MISC: Merging Incorrect Symbols using Constellation Diversity for 802.11 Retransmission

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***Abstract*—802.11 WLANs suffer from high packet losses due to interference and noise. Packet retransmission is a fundamental way to recover a lost packet. To extract useful information from incorrect symbols and improve retransmission efficiency, we present MISC, a packet retransmission scheme that merges incorrect symbols from multiple transmissions to produce correct ones. MISC proactively creates constellation diversity by rearranging the constellation maps in retransmissions. MISC addresses practical implementation issues and makes minimum amendments to integrate into current 802.11 WLAN framework. We implement MISC in an 802.11-based GNURadio/USRP platform and conduct extensive experiments to evaluate its efficacy. Experiment results demonstrate that MISC can substantially improve the throughput.**

I. Introduction

802.11 WLANs suffer from high transmission errors due to interference and noise. When a packet gets corrupted and fails the checksum test, current 802.11 receiver discards the corrupted packet and attempts to receive a clean packet through packet retransmission. As a growing number of wireless devices contend limited unlicensed spectrum (e.g., 2.4G ISM band), such a scheme is inefficient and results in even more retransmissions [8].

In this paper, we propose MISC, an extension to current 802.11 framework, which merges incorrect symbols leveraging constellation diversity to improve packet retransmission efficiency. MISC allows the receiver to jointly decode a packet based on multiple retransmissions. The constellation points are shuffled for successive retransmissions in a way that each constellation point will have completely different neighboring points from the former transmission. For each received symbol in a packet, we store the distances from this PHY symbol to each point on the constellation map. To combine multiple packets, we sum up the distances in different transmissions and pick the constellation point with the minimum overall distance. As MISC proactively creates constellation diversity by using alternative comstellation maps for retransmissions, the symbol distances between the received symbol and potential incorrect candidates rapidly increase, while the distance to the correct point remains statistically low. By doing so, the receiver can correct symbol errors leveraging constellation diversity and achieve higher retransmission efficiency.

We design MISC in a way that minimum amendments are needed to integrate into current 802.11 WLAN framework. Practical challenges are addressed in implementing MISC under 802.11 framework. In particular, we deeply study the way of constellation map alternation on sequential transmissions that achieves balance between decoding performance and overhead, and allows easy integration into 802.11 protocol stack. We consider a practical extension on 802.11 PHY PLCP header to support packet identification and precise synchronization of constellation map over the wireless nodes. The overall extra storage and computation overhead as well as the design complexity incurred by MISC have been carefully controlled and tailored to the 802.11 transceiver architecture.

We implement and evaluate MISC with testbed experiments on the 802.11-based GNURadio/USRP platform. The experiment results suggest that MISC can substantially improve transmission efficiency. Targeting at correctly decoding physical layer symbols, MISC can combat symbol errors across a wide range of SNRs, which fundamentally reduces decoding BER and thus the number of retransmissions. The main contributions of this paper are summarized as follows:

- We present a symbol-level packet combining strategy with alternative constellation maps to recover from corrupted symbols. Alternative constellation maps enrich symbol diversity and complement temporal/spatial diversity, which substantially improves error recovery efficiency.
- We make minimum extension on current 802.11 WLAN framework to integrate MISC retransmission and combining strategy. Practical issues are considered and addressed in such integration.
- We prototype MISC on the 802.11-based GNURadio/USRP platform and conduct experimental evaluation under practical settings.

To the best of our knowledge, this is the first work that considers the constellation diversity on retransmissions and tailors the design to current 802.11 WLAN framework. In the rest of this paper, we summarize related work and motivate our work in Section II. We introduce background in Section III. We describe the technical details of MISC design in Section IV. We address several practical issues when implementing MISC in 802.11 WLANs in Section V. We evaluate MISC and present experiment results in Section VI and conclude this paper in Section VII.

II. Related work and Motivation

Our design builds on top of a large body of research works in correcting communication errors and focuses on improving retransmission efficiency for current 802.11 WLAN. Considering the wide deployment of 802.11 devices, we would like to make minimum extensions to the WLAN framework so as to allow easy integration into the 802.11 protocol stack. In the following, we briefly introduce related works and motivate our design choices.

The benefits of careful constellation mapping design in reducing communication errors have been well acknowledged. Some research efforts have designed various bits-to-symbol

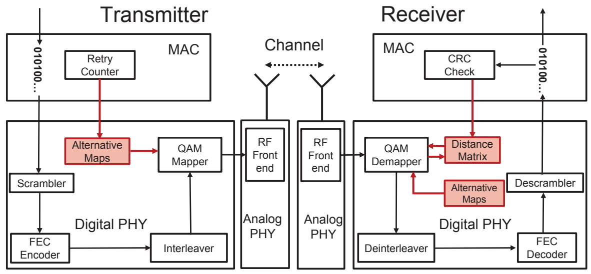
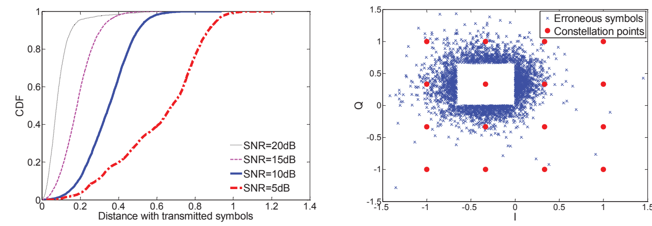


Fig. 1. 802.11 Block Diagram with MISC. The colored blocks are MISC extensions to 802.11. Some other standard operations such as OFDM modulation are not included.



