

  However, receiver combining techniques can be used to receive data transmitted from an antenna. These combining techniques [3] are used before the proposed technique is utilized. The proposed technique works on the signals that are segregated by the existing combining techniques, for each transmitting antenna separately.

2.2 Proposed Technique at the Transmitter

Alamouti coding [1] is one of the frequently used antenna techniques to improve the reliability of the data transmitted. When an MS is equipped with single antenna, Alamouti coding technique uses time (or frequency) slots for transmitting data redundantly. When equipped with multiple antenna, each antenna transmits data across all the OFDM slots, and receiver uses combining techniques to retrieve the transmitted data.

The proposed technique is described as follows: When an MS is allocated n_{ofdm} slots to transmit in a single frame, MS transmits variants of same data across both antenna in t_{ofdm} slots. The technique is enabled only when one stream is received with SNR higher than the threshold and other stream is received with SNR lower than the threshold from an MS. The redundant data (in form of signals) in t_{ofdm} slots across both the antenna will be used by the proposed error correction mechanism at the BS.

The data transmitted at an MS in 4 OFDM slots across multiple antenna with $t_{ofdm} = 2$ is shown in Figure 3. The first two OFDM slots across both the antenna transmit variants of same data. Different data is transmitted in remaining OFDM slots. We derive the optimal t_{ofdm} value when the error detection and correction mechanism is utilized at the BS. For the following analysis, we follow the notation that each OFDM slot comprises of two OFDM symbols. In an IEEE 802.16 network, the packet error ratio of a Protocol Data Unit (PDU) transmitted using OFDM symbols is given as

$$p_{pdu} = 1 - (1 - p_{ofdm})^{n_{ofdm}} \tag{2}$$

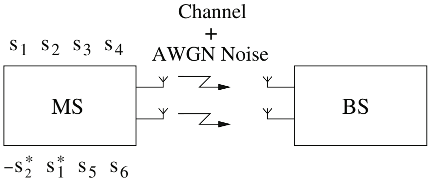

Fig. 3. Data Transmitted in the Proposed Technique

where p_{ofdm} denotes the probability of receiving an erroneous OFDM symbol and n_{ofdm} is the number of OFDM symbols required to transmit the PDU [6]. When a PDU can be transmitted in a single frame using n_{ofdm} symbols across two antenna, the packet error probability of PDU in Eq. (2) can be modified as

$$p_{pdu} = 1 - [(1 - p_{ofdm1})^{k_1} \times (1 - p_{ofdm2})^{k_2}] \tag{3}$$

where k_1 and k_2 are the number of OFDM symbols transmitted, p_{ofdm1} and p_{ofdm2} denote the probability of receiving an erroneous OFDM symbol transmitted from antenna 1 and 2, respectively. Sufficient condition being $k_1 + k_2 = n_{ofdm}$.

With out loss of generality, we assume that the data transmitted from a single antenna will receive equal interference for all the OFDM slots used at that antenna (Assumption 1). In a single frame (of 5 ms duration), the probability of an error occurring in k_i OFDM symbols transmitted from an antenna is same as error occurring in a single OFDM symbol. Based on this assumption, Eq. (3) can be modified as

$$p_{pdu} = 1 - \ [(1 - p_{ofdm1}) \times (1 - p_{ofdm2})\ ] \tag{4}$$

Eq. (4) assumes that the receiver (BS) does not incorporate any error correction mechanism. By enabling an appropriate error correction mechanism at the BS and providing t_{ofdm} symbol redundancy in the data being transmitted from both antenna, Eq. (4) can be modified as

$$\begin{aligned} p_{pdu} &= \overline{X}\ Y\ (1 - \mathbb{P}(\chi_1 = k_1 - t_{ofdm} | \nu_2 = k_2)) \\ &\quad + X\ \overline{Y}\ (1 - \mathbb{P}(\chi_2 = k_2 - t_{ofdm} | \nu_1 = k_1)) + \ \overline{X}\ \overline{Y} \quad where \\ X &= (1 - p_{ofdm1}), Y = (1 - p_{ofdm2}),\ \overline{X} = (p_{ofdm1})\ and\ \overline{Y} = (p_{ofdm2}) \end{aligned} \tag{5}$$

