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Description	

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Preserving The Coding Structure in Relay Transmission in The Presence of Unknown Interference

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Abstract—**The primary goal of this paper is to provide a comparative assessment to the two cases where different criteria are used in joint user minimum mean squared error (JU MMSE) spatial filtering in wireless relay networks in the presence of unknown interference. In the relay networks, even though multiple access coding (MAC) has been proposed at the first time-slot to provide the separability of the signals transmitted from the multiple users, and space-time transmission (STT) at the second time-slot to achieve the diversity gain, additional constraint in JU MMSE spatial filtering to preserve the MAC-encoded/ST-encoded signal structure places floor in bit error rate (BER) performance, while imposing no additional constraint places no error floor.**

I. INTRODUCTION

Recently, relay networks have become one of the core topics in wireless communication research community due to the recognition that wireless relay networks can provide flexible solutions to various problems in designing wireless communication networks, such as coverage extension, capacity enhancement, interference management [1]. In this paper, multiple access coding (MAC) is used in conjunction with the space-time transmission (STT) as transmission techniques in two-hop relay systems where one user is assumed to be blocked from the destination. At the first time-slot, MACs [3] are designed for the multiple users' simultaneous transmission so that the signal separability can be achieved at the receiver side; despite the redundancy incurred by MAC, throughput gain can be achieved due to the increased number of codewords having the same code length. At the second time-slot, the un-blocked users work as mobile relay stations to the blocked user. They form virtual distributed antennas and forward the blocked user's signal to the destination in a cooperative manner by using a ST code [5] [7] [8]. Obviously, the aim of the STT via ST coding is to achieve diversity gain.

At the receiver, an interference suppression technique based on the joint user minimum mean square error (JU MMSE) algorithm is proposed so that the multiple users' MAC-encoded/ST-encoded signal structure can be preserved [9]. Two different criteria for JU MMSE spatial filtering have been considered: one is to minimize the MSE between the spatial filter output and the actually received *composite signal* comprised of the desired MAC-encoded/ST-encoded signals, which is referred to as H-Criterion [12] [13], where H represents the actual channel matrix; the other is to minimize MSE also between two terms but the desired signal term should not necessarily be the actually received *composite signal*, referred to as A-criterion [10] [11], where A represents an equivalent channel matrix.

It is shown from numerical results that with the A-Criterion, the number of the receive antennas, required to suppress unknown interference (UKIF) while preserving the MAC-encode/ST-encoded signal structure at the spatial filter output, is *1+ UKIF number*; If this condition is satisfied, A-Criterion places no error floor. On the contrary, the H-criterion places error floor, if the receiver does not have enough antennas. The reason for this is because the H-Criterion imposes additional constraints to preserve the MAC-encode/ST-encoded signal structure at the spatial filter output even though signal separability is not the objective of JU MMSE, but the objective of MAC decoder. To satisfy the constraints the available degrees-of-freedom (DOF) has to be wasted.

This paper is organized as follows. Section II provides an introduction to the system model. In Section III the proposed protocols applicable to the introduced system setup are presented. Section IV proposes two JU signal detection algorithms based on an MMSE criterion that detects multiple users' *composite signal* while suppressing UKIF. Numerical results are presented in Section V. Finally, Section VI concludes the paper.

The following mathematical notations are used throughout this paper:

1) $(\cdot)^{(k)}$ indicates dependence of $(\cdot)$ on the time-slot index k, k = 1, 2,
2) $(\cdot)^T$, $(\cdot)^H$, and $E\{(\cdot)\}$ denote transpose, conjugate

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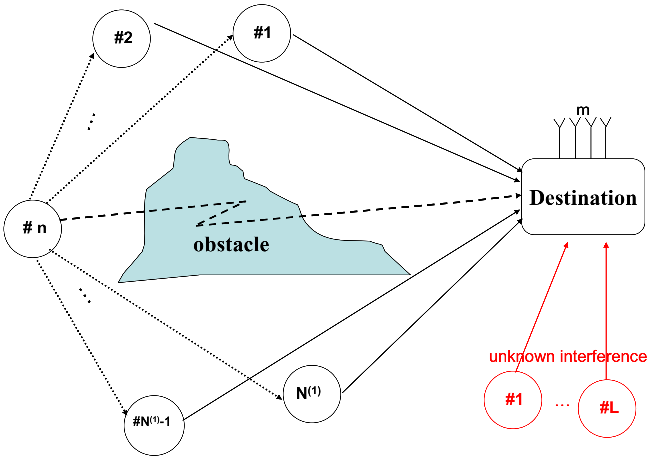

Fig. 1. System structure with $N^{(1)}$ + L + 1 nodes, $N^{(1)}$ desired users, L unknown interference users, and one destination, and the user n is blocked from the destination.

transpose, expectation of $(\cdot)$, respectively,

3) $(\cdot)_j$ stands for the j^{th} column, and
4) matrices and vectors are indicated by bold face while their elements are indicated by lower case.

