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Abstract—In this paper, we present a low complexity maximum likelihood (ML) detection based on the sphere decoder (SD) for distributed time-reversal space-time block code (D-TR-STBC) with frequency selective fading links. Unlike direct transmission, the relay-assisted transmission results in higher number of taps for the resultant end-end channel. The complexity of Viterbi algorithm (VA) grows exponentially with the channel memory and the signal modulation order. Hence makes it prohibitive for the above scenario. On the other hand, the complexity of SD is a low-degree polynomial in the block length and does not vary significantly with the channel memory and the modulation order over the signal to noise ratio (SNR) range of interest. This offers a significant computational reduction over VA specifically for relay networks that provide higher diversity. To corroborate our claims, we have shown the simulation results comparing the average complexities of SD and VA for various system settings. A further reduction in the average complexity of SD is achieved for D-TR-STBC with multiple relays and with relay selection.

I. INTRODUCTION

The use of terminals of multiple users to form a virtual array and thereby achieving spatial diversity to improve the reliability in wireless communication systems in a distributed manner has emerged as one of the interesting topic of ongoing research [1], [2]. Cooperative diversity protocols relay the information transmitted by the source to the destination through multiple cooperating terminals. In D-TR-STBC, the source and relays transmit signals based on agreed code design and achieve diversity at the destination. Single carrier transmission is attractive over OFDM because it avoids problems such as large peak-to-average ratio and sensitivity to carrier offsets. Furthermore, TR-STBC is an attractive alternative to STBC-OFDM with the ability of preserving multipath diversity [3].

To achieve optimal ML performance generally requires joint detection of the symbol block using algorithms such as sphere decoder (SD) and Viterbi algorithm (VA). The complexity of VA is exponential with the channel memory and the modulation order, but linear in the signal block. Over a wide range of SNRs, the average complexity of SD is a polynomial and does not vary significantly with channel memory or modulation order, but the worst case complexity exponential in terms of the signal block length. In [4], authors propose two hybrid ML detection techniques that combine the properties of the SD and the VA to reduce the worst case complexity from larger signal block lengths.

In [5], [6], [8], it has been shown that for moderate block lengths SD offers computational reduction over the VA for larger channel memory and modulation orders. In the presence of frequency selective fading links between the terminals, the relay assisted transmission link has a channel memory equal to the sum of channel memories in the source to relay and the relay to destination link and is generally larger than the channel memory in the direct link. This makes the VA impractical owing to its prohibitive complexity and hence favors the choice of SD.

The system under investigation are (1) a simple two-hop wireless network and (2) a D-TR-STBC system with M relays, both having frequency selective fading links. D-TR-STBC signaling is realized with the help of relays transmitting together with the source in a conformation to form an orthogonal space-time block code (OSTBC) or quasi-orthogonal space-time code (QOSTBC) design. The relay terminals use amplify and forward (AF) based relaying. All the terminals are assumed to have equal transmit power for the co-operative transmission.

In this work, we utilize the computational advantages of SD over VA for the above frequency selective channels with memory. We present a comparison of the average complexity of SD vs. VA for various system configurations with different channel taps, signal modulation orders and block length. For the case of multiple relays, we study the D-TR-STBC system that employ higher order OSTBC and QOSTBC and also opportunistic relay selection. In both cases, the simulation results show that the complexity of SD is more practical than that of the VA. Particularly for D-TR-STBC with relay selection, SD has been shown to offer a significant computational reduction over VA under equal performance criteria.

The rest of the paper is organized as follows. In section II, we discuss the transmission setups. Section III presents the two ML signal detection schemes SD and VA and the complexity considerations for the D-TR-STBC. In section IV, we show the numerical simulation results on the comparison of average complexity between the two schemes and discuss the results. Finally, section V concludes our work.