where X and Y denote the probability of receiving the signals from antenna 1 and 2 without errors, while $\overline{X}$ and $\overline{Y}$ is the probability of receiving signals with errors. $\mathbb{P}(\chi_1 = k_1 - t_{ofdm} | \nu_2 = k_2)$ is the probability of correcting the erroneously received k_1 OFDM symbols transmitted from antenna 1 when k_2 OFDM symbols from antenna 2 are received without error. Similarly, $\mathbb{P}(\chi_2 = k_2 - t_{ofdm} | \nu_1 = k_1)$ can be defined. This correction probability is dependent on the correction mechanism used at the BS.

2.3 Proposed Technique at the Receiver

Alamouti coding [1] transmits data such that both original and conjugate forms of the data are transmitted across different antenna simultaneously. This technique is independent of any physical layer technology. Our proposed technique assumes OFDM technology at the physical layer. The error signal determined from the redundant data in t_{ofdm} OFDM slots is used for correcting the data in the remaining OFDM slots of the erroneous stream [Theorem 2 in Appendix].

We determine the error signal that differentiates the signals of erroneous stream and non-erroneous stream in the first t_{ofdm} slots. The error signal is the signal when convolved with an erroneous stream of signals, will improve the SNR of the stream.

Some of the plausible filters for proposing an error correction and detection mechanism are analyzed as follows. Weiner filter [5,13] is one of the stationary filters that statistically determines the effective channel state, and thus improves the SNR of the received signal by at least 2 dB [5]. The disadvantage of Weiner filter is that, it assumes the underlying process to be Wide Sense Stationary. In the proposed technique, the input data need not be stationary and Weiner filter is not applicable.

Matched filter efficiently compares a compound signal with an ingredient signal and maximizes the SNR of the compound signal with respect to the ingredient signal, and is used for packet recognition [10]. However, the expression to estimate error using Matched filter is dependent on the input signal i.e., Matched filter provides different estimates for different ingredient signals. Hence, the error estimated in one OFDM slot can not be used for other OFDM slots and Matched Filter is not applicable.

Kalman filter [5,13,14] efficiently estimates the noise in the received signal by measuring the noise from the previously received signals, and is adaptive in nature. For each iteration, Kalman filter updates the estimated value and estimates the values accurately, stabilizing with time.

A variation of Kalman filter applied at sub-carrier level [4] considers using of OFDM symbols for transmitting data. The per sub-carrier Kalman update recursively estimates for a set of sub-carriers in a single time slot. Several iterations are possible for each OFDM symbol, and the estimated values are accurate after 40 iterations (Observation 1 in Appendix). Hence, per sub-carrier Kalman filter is apt for error detection in our proposed technique and we use Kalman filter to efficiently estimate the difference between the erroneous and non-erroneous stream. Details of Kalman filter parameters are tabulated in Table 1.

The flow diagram for decoding the signals received at two antenna of the BS is shown in Figure 4. The SNR of each signal is checked for acceptance based on the threshold value. When one of the streams is received with SNR$\geq$Threshold and the other stream is received with SNR<Threshold, the proposed technique is utilized. When both the signals are received with SNR below the Threshold, both signals are rejected.

Table 1. Mapping of Kalman Filter Parameters at the Receiver

Parameter	Description	Relevance Parameter in the Technique
x	State Vector Estimate	Error Estimate
H	Observation Matrix	Data in Non-erroneous Stream
Z	Observation Vector	Data in Erroneous Stream
A	State Transition Matrix	Identity Matrix
B	Input Matrix	Null Matrix
u	Input Control Vector	Null Matrix
v and w	Gaussian Noise	Gaussian Noise