II. SYSTEM MODEL

Consider a communication system with $N^{(1)} + L$ users transmitting their signals to a common destination, as shown in Fig. 1. The destination has m ($m \geq L+1$) antenna elements while each user has only one antenna. Of the $N^{(1)} + L$ users, $N^{(1)}$ are the desired users and L UKIFs. Due to the life longevity requirement of the user terminals, each user's transmit power is limited. Hence, it may happen quite often that one or some of the users are blocked from the destination due to obstacles. In this paper, only one of the desired users, the user n without loss of generality, is assumed to be blocked. In this scenario, with the help of the neighboring desired users, the signal from the user n can be relayed by its neighboring unblocked users and finally delivered to the destination. A simple example is the case where transmission of the blocked user n is divided into two phases: at the first transmission phase, all the $N^{(1)}$ users transmit their signals to the common destination, where the user n broadcasts its signal to all its neighboring users. However, it is unlikely that all the neighboring users can receive correctly the signal transmitted from the blocked user. Therefore, this paper assumes that only the $N^{(2)}(\leq N^{(1)}-1)$ users that detect no errors in the received signal from the blocked user will forward the signal at the second transmission phase. Simultaneously, also L UKIFs transmit their signals to their destinations, and their signals may reach the receive antennas of the desired users' destination at the first and second phases if they have the same spectrum bandwidth and allocation as the desired users.

The channel is suffering from frequency flat Rayleigh fading, and the fading variation stays the same during each transmission (= block fading). The received signal vector $\mathbf{r}^{(k)}$ can be expressed as

$$\begin{aligned}
\mathbf{r}^{(k)} &= \underbrace{\mathbf{H}^{(k)}\mathbf{S}_D^{(k)}}_{desired} + \underbrace{\mathbf{G}^{(k)}\mathbf{S}_I^{(k)}}_{UKIF} + \underbrace{\mathbf{n}^{(k)}}_{noise} \\
&= \left[\mathbf{H}^{(k)}\ \mathbf{G}^{(k)}\right]\left[\mathbf{S}_D^{(k)}\ \mathbf{S}_I^{(k)}\right]^T + \mathbf{n}^{(k)} \\
&= \mathcal{H}^{(k)}\mathcal{S}^{(k)} + \mathbf{n}^{(k)} \qquad (1)
\end{aligned}$$

with

$$\mathbf{H}^{(k)} = \begin{vmatrix} h_{1,1}^{(k)} & \dots & h_{1,N^{(k)}}^{(k)} \\ \vdots & \ddots & \vdots \\ h_{m,1}^{(k)} & \dots & h_{m,N^{(k)}}^{(k)} \end{vmatrix} \qquad (2)$$

and

$$\mathbf{G}^{(k)} = \begin{vmatrix} g_{1,1}^{(k)} & \dots & g_{1,L}^{(k)} \\ \vdots & \ddots & \vdots \\ g_{m,1}^{(k)} & \dots & g_{m,L}^{(k)} \end{vmatrix}, \qquad (3)$$

where $h_{i,j}^{(k)}$, $1 \leq i \leq m$ and $1 \leq j \leq N^{(k)}$, and $g_{i',j'}^{k}$, $1 \leq i' \leq m$, and $1 \leq j' \leq L$, stand for, respectively, the complex channel gains between the user j and the i^{th} antenna element, and between the interferer j' and the i'^{th} antenna element of the common destination. The losses due to shadowing and propagation distance between the transmitter and the common destination are already included in the channel matrices $\mathbf{H}^{(k)}$ and $\mathbf{G}^{(k)}$. $\mathbf{S}_D^{(k)}$ and $\mathbf{S}_I^{(k)}$ are the symbol vectors transmitted from the desired users and UKIFs, respectively. $\mathbf{n}^{(k)}$ is additive white Gaussian noise vector, sorting up the noise components with the m antenna elements, each being assumed to have a power σ^2.