(a) (b)

Fig. 2. (a) CDF of the distance between a received symbol and its actual transmitted symbol with different SNRs. (b) Incorrectly decoded symbols of (-0.33+0.33i) at SNR of 10dB.

mappings to improve reliability of one transmission. Trellis-Coded Modulation (TCM) combines coding and modulation, and develops "mapping by set partitioning" to increase the distance between sets of bits. Bit-Interleaved-Coded-Modulation (BICM) interleaves the encoder output bits to improve performance of coded modulation [27]. The problem of finding the most suitable signal mapping for BICM schemes over AWGN channels is addressed in [24]. Despite these careful bits-to-symbol mapping designs which enhance packet robustness to errors over one transmission, a packet may still get lost due to fading, interference and noise in wireless networks.

Packet retransmission is a fundamental approach in 802.11 WLAN to correct and control errors. ARQ (Automatic Repeat reQuest) requests a retransmission upon detecting a corrupted packet and discards the corrupted one. Type I Hybrid ARQ combines FEC and ARQ to benefit from both [6] and is currently used in 802.11 WLANs. Some recent cross-layer designs have recognized the inefficiency of retransmitting an entire packet when only a small portion of the packet is corrupted. PPR [3] uses SoftPHY hints to evaluate which bits are more likely in error and only retransmits the error parts rather than entire packets. In Maranello [22], the receiver computes block checksums and sends them back to the transmitter, which allows the transmitter to retransmit the blocks whose checksums are incorrect. Those designs typically discard the entire corrupted packet or the corrupted portion of a packet, and try to recover the errors through retransmissions by replacing the erroneous bits with the correct ones.

Packet combining techniques have been extensively studied to combine corrupted packets to recover errors [2, 5, 6, 18]. Chase Combining [2] stores and combines a packet and its retransmissions to counteract errors. Hybrid ARQ with Incremental Redundancy (IR) retransmits extra redundant bits in retransmissions and combines all packets together to decode [6]. SOFT [5] considers networks with multiple access points and cooperatively reconstructs the original packet. Those works make better use of corrupted packets, but they heavily rely on temporal/spatial diversity which is subject to channel conditions and network topologies.

Many other works explore to enrich diversity in packet combining by designing various bits-to-symbol mapping strategies for multiple packets. Constellation rearrangement is used for parallel transmissions in a cooperative relay network [13]. An ARQ scheme that considers the effect of rearranging mapping for Continuously Phase Frequency Shift Keying (CPFSK) modulation is proposed in [23]. [15, 16] observe the different reliability of bits in Gray constellation maps and balance the protection in retransmissions by swapping the more reliable bits with less reliable ones. [20] designs the optimal constellation maps for retransmissions. All those works demonstrate promising performance of constellation rearrangement in various scenarios (e.g., with different network topologies, modulation schemes, and constellation maps). However, many practical issues need to be addressed to integrate constellation rearrangement to improve retransmission efficiency of 802.11 WLAN.

In this work, we explore to design an efficient retransmission scheme by enriching constellation diversity. We would like our design to be readily applicable to current 802.11 WLAN framework with minimum extensions. Although many algorithms have been proposed to generate optimal constellation maps for retransmission, those algorithms typically incur prohibitive computation overhead, which calls for a systematic design to balance performance and overhead. Besides, we need to synchronize the constellation maps between the transmitter and the receiver. In 802.11 WLAN, a receiver may overhear packets over multiple links. Thus, in order to combine and decode the packets, a receiver needs to identify the packets before decoding them. Current 802.11, however, does not expose sufficient information for a receiver to identify a packet (e.g., its source and destination) at PHY layer, which requires a cross-layer naming mechanism.

III. BACKGROUND

We present an overview of 802.11 wireless communication. We experiment with USRP software radios to show symbol error patterns in 802.11. We use an illustrative example to present how we leverage the error patterns and correct errors.

A. 802.11 Wireless Communication

Most modern WLANs are based on IEEE 802.11 standards. 802.11 standards define Media Access Control (MAC) layer and PHY (physical) layer specifications.

The working flow of a pair of 802.11 transmitter and receiver is described in Figure 1. In order to provide reliable and efficient transmission, a stream of data bits which are passed from MAC layer will go through a scrambler, an FEC encoder and an interleaver in the PHY layer before they are mapped to complex symbols and sent to the air via the antenna(s). Specifically, the scrambler first randomizes the bit stream to avoid long runs of only '1's or '0's for synchronization and energy concerns. Then the FEC (Forward Error Correction) encoder encodes the data bits using FEC codes so that the coded bit stream can correct some bit errors without retransmission at the receiver. The most commonly used FEC codes in 802.11 are Convolutional codes. The interleaver shuffles the coded bits across different code words so that the bursty bit errors

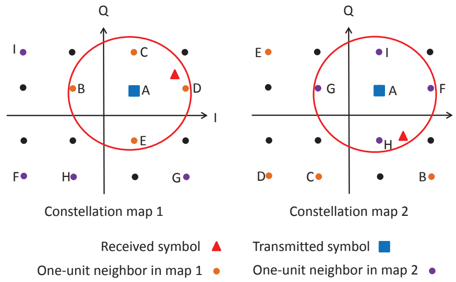
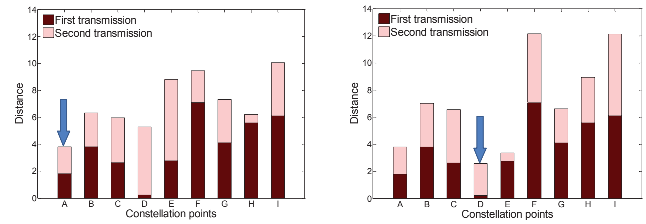


Fig. 3. The intuition of using an alternative constellation map in retransmission. In constellation map2 used for retransmission, neighboring constellation points *B,C,D,E* and faraway constellation points *G,H,F,I* exchange positions.