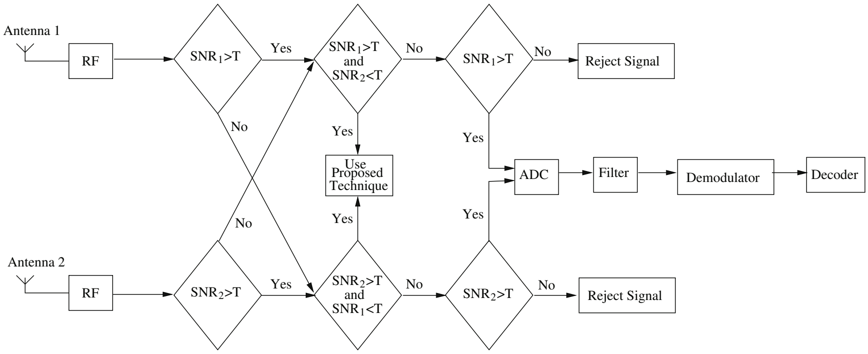

Fig. 4. Signal Flow at the Receiver

The error correction mechanism is triggered only when one of the streams is received with errors and the other is received without errors (SNR<Threshold). Assuming that data is transmitted redundantly in t_{ofdm} OFDM slots at each antenna, data in the first OFDM slot at each antenna is given as input to the Kalman filter. Each OFDM slot is split into several sub-carriers (48 in WiMAX), and Kalman filter is used to estimate the error for each sub-carrier, as explained in Figure 5. As the number of sub-carriers in one OFDM slot (48) is greater than 40, the estimated value converges and we can estimate the error for the remaining sub-carriers. Thus, error in the erroneous stream compared to non-erroneous stream is estimated. The error determined in first OFDM slot remains constant, and can be used to correct data in the remaining OFDM slots [Theorem 2 in Appendix]. The data in remaining OFDM slots of the erroneous stream is convolved with the error signal, and data is corrected [Theorem 1 in Appendix].

An MS utilizes multiple antenna only when the number of slots allocated is higher than a threshold value (8 in simulations), which is dependent on the SNR of the received signals. The optimal number of OFDM slots t_{ofdm}, in which data is to be transmitted redundantly across different antenna is determined as below. The estimated error is accurate after 40 iterations [Observation 1 in Appendix]. Since 48 sub-carriers available in an OFDM slot provide iterations ≥ 40, the error estimated using the first OFDM slot is sufficient to determine

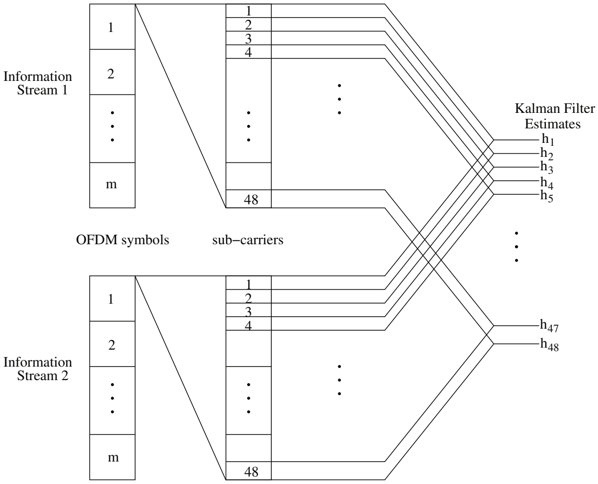

Fig. 5. Proposed Error Detection Mechanism at the Receiver

the error efficiently. Hence, an optimal redundancy of data in $t_{ofdm} = 1$ OFDM slot across different antenna at an MS is required for the proposed technique to improve performance of the network.

3 Evaluating the Proposed Technique

We use standard ns-2 simulator with a WiMAX patch provided by NIST [9] for evaluating the proposed technique. We conducted simulations at 3.5 GHz carrier frequency with a bandwidth of 7 MHz, and each OFDM symbol constitutes 102.8 μs and uses QPSK 3/4 modulation technique. Each MS and the BS is equipped with two antenna. A Constant Bit Rate (CBR) traffic is generated at each MS with a constant packet size of 1500 $bytes$. We compare the proposed technique with Alamouti technique and a technique that uses single antenna, by measuring the throughput and reliability of the data transmitted in the network. We also assume that for a single OFDMA frame of 5ms, data transmitted across each antenna will have constant channel coefficient and noise terms at each receiving antenna.