Let us assume that all users have the decode-and-forward capability for the relaying of the signal from user n and the links between the $N^{(1)} - 1$ neighboring users and the destination support better transmission quality than the direct link of the blocked user n. At the second time-slot the signal originated by the user n is forwarded by the $N^{(2)}$ neighboring users. The transmission power totaling over all mobile relay stations is fixed to a certain value, which is a parameter specifying signal-to-interference power ratio (SIR); SIR at the first time-slot is defined as the power ratio between the unblocked user having the largest power and total power from L UKIFs.

III. PROPOSED PROTOCOLS

According to the system model introduced in Section II, this section proposes a new cooperative relay protocol at the transmitter side. MAC is used at the first time-slot (see Fig. 2) for the user separability at the common destination as well as for the total throughput enhancement; STT is used at the second time-slot (see Fig. 3) to achieve spatial diversity over flat Rayleigh fading channels with the relay links.

A. *Multiple access coding at the first time-slot*

The Kasami code [3] is one of the best-known MACs. It guarantees the signal separability while increasing the total throughput for binary signal transmission over real-valued

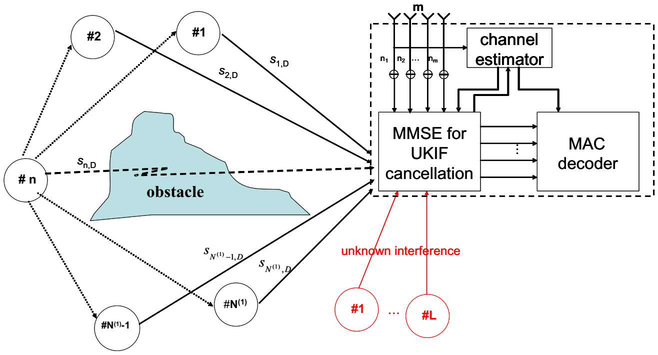

Fig. 2. The transmission at the first time-slot.

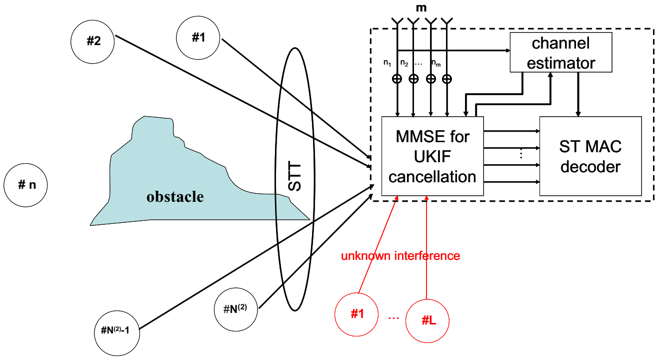

Fig. 3. The transmission at the second time-slot.

channels. The $N^{(1)}$-user Kasami code has $N^{(1)}$ codebooks, denoted as $\mathcal{C}_i$, $1 \le i \le N^{(1)}$. Each codebook includes ξ_i codewords having $N^{(1)}$ symbols.

Assume that the user i uses the codebook $\mathcal{C}_i$. The transmitted vector $\mathbf{S}_D^{(1)}$ in Eq. 1 collects the symbols in the transmitted codewords from all users at each symbol timing. The matrix $\mathbf{S}^{(1)}$ comprised of the codewords transmitted from the $N^{(1)}$ users is then denoted as $\mathbf{S}^{(1)} = [\mathbf{s}_{1,D}, \mathbf{s}_{2,D}, ..., \mathbf{s}_{N^{(1)},D}]^T$ with $\mathbf{s}_{i,D} \in \mathcal{C}_i$ and $\mathbf{s}_{i,D} = [s_{i,D}(1), s_{i,D}(2), ..., s_{i,D}(N^{(1)})]^T$ with $1 \le i \le N^{(1)}$. Thus, the set $\mathbb{S}$ comprised of all combinations of codewords selected from the $N^{(1)}$ users has $\prod_{i=1}^{N^{(1)}} \xi_i$ elements in total. Even though all users transmit their signals at the same time using the same frequency, they can be uniquely decoded and identified without ambiguity at the destination if and only if, for any matrix $\mathbf{X}$, $\mathbf{X} \in \mathbb{S}$, no $\mathbf{Y}$ ($\mathbf{Y} \in \mathbb{S}$ and $\mathbf{Y} \ne \mathbf{X}$) exists, such that

$$\sum_{j=1}^{N^{(1)}} h_{i,j}^{(1)} \left(\mathbf{X}(j) - \mathbf{Y}(j)\right) = 0. \tag{4}$$

where $h_{i,j}$ is, as defined in Eq. 2, the complex channel gain. $\mathbf{X}(j)$ and $\mathbf{Y}(j)$ are the j^{th} row of matrices $\mathbf{X}$ and $\mathbf{Y}$, respectively.