(a) Alternative map (b) Same map

Fig. 4. Distances between the received symbols and candidate constellation points: the received symbol can be jointly decoded to the transmitted 'A' by using alternative constellation maps for two transmissions.

are dispersed and may be corrected by several code words at receiver. Next, the coded and interleaved bits are modulated to complex symbols. Taking 16 QAM (Quadrature Amplitude Modulation) as an example, each set of four bits is mapped to one of the sixteen constellation points in the complex plane. Finally the stream of complex symbols are transmitted using two orthogonal sinusoidal waves.

The reception is approximately the reverse process of transmission. A complex symbol is first mapped to the nearest constellation point in the constellation map. Due to interference and noise, the received symbols often get dispersed from the transmitted constellation points [23]. A symbol error occurs if the dispersed symbol is closer to a wrong constellation point than the transmitted constellation point. Symbol errors result in bit errors. When the stream of bits output by the symbol demapper go through the deinterleaver and FEC decoder, some bit errors may get corrected. But when the number of bit errors is beyond the correcting capability of the FEC codes, a packet cannot be recovered. In a noisy wireless network, one may need to retransmit several times to deliver a packet consisting of thousands of individual symbols.

B. Symbol Errors in Practice

We now carry out preliminary experiments using 2 USRP N210 [1] nodes to study the symbol error patterns. Figure 2(a) depicts CDF of the distance between received symbols and the transmitted points with varied channel conditions, where the minimum distance between two constellation points is 0.67. When channel condition deteriorates and SNR decreases, symbols influenced by stronger noise are generally pushed further away from the transmitted symbol point. Nevertheless, even at a low SNR of 5dB, around 80 percent of received symbols are within a distance of 0.8 from their transmitted symbol points. Such an error locality generally holds across a wide range of channel conditions.

Figure 2(b) presents detailed symbol error instances where 1000000 16QAM symbols were transmitted at a SNR around 10dB. We plot incorrectly received symbols of the point (-0.33+0.33i). Most of the them fall within the neighborhood of the transmitted symbol point on the constellation map. Such error "locality" pattern has been used in previous communication designs, e.g., Gray mapping and Unequal Error Protetion (UEP) [11]. In this paper, we leverage such locality in a different way in retransmissions to create constellation diversity for error recovery.

C. An Illustrative Example

We use an illustrative example to explain how MISC exploits alternative constellation maps to better combine incorrect symbols. In Figure 3, we consider the two unsuccessful transmissions of symbol *A* on constellation map 1 and 2. The received symbols denoted by the triangle would concentrate around *A*'s neighborhood, where we use circular ranges to approximate. The key difference between the two maps is: neighbor points around *A* are completely replaced. (The design to replace neighbors of all constellation points is shown in Section IV-B).

The benefit of using such alternative constellation maps is that the distances between the received symbols and incorrect constellation points increase fast, while the distances between received symbols and transmitted points remain statically the same and comparatively low. Therefore, combining the two transmission trials, we add up two 16-tuple distances of the received symbols to each of the 16 constellation points. Using the combined symbol distances we pick the constellation point with the smallest distance sum as the decoded symbol.

The above combining and decoding operation is shown in Figure 4 to illustrate the effect of using an alternative map compared to using the same map in retransmission. The deep-colored and light-colored areas show the distances between the received symbols and candidate constellation points measured in the first and second transmission respectively. In Figure 4(a), using either transmission alone, the receiver decodes to the nearest point in one transmission i.e. *D* or *H* rather than the transmitted *A*. If we merge the two incorrect symbols by calculating the distance sum, however, the transmitted symbol point *A* can be correctly decoded as indicated in Figure 4(a). While in Figure 4(b), we see that using the same constellation map cannot benefit from the diversity gain of alternative maps and still suffers a fair chance of incorrectly decoding the symbol to a nearby point (e.g., point *D*).

This example suggests that the partial information hidden in corrupted symbols resulted from error locality can be exploited to recover the transmitted symbol at the receiver when we retransmit packets using alternative constellation maps. To make use of corrupted symbols, we measure the distances between received symbols and each constellation point and add up the corresponding distances in multiple transmissions. More importantly, the constellation rearrangement effectively enriches retransmission diversity, which substantially improves combining and decoding efficiency.

IV. MISC DESIGN

In this section, we present a detailed design of MISC that extends 802.11 WLAN framework to utilize corrupted packets and improve retransmission efficiency. We first present an overview of MISC in Section IV-A. We then describe constellation mapping design and combining principle in Section

IV-B and IV-C respectively. We finally provide the complete algorithms for the sender and receiver in Section IV-D.

A. MISC Overview

MISC is a packet retransmission and combining scheme designed for 802.11 WLAN. We implement MISC as an extension to current 802.11 as shown in Figure 1. In particular, MISC adds the following two key components:

- *Alternative Maps* that provide alternative constellation mappings for *QAM Mapper/Demapper* to use in retransmissions.
- *Distance Matrix* that stores accumulative Euclidean distances between received symbols and candidate constellation points in several transmissions of the same packet.

At a high level, MISC works as follows. At the transmitter, the QAM modulator maps bits to symbols using different constellation maps in retransmissions in a way that each PHY symbol has different neighhors on constellation maps. At the receiver, the demapper selects the corresponding constellation map and use it to demap. At the same time, the demapper outputs the distance information of each symbol comprising I and Q component to the *Distance Matrix* and updates the matrix. Then, the updated accumulated matrix which is a combination of several transmissions is fed back to the demapper and the demapper finds the nearest constellation point for each symbol in terms of the sum of distances.