As shown in Figure 6, the throughput of the network increases until the number of MSs reach a value of 20, as sufficient traffic is induced in the network. The throughput in the Alamouti coding technique is close to the throughput of single antenna technique even though it uses 2 antenna, because the entire data is transmitted redundantly on the other antenna. However, since the reliability is high for the data transmitted using Alamouti technique, throughput is slightly higher in Alamouti technique compared to single antenna technique. Since, the number of redundant OFDM slots in the proposed technique is only 1, an improvement in the throughput of the network is visible.

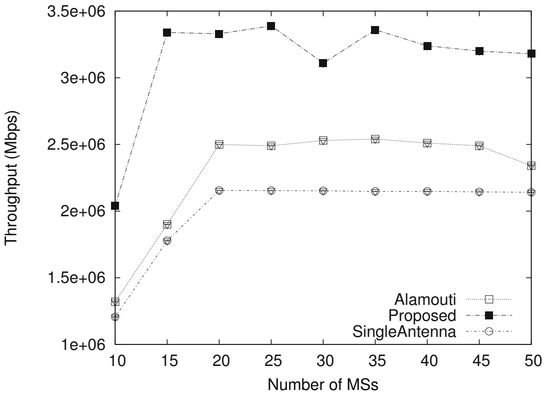

Fig. 6. Throughput of the Network Versus Number of MSs in the Network

As can be seen in Figure 7, the Alamouti technique maintains the highest reliability value while the single antenna technique maintains the lowest. For the simulations, reliability is the ratio of number of packets received successfully to the number of packets transmitted. This is because the data is entirely replicated at other antenna also. The reliability of the transmitted data in the proposed technique matches with Alamouti technique when the number of MSs in the network is less than 20, and maintains value in between the values of Alamouti and single antenna technique. This improvement in reliability is due to the usage of filtering at the receiver and elimination of error in the erroneously received signal. However, the proposed technique works only when one SNR<Threshold and another SNR≥Threshold. Hence, the value of reliability is not always same as Alamouti technique.

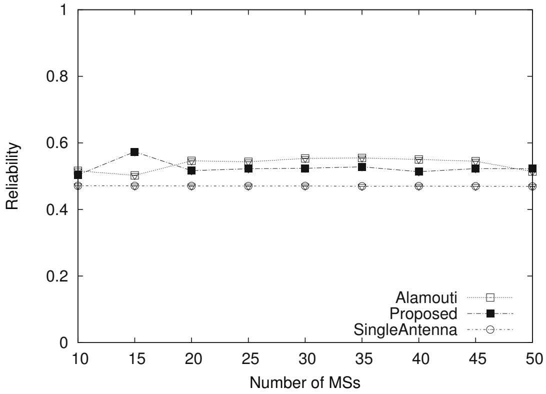

Fig. 7. Reliability of the Transmitted Data Versus Number of MSs in the Network

4 Conclusion

In this paper, we proposed a transmission technique across multiple antenna that exploits the usage of OFDM technology in WiMAX networks. We also proved that by transmitting redundant data in OFDM slots ($t_{ofdm} = 1$ slot) at different antenna of an MS and using efficient error correction mechanism at the receiver (BS), the reliability of the transmitted data is improved. While other techniques that improve the reliability have considerable reduction in achievable throughput, the proposed technique maintains the reliability by reducing the throughput marginally compared to multiplexing techniques. We use extensive simulations and show that our proposed mechanism performs better than other MIMO techniques.

The transmission technique proposed in this paper assumes that irrespective of the signal processing techniques over an existing signal, the domain of the noise term in the processed signal remains in the same domain as the preprocessed (existing) signal. However, this assumption is highly idealistic in nature and is considered practically impossible. Solving the proposed problem when this assumption is relaxed (close to realistic conditions) remains as a challenge and can be considered as future work.

Acknowledgements. This work was supported by the Department of Science and Technology, New Delhi, India.

Appendix

Theorem 1. In any network with a frame size of 5 *ms* using OFDM symbols for transmission, when two streams I_1 and I_2 transmitted from a single terminal (MS) are received at two antenna of another terminal (BS), we can correct one erroneous signal if the other signal is received without errors.