The Kasami code, originally designed for binary transmission over real-valued channels, can be extended to the transmission over complex-valued channels, where in this paper symbols in the codewords are defined over the Galois field GF(4) corresponding to QPSK. Examples of MAC obtained through computer search for the $N^{(1)}$-user's case, $1 \le N^{(1)} \le 4$, can be found in [14].

B. Space-time transmission at the second time-slot

At the second time-slot, distributed STT [16] is used by the mobile relay stations, as shown in Fig. 3. A distributed ST code is used when relaying the signal vector transmitted from the blocked user (=n) via the $N^{(2)}$ neighboring users. It is assumed that the mobile relay stations are synchronized [1]. It has been known that some classes of the ST codes, e.g., [6], can achieve full diversity, regardless of the number of transmit antenna elements. However, in-depth consideration about the code choice for STT is out of the scope of this paper.

IV. JU MMSE

The key idea behind JU MMSE technique is that UKIFs are suppressed, while preserving the MAC-encoded/ST-encoded *composite signal* structure. Two JU MMSE criteria [15], $\mathcal{A}$-criterion [10] [11] and H-criterion [12] [13], were presented in this Section.

For the simplicity in notation, we remove the subscript $^{(k)}$ in this Section. For the optimal solution pairs $[\mathcal{W}_A, \mathcal{A}]$ and $[\mathcal{W}_H, \mathbf{H}]$, adding different subscript $^{(k)}$ distinguishes the final results for the first and second time-slots.

A. JU MMSE $\mathcal{A}$-criterion

The JU MMSE detector determines the spatial filtering weights $\mathcal{W}_A$ and $\mathcal{A}$ according to error cost function $e_{\mathcal{A}}$,

$$\arg\min_{\mathcal{W}_\mathcal{A},\mathcal{A}} E\left\{\|e_\mathcal{A}\|^2\right\} = \arg\min_{\mathcal{W}_\mathcal{A},\mathcal{A}} E\left\{\left\|{\mathcal{W}_A}^H\mathbf{r} - \mathcal{A}^H\mathbf{S}_D\right\|^2\right\}, \tag{5}$$

where matrices $\mathcal{W}_A$ and $\mathcal{A}$ are subjected to an appropriate constraint in order to avoid the trivial solution $[\mathcal{W}_A, \mathcal{A}] = [\mathbf{0}, \mathbf{0}]$ [10] [11].

Following the mathematical derivation process shown in [10] [11], we can easily obtain the i^{th}, $1 \le i \le m$, column of the optimal solution of matrix pair $\mathcal{W}_A$ and $\mathcal{A}$, as

$$\mathbf{w}_i = \left(\mathbf{M} - \sum_{j=1,j\ne i}^{N} \mathbf{h}_j\mathbf{h}_j^H\right)^{-1} \mathbf{h}_i \tag{6}$$

and

$$\mathbf{a}_i = \left[\mathbf{h}_1^H\mathbf{w}_i,\ \cdots,\mathbf{h}_{i-1}^H\mathbf{w}_i,\ 1,\ \mathbf{h}_{i+1}^H\mathbf{w}_i,\ \cdots,\mathbf{h}_N^H\mathbf{w}_i\right]^T, \tag{7}$$

respectively, where

$$\mathbf{M} = \mathcal{H}\mathcal{H}^H + \sigma^2\mathbf{I}. \tag{8}$$

---

[1] In most practical applications, relay stations are within a short distance from the common destination, for which this assumption is reasonable [17]

B. JU MMSE H-criterion

Instead of using $\mathcal{A}\mathbf{S_D}$ in Eq. 5, the received *composite signal* comprised of the desired signal components alone, $\mathbf{HS_D}$, is used as the reference signal for the JU MMSE detection with the H-criterion. The cost function e_H can then be given as

$$\arg\min_{\mathcal{W}_H} E\left\{\|e_H\|^2\right\} = \arg\min_{\mathcal{W}_H} E\left\{\left\|\mathcal{W}_H^H\mathbf{r} - \mathbf{HS}_D\right\|^2\right\}, \tag{9}$$