B. Design of Alternative Constellation Maps

Our goal of using alternative constellation maps is to allow each symbol to have different neighbors in retransmissions so as to increase accumulated inter-symbol Euclidean distances in retransmissions. An alternative map generation algorithm needs to permutate M constellation points to generate N constellation maps, $\mathbf{X}^i = [x_1^i, x_2^i, \ldots, x_M^i], i = 1, 2, \ldots, N$. Minimum Accumulated Squared Euclidean Distance (MASED) is defined as [28],

$$\mathit{MASED}(N, \mathbf{X}) = \min \sum_{i=1}^{N} ||x_j^i - x_k^i||^2 \quad 1 \leq j, k \leq M, j \neq k \tag{1}$$

We denote a permutation scheme as S, then the optimal S should maximize the MASED as follows.

$$\hat{S} = arg \max_{S} \mathit{MASED}(N, \mathbf{X_S}) \tag{2}$$

Generating maps using the optimal permutation designs is precluded in an 802.11 system with tight time constraint and storage limit (which is explained in Section V-A). Here, we propose a lightweight map generation approach that involves negligible overhead while still creating constellation diversity. Without loss of generality, we first present our design in the 16QAM setting. We propose to construct alternative constellation maps in the following manner. We refer to the original 16QAM constellation map as a 4×4 matrix $\mathbf{C}_O$, where each entry represents a constellation point. Similarly, we refer to the constellation map after permutation as $\mathbf{C}_P$. In order to allow each constellation point to have different neighbors, we permutate the constellation map as follows.

$$\mathbf{C}_P = \mathbf{P}\mathbf{C}_O\mathbf{P}, \tag{3}$$

where $\mathbf{P}$ denotes the permutation matrix as follows.

$$\mathbf{P} = \begin{bmatrix} 0 & 0 & 1 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 \end{bmatrix}. \tag{4}$$

Intuitively, the neighboring constellation points in $\mathbf{C}_O$ are moved in such a way that they are not next to each other in $\mathbf{C}_P$. The operation of multiplying $\mathbf{P}$ on the left side of $\mathbf{C}_O$ ensures that the points next to each other in column would be moved apart after permutation. Similarly, the operation of multiplying $\mathbf{P}$ on the right side of $\mathbf{C}_O$ guarantees that the points next to each other in row would be separated. Therefore, the joint effect is that every constellation point will have new neighbors in the alternative constellation map after permutation. One may use a similar permutation matrix (e.g., the one in mirror with $\mathbf{P}$) as well. For other modulation schemes, such as 64QAM and 256QAM, although the error locality area may cover more than the one-step neighboring points, similar permutation matrix can be easily derived to push away these broad-sense neighboring points.

C. Packet Combining

1) Combining and Decoding Principle: As wireless channel condition varies over time, retransmitted packets may experience distinctive channel conditions. While some packets may suffer from severe noise and interference, others may be transmitted over relatively good channels. It is thus reasonable to weigh the different packets according to their qualities. We mathematically analyze the packet recovery probability and adopt maximum-likelihood recovery strategy which achieves optimum packet combining performance for independent Additive White Gaussion Noise (AWGN) channels.

Let $\mathbf{Y} = [y_1, y_2, \ldots, y_N]$ be N normalized transmission receptions of the same symbol in N packets over different independent fading channels with AWGN. Let $\mathbf{X} = [x_1, x_2, \ldots, x_M]$ be the M possible constellation points. A maximum-likelihood decoder is to select a constellation point, x_j, to maximize the probability of receiving $\mathbf{Y}$ given that x_j is transmitted.

$$\max_{x_j}\{p(\mathbf{Y}|x_j)\} = \max_{x_j}\{\prod_{i=1}^{N} \frac{1}{\sqrt{2\pi\sigma_i^2}} e^{-\frac{(y_i - x_j)^2}{2\sigma_i^2}}\}, \tag{5}$$

where σ_i^2 is the noise variance in the ith AWGN channel.

Taking the natural logs and dropping terms which are not a function of x_m, we obtain

$$\max_{x_j}\{\ln p(\mathbf{Y}|x_j)\} \propto \max_{x_j}\{\sum_{i=1}^{N} -\frac{(y_i - x_j)^2}{\sigma_i^2}\} \tag{6}$$

Omitting the negative sign by taking a min rather than max, we obtain

$$\max_{x_j}\{\ln p(\mathbf{Y}|x_j)\} \propto \min_{x_j}\{\sum_{i=1}^{N} \frac{1}{\sigma_i^2} ||y_i - x_j||^2\}, \tag{7}$$

where $||.||^2$ is the squared Euclidean distance. For simplicity of description, we use distance to refer to the squared Euclidean distance in the rest of the paper.

Algorithm 1 MISC transmitter algorithm

INPUT: bits // Data bits from QAM Mapper input

C←**C**$_O$
while No ACK **do**
  C←**PCP** // Permutate matrix
  symbols←map(bits, **C**) // Map bits to symbols using map **C**
end while

Algorithm 2 MISC receiver algorithm

INPUT: symbols //Symbols from QAM Demapper input

Select the constellation map **C**
Measure channel noise variance
distMatrix←calculate_dist(symbols, **C**)
distMatrix_aggregated←distMatrix_aggregated+distMatrix
bits←inverse_map(distMatrix_aggregated)
crc_pass←crc_check(bits)
if crc_pass == 1 **then**
  send_ack()
else
  wait()
end if

2) Channel Measurement: To maximize the recovery probability, the receiver should combine the packets and decode them according to channel conditions following Eq.(7). In practice, the criteria Eq.(7) indicates that the packets with lower SNRs should contribute less to the cumulative decoding compared with those with higher SNRs.

In our experiments, we measure the background noise per packet using OFDM pilots. Most existing Network Interface Cards (NIC) exports per packet Received Signal Strength Indicator (RSSI) and noise measurements. Recent 802.11 NICs also provide fine-grained channel state information (CSI) which reports SNR and phase on subcarrier basis [10].