Proof. The channel gain for a stream of data transmitted from an antenna in a 5 *ms* frame is constant [2] irrespective of the fading distributions. Let stream $I_{1(2)}$ has a channel gain of $h_{1(2)}$ with Gaussian noise as $n_{1(2)}$. Here, $n_{1(2)}$ is the Circularly Symmetric Gaussian Random Variable taken from $(0, N_{\sigma^2})$, where N_{σ^2} is average noise value < 1. Let I_1 stream is received without errors (SNR$\geq$Threshold) and I_2 stream is received with errors (SNR$<$Threshold). Let stream I_1 is transmitted with signals d_1, d_2, d_3 and stream I_2 is transmitted with signals d_1, d_4, d_5 across 3 OFDM slots. The transmission of signals across the channel can be written as

$$s_1^1 = h_1 * d_1 + n_1 \tag{6}$$

$$s_1^2 = h_2 * d_1 + n_2 \tag{7}$$

Calculating d_1 from Eq. (6) and substituting in Eq. (7),

$$s_1^2 = h * s_1^1 + n, \tag{8}$$

where $h = h_2/h_1$ and $n = n_2 - n_1 * h_2/h_1$.

Hence, by convolving the erroneous stream (I_2) signals with $h^{-1} = (h_2/h_1)^{-1}$, the channel gain is shown to be same as that of stream I_1. It is to be noted that the noise also is improved by the same factor. However, since noise term $n_{1(2)}$is the Circularly Symmetric Gaussian variable, the noise value remains in $(0, 1)$. Hence, the power of noise is improved marginally compared to the channel gain. Since the channel gain is improved with marginal change in power of the noise, the SNR of the stream I_2 increases. Also, the channel gain in I_2 is improved to that of I_1 with minor variations in noise. Hence, the error in stream I_2 is corrected.

Theorem 2. The error (h in Theorem 1) that we determine for erroneous stream I_2 using the first OFDM slot remains constant for all the remaining OFDM slots, and can be utilized to improve the quality of the received signal.

Proof. Following from Eq. (7), we can determine s_4^2 with data transmitted as d_4 to be

$$s_4^2 = h_2 * d_4 + n_2 \tag{9}$$

Now, convolving s_4^2 with $h^{-1} = (h_2/h_1)^{-1}$ gives

$$s_4^2 * h^{-1} = (h_2 * d_4 + n_2) * (h_1/h_2) = h_1 * d_4 + n_2 * h_1/h_2 \tag{10}$$

Since the channel gain is improved to h_1, the quality of the received signal is improved. Also, the value of h is achieved only from the first OFDM slot and the same h is used to improve the quality of the remaining OFDM slots. Hence, the quality of the received signal is improved by determining the h from the first OFDM slot and applying for the remaining OFDM slots.

Observation 1. The value of the estimate from the Kalman filter converges after 40 iterations (estimations).

We generate the plot using MATLAB, by transmitting integers as the correctly and wrongly received signals and estimated the value of error signal. As we know that the data is transmitted in form of constellations for each modulation type, we denote that the data in each constellation (bits) can be represented as integers. In a constellation, the probability of converting adjacent point is high compared to others [11]. Thus, we assume that we get different integers for different constellations. The approximate error percentage is as plotted in Figure 8. As can be seen, the initial estimates constitute an error estimate of up to 30%, and as the number of estimates cross 40, the error percentage remains stable at $1\% - 5\%$.

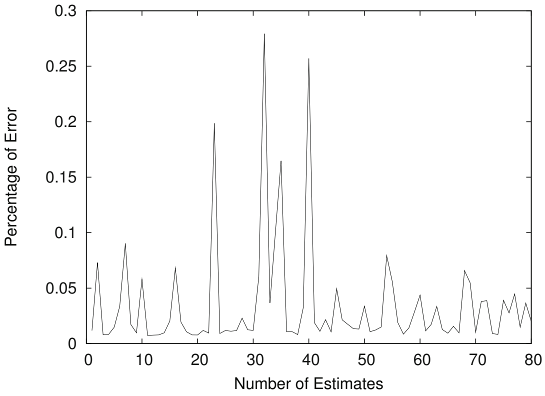

Fig. 8. Reliability of the Transmitted Data Versus Number of MSs in the Network

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