The optimal spatial filtering weight vector $\mathcal{W}_H$ is given by [12] [13]

$$\mathcal{W}_H^H = \mathbf{HH}^H\mathbf{M}^{-1}, \tag{10}$$

V. NUMERICAL RESULTS

We exploit an example scenario to assess the system performance with two different JU MMSE criteria. In the example scenario, there are 3 ($N^{(1)}$ = 3) desired users and one interference user (L = 1). Among the 3 desired users, one is blocked from the destination, and the other two users ($N^{(2)}$ = 2) forward the signal from the blocked user to the destination at the second time-slot. The Alamouti ST block code [4] is assumed as an example of distributed STT in the simulations. The destination has 2 (m = 2) receive antenna elements. It is assumed that the coded symbols are transmitted in frame with 3072 symbols. It is also assumed throughout this section that SIR = 0 dB at the first and second time-slots. We evaluate average bit error rate (BER) as the performance measure.

A. Multiple access coding at the first time-slot

A 3-user MAC that has 3 codebooks having 4, 4, and 36 codewords, respectively, was used in the simulations. The codewords of the 3-user MAC used are presented in [14]. It improves the total throughput over the orthogonal 3-user signaling by 3.17 bits/symbol at the expense of increased complexity for the MAC decoder. To compensate the total throughput loss of the blocked user due to the orthogonal resource allocation at the relaying transmission, we assign the codebook with the largest number (=36) of codewords to the blocked user (= user 3). The 2 other users use the rest of codebooks, each having 4 codewords.

BER performances of the 3-user MAC with m = 1 without UKIF and with m = 2 with UKIFs are presented in Fig. 4 and Fig. 5, respectively. As a reference, the BER curve with uncoded transmission is presented in the Fig. 4. It is observed in Fig. 4 that the BER curves of MAC are parallel shifted to the left due to the coding gain provided by MAC. Figure 5 provides a comparative result of performances of two different JU MMSE criteria. It is observed in Fig. 5 that a floor is placed to the BER curves with the H-criterion when SNR value becomes large while the curves with the A-criterion tend to have a constant slope. Even though signal separability is not the objective of JU MMSE spatial filtering, but the objective of MAC decoder, a floor happened to the H-criterion. The reason for this is because the H-Criterion imposes additional constraints to preserve the MAC-encoded signal structure at the spatial filter output, and to satisfy the requirement for the constraints the available DOF has to be wasted; If the receiver does not have enough DOF, error floor is placed. On the contrary, with the A-Criterion, no additional constraints are imposed, resulting in no error floor placed. It is also found from the user 3's BER curves of both criteria that user 3 has always worse performance than user 1 and user 2 in the presence of UKIF with same SNR. This is because the smaller Euclidean distance of user 3's codewords.

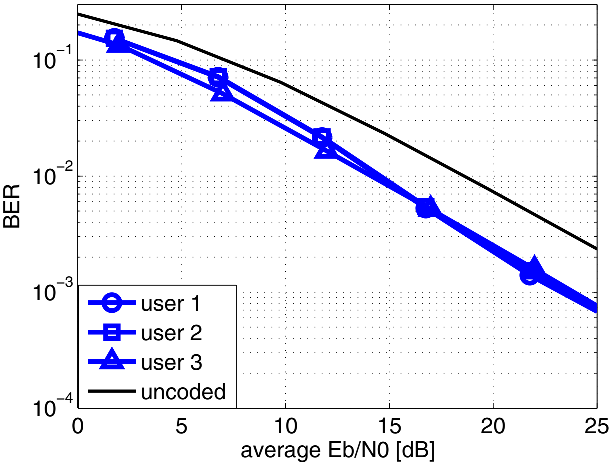

Fig. 4. BER performance of MAC in case of m = 1 and L = 0

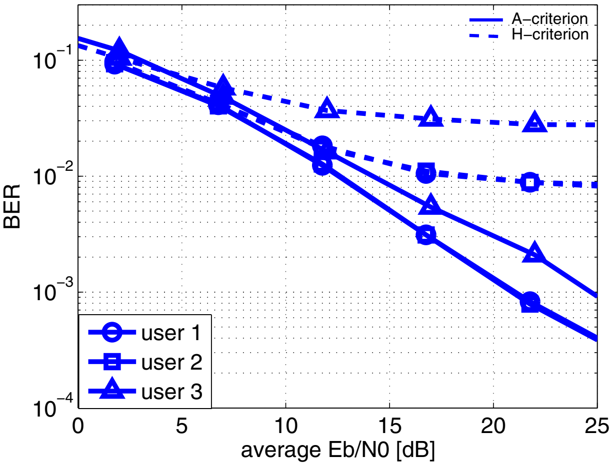

Fig. 5. BER performance of MAC with A-criterion and H criterion in case of m = 2 and L = 1 .