D. MISC Algorithms

We present the overall operations of MISC in the following. We also demonstrate a modified 802.11 block diagram for MISC in Figure 1. Algorithm 1 defines the behaviors of a transmitter. If no ACK is received after a timeout, the transmitter retransmits the packet as a native 802.11 node. The only difference is, in each retransmission, the transmitter first permutates the constellation map. Then the transmitter maps the bits that are already FEC encoded and interleaved into physical layer symbols and sends them to the receiver.

Algorithm 2 defines the behaviors of a receiver. Based on an appropriate constellation map, the receiver calculates the distance between a received symbol and each constellation point. Next, it updates the *Distance Matrix* of each symbol in the packet by adding the weighted distances. The receiver decodes using the updated *Distance Matrix* for each symbol by selecting the constellation point with minimum value. Then the aggregated packets as a whole is passed on to other blocks and finally is checked with error-detecting codes. If the aggregated packet can pass the CRC test, the receiver ACKs the transmission and releases the memory of *Distance Matrix*.

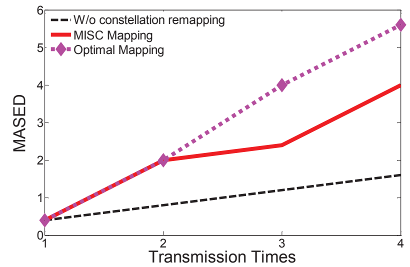


Fig. 5. The growth of MASED (Minimum Accumulated Squared Euclidean Distance) for 16QAM.

Otherwise, the receiver keeps receiving retransmissions and tries to merge more symbols. Compared to an unmodified 802.11 receiver, the differences of MISC are two folded: first, MISC demodulates retransmitted symbols using different constellation maps; second, instead of directly demodulating one single packet, MISC uses the information in this single packet to update *distance matrix* and use this accumulated matrix to demodulate.

V. Practical Issues

In this section, we describe how MISC is implemented by making small modifications to current 802.11 MAC-PHY system design, while keeping all its features. Several practical issues are addressed as follows.

A. Map Generation and Index

The problem of finding optimal alternative maps can be formulated into the well-known Quadratic Assignment Problem (QAP), which was initially proposed to model the assignment problem of M facilities to M locations with distance constraints [21]. The QAP has been considered as one of the most difficult problems and extensively studied in optimization literatures [19, 20]. Most exact solutions to the QAP typically involve branch-and-bound searching with a computational lower bound of $O(M^5)$. If alternative maps are generated by solving QAP, we have two implementation options. One option is to implement QAP solvers in 802.11 nodes and generate retransmissions maps in real time when they are needed. But the excessive computation time involved in map generation using existing QAP algorithms precludes this option in 802.11 systems which has tight timing requirements. The other option is to compute a sequence of maps offline and load them to the transmitter and receiver in advance. This approach requires the transmitter and receiver to store a large number of alternative maps whose number equals to the maximum retransmission times for each applicable modulation scheme. Such storage overhead makes the second option undesirable in 802.11 drivers with limited memory. Moreover, existing exact solutions to QAP can only apply to $M \leq 16$, while approximation solvers are needed for larger constellation maps (e.g., 64-QAM and 256-QAM).

MISC's lightweight map generation algorithm (Section IV-B) can be readily implemented in practical 802.11 nodes. For an M-QAM scheme, only one $\log_2 M \times \log_2 M$ permutation matrix is sufficient to generate alternative maps. The computation time and complexity is negligible, since only two matrix multiplications are needed for each permutation. The memory overhead is very small, as the storage only includes one permutation matrix for one modulation scheme and is constant regardless of retransmission times.

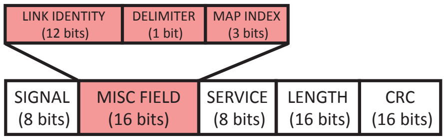


Fig. 6. Modifications to 802.11 PHY PLCP header for MISC.

We compare the growth of MASED (Minimum Accumulated Squared Euclidean Distance) of the optimal remapping design proposed by [20] which has prohibitive computational cost and our approach in Figure 5. Larger MASED indicates stronger capability to combat noise. Although MISC mapping design does not increase MASED as fast as the optimal design, it achieves substantial gain over retransmission without constellation remapping. According to experiment results (in Section VI), our approach generates alternative constellation maps which provide quite close performance to the optimal maps.

As MISC uses an alternative constellation map for each retransmission, we need to synchronize the maps between transmitter and receiver. Our map generation scheme permutates the constellation map $\mathbf{C}_O$ to obtain the permutated map $\mathbf{C}_P$ according to $\mathbf{C}_P = \mathbf{P}\mathbf{C}_O\mathbf{P}$. We have $\mathbf{P}^4$=$\mathbf{I}$ for 16QAM, where $\mathbf{I}$ denotes an identity matrix. Thus a sender only needs to alternate among 4 constellation maps if 16-QAM is used. For an M-QAM scheme, a cycling of constellation maps includes $\log_2 M$ maps. MISC defines a 3-bit Map Index which is already sufficient for 256QAM, and put it in MISC field as depicted in Figure 6. A receiver first extracts the MISC field and finds out the constellation map used in encoding at the transmitter. Then, the receiver can further decode the following payload symbols using the synchronized map.

B. Packet Identifying

In a practical 802.11 network, a receiver may receive packets from multiple transmitters. MISC needs to distinguish packet senders and combine PHY symbols of retransmitted packets accordingly. Current PHY PLCP header however does not include the transmitter or receiver ID. Thus, we add a MISC field into PLCP header as depicted in Figure 6. We hash the transmitter and receiver MAC address into a 12-bit Link Identity, which is used to identify different wireless links when combining packets. In a practical network consisting of multiple links, two links may possibly be hashed into the same identity. Since the collision probability for a 12-bit identity is as small as 1/4096, its impact in an 802.11 WLAN normally with small coverage is negligible.

In 802.11 networks, stop-and-wait retransmission protocol is adopted [26], meaning that after sending one packet, the transmitter will not move on to the next packet until an ACK is received and it will retransmit the same packet upon detecting a timeout. Thus, for the same link, the transmitter keeps transmitting the same packet until the delivery is successful or a retry limit is reached. A one-bit Delimiter is used to signal the start of a new transmission. It alternates between ”1” and ”0” when the transmitter moves on to the next packet. The receiver also alternates Delimiter when one delivery succeeds.

At the receiver, MISC checks the Link Identity as well as the Delimiter. The receiver merges retransmitted packets for the same original packet and tries to decode them. For each original packet, the receiver will maintain a *Distance Matrix*.

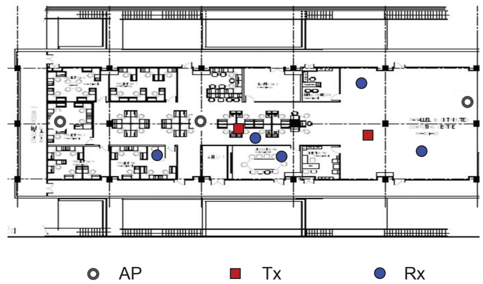


Fig. 7. Experimental testbed layout: 3 access points (AP) are deployed in the lab. The USRP transmitter (Tx) and the receiver (Rx) are moved over different locations in the lab.

When receiving a packet, the receiver first checks whether it is a retransmitted packet by looking up the Delimiter. If it is a retransmitted packet, the receiver updates the corresponding *Distance Matrix* associated with the Link Identity. If the Delimiter indicates the start of an original packet, the receiver will clear the *Distance Matrix* and start a new packet decoding process. Thus, we need a separate *Distance Matrix* for each wireless link. In practice, we save up to 50 *Distance Matrices* which suffice in current WLAN settings. When more than 50 wireless links are established, we maintain the *Distance Matrices* for latest links and clear the obsolete ones when necessary in a FIFO manner. In the worst case, when no *Distance Matrix* is available for a new packet, our approach degrades to the current 802.11 scheme which does not reuse corrupted packets.

C. MISC Field

We extend the 802.11 PHY PLCP header and add the MISC field which contains the Link Identity, Delimiter and Map Index as shown in Figure 6. Note that PLCP header is normally transmitted at the lowest rate of 802.11 (e.g., BPSK with 1/2 FEC coding in 802.11a) to ensure reliable transmission. Since a fixed constellation map is used for the PLCP header independent of our MISC constellation maps, a receiver can decode the MISC field in the PLCP header without knowing the constellation map for the payload symbols. In addition, similar to other fields in PLCP header, the MISC field is well protected against noise. Therefore, even when payload symbols are corrupted, the PLCP header including MISC field may survive to facilitate the combing and decoding operations to recover from errors.

D. Integrate MISC into 802.11

To implement MISC in 802.11 nodes, the only modification to the transmitter operation is to use different constellation maps during retransmissions. This is feasible in practice by simply performing a bits-to-bits mapping before bits-to-symbol modulation. MISC makes no modification to the MAC layer retransmission protocol, as the same payload bits are re-transmitted when a timeout is detected. On the contrary, many other works, such as PPR [3], Ziptx [4], Hybrid ARQ with Incremental Redundancy [6] etc., require major modifications to the native 802.11 MAC layer retransmission scheme.

At the receiver, the distance between each received symbol and constellation point is readily available for MISC, since conventional demodulation schemes also need to know them for decoding packets. The distance information is accumulated in *Distance Matrix* and fed back to the QAM demapper. Then

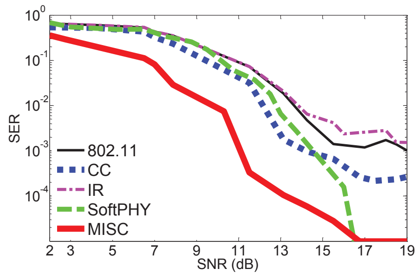


Fig. 8. SER across various channel conditions.

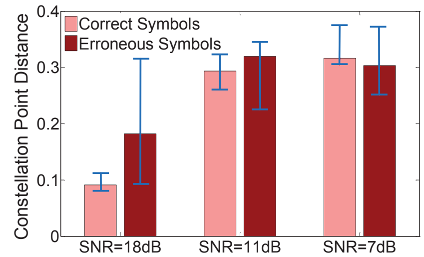


Fig. 9. Average distance to the nearest constellation point (the error bars denote the 20th and 80th percentile values): Erroneous symbols and correct symbols exhibit similar patterns in physical layer over lossy channels.

the received symbol is decoded as the nearest constellation point, which is the same as a conventional QAM demapper.

As the *Distance Matrix* is incrementally merged and updated when a new packet arrives, MISC only needs to store one copy of *distance matrix* for each original packet which aggregates all corrupted packets yet only records the sum. As MISC only needs to find the minimum value in the matrix for each symbol, the *distance matrix* can be further pruned by eliminating some candidate points with large distances to the received symbol. Thus, the memory storage overhead and decoding complexity remain constant as the number of retransmissions increases. The total extra storage overhead and computation complexity incurred by MISC is very small and acceptable.