It should be emphasized that with A-criterion even though $N^{(1)} > m$ ($3 > 2$), still the multiple users' symbols can well be separated. Therefore, since L antenna elements are required to suppress L UKIFs, the number of the elements required to detect the multiple users' *composite signal* is L+1 with JU MMSE A-criterion.

B. Space-time transmission at the second time-slot

At the second time-slot, the Alamouti ST block encoding [4] is performed over the two mobile relay stations. The BER curves with user 3 with equal power allocation among relay stations are shown in Fig. 6. For the comparison, the BER

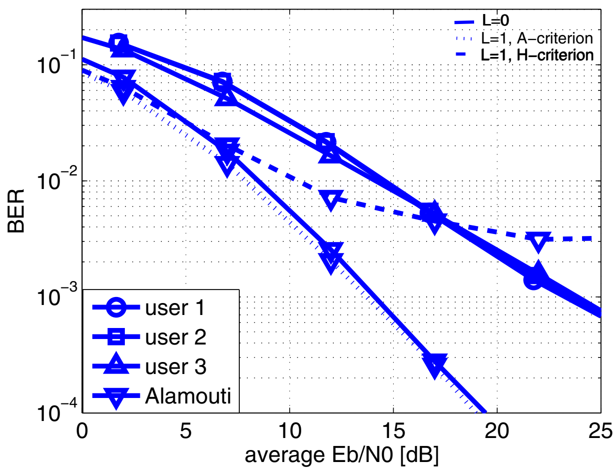

Fig. 6. BER performance of Alamouti block code with m = 1 and L = 0, m = 2 and L = 1 with A-criterion and H-criterion.

curves of MAC with the $m = 1$ and $L = 0$ are plotted in the same figure. There are three cases for the Alamouti STT in Fig. 6: *a*) m = 1 and L = 0 (without UKIF) [14]; *b*) m = 2 and L = 1 with A-criterion; *c*) m = 2 and L = 1 with H-criterion. Comparing *a*) with BER curves of MAC we can clearly observe the increase in the diversity order. This is simply due to the diversity gain provided by STT. It is also found that the BER curves with *a*) and *b*) have the same decay, even though the case *b*) assumes 2 receive antenna elements with 1 UKIF. This is because UKIF is canceled by JU MMSE, for which the DOF with the m = 2 antenna setting has to be used. Whereas, a floor is placed to the BER curve with the H-criterion when SNR value becomes large, the same observation as in the case of MAC at the first time-slot.

VI. CONCLUSIONS

A joint use of MAC and distributed STT has been proposed in this paper for wireless cooperative relaying communication systems. It has been proven through numerical simulation results in a representative relaying scenario that both BER and throughput can be improved by MAC due to the signal separability and the increased number of codewords, respectively. Furthermore, STT with mobile relay stations enables the transmission between the blocked user and the destination, and simultaneously diversity gain can be achieved.

To exploit the benefits of MAC and STT in the presence of UKIF, JU MMSE spatial filtering technique is used, which can suppress UKIF components while keeping the MAC-encoded/ST-encoded signal structure of the multiple users' transmitted *composite signals* at the output of the spatial filter. Two different JU MMSE criteria are proposed for the spatial filtering: A-criterion and H-criterion. It is found from the numerical results that the A-criterion can provide better BER performance than the H-criterion at both time-slots when the destination has no enough DOF. The JU MMSE A-criterion minimizes the number of required antenna elements at the destination to $L + 1$ because detecting the received *composite single* signal comprised of the $N^{(k)}$ desired signals imposes decrease in DOF only by one. However, an error floor placed with the H-criterion, despite the signal separability provided by MAC at the first time-slot and diversity again achieved by STT at the second time-slot. The reason for this is because the H-Criterion imposes additional constraints to preserve the MAC-encoded/ST-encoded signal structure at the spatial filter output. To satisfy the requirement for the constraints the available DOF has to be wasted.

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