VI. Implementation and Evaluation

A. Experiment Setup

We test MISC based on the GNURadio/USRP software defined radio platform. MISC builds on top of a WiFi-like OFDM physical layer implementation based on the GNURadio platform. As the current USRP frontends do not support the full 20/40MHz bandwidth required in WiFi, we configure the software radios to operate on OFDM with 600KHz frequency band in the 2.4GHz range. The 600KHz band is divided into 64 subcarriers among which 48 subcarriers are used for data transmission, and 4 pilot tones are used for channel estimation. Due to large transmission latency of PHY symbols between the USRP and the PC, we do not implement carrier sense in current software defined radio testbed. In principle, MISC can work with a wide range of modulation schemes. We mainly focus on 16QAM with 4 alternative constellation maps. We preload the permutation matrix into USRP nodes so they can calculate the four alternative maps. During the experiment, 500 packets are transmitted and received, and the size of each packet is 1500 bytes.

We conduct the experiments in our research lab where 3 WiFi access points are deployed and several clients (e.g., smart phones, laptops, etc.) connect to the access points over time. We vary the transmit power to investigate MISC's performance at various channel conditions. We also move the transmitter and the receiver inside the lab to study MISC with location-dependent interference and multi-path effects. Figure 7 shows our experimental environment.

We compare the following retransmission schemes.

- **802.11 retransmission:** This is the current 802.11 retransmission, which retransmits the same packet if the packet transmission fails. It adopts the 802.11 default Gray-code constellation map.
- **Chase Combining (CC):** This approach combines and decodes corrupted packets to recover a clean packet [2]. It reuses corrupted packets but cannot make full use of symbol error locality because the same constellation map is used throughout the retransmissions.
- **Incremental Redundancy (IR):** This approach transmits newly coded redundant bits for error correction when the first transmission fails [6]. The redundant bits are incrementally sent to correct errors in the corrupted packet.
- **SoftPHY based retransmission:** This approach represents partial packet recovery schemes where only the received symbols with low confidence level (i.e., more likely in error) are retransmitted. In our experiment, SoftPHY hints for QAM are calculated to serve as confidence levels [3], which measure the distance between received PHY symbols and the closest constellation points.
- **MISC retransmission:** This implements the proposed MISC approach of this paper. The distinctive feature of our approach is that it creates constellation diversity in retransmission to improve symbol merging efficiency.

We consider the following performance metrics.

Symbol Error Rate (SER): SER is the number of symbol errors divided by the total number of symbols in a packet. In our experiments, SER is measured in *QAM demapper* before symbols are mapped to bits, which generally dictates PHY layer demodulating performance.

Bit Error Rate (BER): BER is the number of bit errors divided by the total number of transmitted bits in a packet. In our experiments, BER is measured after the PHY symbols are decoded into bits and the number of bit errors can be further corrected by other technologies according to 802.11 setting [17]. The reason for measuring BER is that the relationship between bit errors and symbol errors depends on the particular design of a constellation map and bit error correction ability of other components in the receiver. Therefore, we evaluate both SER and BER of MISC compared with benchmark schemes.

Number of retransmissions: This is the number of retransmissions that a sender needs to successfully deliver the packet. We expect a retransmission scheme to deliver a packet with minimum number of retransmissions.

B. Performance Comparison

Recover symbol errors. We compare SER of 802.11, Chase Combing (CC), Incremental Redundancy (IR), SoftPHY based retransmission and MISC retransmission schemes across various channel conditions. We let a transmitter send packets and retransmit once using different retransmission schemes. For different SNRs, we average the results over all packets and present results in Figure 8. For 802.11 retransmission scheme,

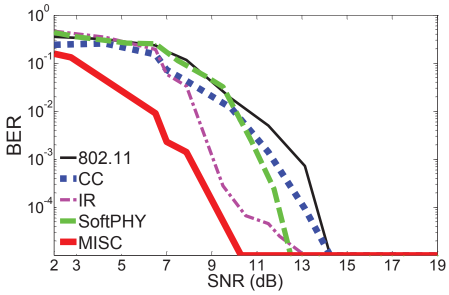


Fig. 10. BER across various channel conditions when bit interleaver and 1/2 convolutional codes are adopted.

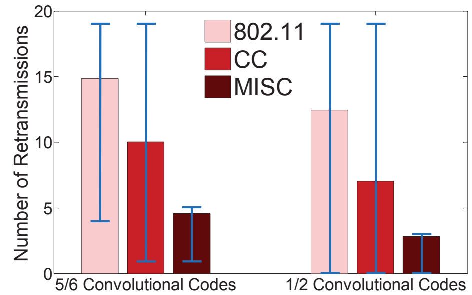


Fig. 11. Average number of retransmissions (the error bars denote the 20th and 80th percentile values). (SNR=5-15dB)

we report the lowest SER of the two transmissions. For IR, we report SER of its first transmission because its retransmission is not self-decodable and IR combines and decodes packets at bit-level not symbol-level. For CC and MISC, we report SER after combining and decoding algorithms. The SoftPHY based scheme discards and retransmits only a portion of received symbols with SoftPHY confidence levels below a threshold. In the experiment for a fair comparison, we let MISC retransmit once and SoftPHY scheme retransmit multiple times iteratively in such a way that the retransmitted amount of symbols equal to the packet length. Naturally, 802.11 and IR show the similar SER. We see that when SNR is reasonably high (e.g., 12dB-19dB), CC improves over 802.11 and IR by combining mildly corrupted packets. Yet, CC'gain over 802.11 and IR quickly decreases when the channel condition becomes worse (2dB-11dB). On the other hand, MISC substantially reduces symbol errors compared with the other schemes over a large range of channel conditions.

We also note SoftPHY scheme achieves little gain compared to 802.11 at low SNRs (e.g., 2dB-11dB), while outperforms 802.11, CC and IR at relatively high SNRs (e.g., 15dB-19dB). To understand the reason for such performance variation. We plot SoftPHY measurement for QAM modulation under different channel conditions in Figure 9. Correct symbols represent the symbols that are correctly decoded, while erroneous symbols represent the symbols that are incorrectly decoded. At a reasonably high SNR of 18dB, we find that SoftPHY hints can indeed suggest the decoding confidence, as the correct symbols are generally closer to their nearest constellation points than those erroneous ones. The rationale is that the smaller the distance, the smaller the noise magnitude and thus higher demodulation accuracy. But at the SNR of 11dB representing mild channel conditions, the two bars for erroneous symbols and correct symbols have a smaller gap, meaning that the SoftPHY hints become less informative in distinguishing erroneous symbols from correct ones. When the channel condition becomes worse when SNR is 7dB, erroneous and correct symbols are indistinguishable using SoftPHY hints. The experiment result suggests that the SoftPHY hints become less informative as SNR decreases. When the channel condition is bad, a received symbol closer to its nearby constellation point does not necessarily indicate a more accurate decoding result or a smaller noise magnitude. Therefore, SoftPHY scheme's performance is worse at low SNRs compared to the performance at relatively high SNRs.

Recover bit errors. We note that a low symbol error rate does not directly translate to a low bit error rate, as constellation maps normally encode bits to symbols differently. In our experiment, we use the Gray-code constellation map, i.e., the default constellation map in 802.11 [11] for retransmission schemes that do not alter constellation map and the first transmission of MISC. In a Gray-code constellation map, adjacent constellation points only differ in one bit, which can reduce bit errors according to symbol error locality. As MISC uses alternative constellation maps in retransmissions, the benefit of Gray mapping may get lost. In addition, 1/2 convolutional coding with bit interleaving are used in our experiments as shown in Figure 1 to examine orthogonality of MISC.

We therefore investigate bit-level decoding performance of different schemes at different SNRs and report the results in Figure 10. Different from SER, the BER of IR is the result of combining and decoding two transmisions. We make sure the same amount of redundancy is transmitted in total for IR and other schemes. According to the experiment result, IR generally performs better than 802.11, CC and SoftPHY by transmitting newly coded bits in retransmissions. Nevertheless, MISC outperforms the other four schemes consistently. The performance gain essentially stems from MISC's low symbol error rate.

Number of retransmission. A sender may retransmit a packet several times in order to deliver the packet. Figure 11 shows the number of retransmissions to successfully deliver a clean packet when rate 5/6 convolutional codes and rate 1/2 convolutional codes are adopted. A packet that can pass a 32-bit CRC is regarded as a clean packet. The transmission limit is set to be 19. Comparing the performance of two different coding rates, we observe that retransmission times are reduced for all the schemes when more redundancy is included in a packet. But for each coding rate, MISC requires the smallest number of retransmissions. We also note that MISC with 5/6 coding rate exhibits better performance compared to CC with 1/2 coding rate. It suggests that MISC incurs negligible overhead but achieves even better effect than adding such considerable redundancy in terms of performance gain.

C. MISC Investigation

Effective data rate. An 802.11 transmitter needs to decide the data rate as a combination of modulation scheme and coding rate for each packet. If the selected rate exceeds the highest rate supported by the channel condition, a packet may get corrupted or even lost. When such packet loss happens, MISC gradually decreases effective data rate by retransmitting and combining more packets. When the effective rate of a combined packet is low enough, the original packet can be recovered. In this experiment, MISC starts by transmitting

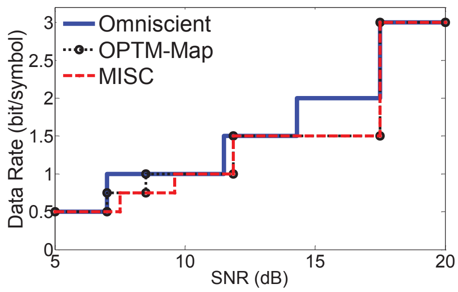


Fig. 12. 1) MISC reduces effective data rate as more packets are retransmitted and combined. 2) MISC's tradeoff of using suboptimal but practical mapping generating method is justifiable.

one packet using 16QAM with 3/4 convolutional coding and keeps retransmitting and combining packets until the combined packet is correct. We then compute the effective data rate for each SNR as the starting rate (transmission rate of the first packet) divided by the number of transmissions required to ensure a packet reception rate higher than 90 percent [9]. Figure 12 plots the effective data rate (the number of information bits per PHY symbol) for MISC under different channel conditions. The same method is used to compute rate for combining packets with optimal design of alternative maps (OPTM-Map). For Omniscient scheme, we transmit packets using a range of combinations of modulation scheme and coding rate as specified in 802.11 standards and plot the highest rate that can ensure a packet reception rate higher than 90 percent for each SNR.

In Figure 12, we find that, as channel conditions deteriorate, MISC can adaptively decrease effective data rate by retransmitting and combining more packets. For instance, when the SNR is reasonably high (e.g., 18dB-20dB), MISC can deliver the packet using one transmission and achieve 3 bit/symbol. When the SNR is mild (e.g., 12dB-18dB), MISC adaptively retransmits one packet which can be merged with previous packet, reducing the effective data rate to 1.5 bit/symbol. Similarly, MISC can retransmit more times (e.g., 3-6 times in this experiment) to further reduce the rate and adapt to worse channel conditions. In addition, we find that MISC's mapping design provides almost the same performance to optimal mapping design in the practical settings. Although there still exist a small gap between MISC and Omniscient scheme, we see that MISC achieves such a performance with little implementation overhead.

VII. Conclusion

Current 802.11 WLANs suffer from interference and noise resulting in frequent packet retransmissions. In this paper, we present MISC, a retransmission scheme that uses alternative constellation maps to enrich constellation diversity by exploiting error locality patterns. MISC effectively merges incorrect PHY symbols, extracts useful information and eventually correct them. We describe feasibility and modifications for existing 802.11 systems to implement MISC. We test MISC based on the GNURadio/USRP platform. Experiment results show that MISC can substantially improve throughput.

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