II. RELAY ASSISTED TRANSMISSION

In this work, we consider a D-TR-STBC system with single and M relays for single carrier relay-assisted transmissions with block-fading frequency-selective channels. The slowly time-varying channels are assumed to remain constant over a frame duration and change independently between frames. Assume the system setups shown in (1) with a source (S), M relay terminals (Ri, i=[1...M]) and a destination terminal (D). The communication between S and D is carried out through the direct and relay-assisted transmission links in two phases during a frame. The channels in S→Ri, S→D and Ri→D are modeled as channel impulse responses (CIR) given by $h_{SD} = [h_{SD}(0) ... h_{SD}(L_{SD}-1)]$, $h_{SR_i} = [h_{SR_i}(0) ... h_{SR_i}(L_{SR_i}-1)]$, and $h_{RD} = [h_{RD}(0) ... h_{RD}(L_{RD}-1)]$ with $L_{SD}$, $L_{SR_i}$ and $L_{RD}$ independent symbol-spaced taps respectively. For the sake of simplicity and without loss of generality, it is assumed that $L_{SR_i} = L_{SR}$ and $L_{RD} = L_{RD}$, $\forall i$. The channel gains of the taps are assumed to be independent zero-mean...
complex Gaussian with unit variance and are weighted with an exponential power delay profile (PDP) $\sigma^2$, such that $\sum_{l=0}^{L-1} \sigma^2(l) = 1$. The additive white noise is distributed as $CN(0, \sigma^2)$. All terminals are equipped with single antennas and operate in a half-duplex mode, hence cannot transmit and receive simultaneously. Relay terminals employ AF based protocol [1], where signals received from the source terminal are amplified and re-transmitted to the destination terminal. The destination terminal is assumed to have a perfect CSI of both $S \to R$ and $R \to D$ links. Linear modulation schemes such as 4-PSK and 8-PSK are considered for the simulations.

Table I shows the D-TR-STBC scheme for single ($M=1$) and $M$ relays ($[R]_M$). In phase 1, $T_1$ symbol blocks broadcasted by $S$ are received by $D$ and $[R]_M$ over $T_1$ time slots. In phase 2, $S$ and $[R]_M$ transmit symbol blocks over $T_2$ time slots. The exact values of $T_1$ and $T_2$ depend on the space-time block code (STBC) design considered for phase 2 transmission, which in turn depends on the number of participating relays, $M$. In other words, $S$ continuously transmits in both phases and $D$ receives from $S$ during phase 1, and from both $S$ and $[R]_M$ during phase 2 of each frame.

In each frame, a total of $T_1+T_2$ time slots are used. A time slot corresponds to the transmission duration of a symbol block of size $Q \times 1$, where $Q=N+P$. The incoming symbols are parsed into $T_1$ symbol blocks $s_i, i=\lfloor 1 \ldots T_1 \rfloor$ of size $N \times 1$. For transmission in frequency selective channels, the symbol blocks are pre-processed to avoid inter-block interference (IBI). A fixed cyclic prefix (CP) of length $P$ is added to the beginning of each symbol block. It is assumed that $P \geq \max(L_{SD}-1, L_{SR}+L_{RD}-2)$ i.e., the upper bound on channel memory length is known. A more detailed explanation on the block transmission with CP can be found in [9]. The IBI at the receiver is avoided by discarding the received signals corresponding to the CP in each block. Insertion of CP at transmitter together with its removal in the receiver yields the following input-output relationship [9]:

$$ y = Hs + w $$

where $H$ is a $N \times N$ circulant matrix with entries $[H]_{i,j} = h((i-j) \mod N)$. Transmission from distributed antennas with frequency selective links use D-TR-STBC. TR-STBC [10] is similar to the STBC design with the conjugate symbols replaced with time-reversed conjugate symbol blocks. Define $L=\max(L_{SD}-1, L_{SR}+L_{RD}-2)$ be the total channel taps and $K$ be the modulation order. Define $P_{SD}, P_{SR}$, and $P_{RD}$ be the average received power, and $H_{SD}, H_{SR}$, and $H_{RD}$ be circulant channel matrices in $S \to D$, $S \to R$, and $R \to D$ links respectively. Assume $P_{SD}=P_{R,D}=P, \forall i$. Let us consider the two phase transmission in frame $n$ for D-TR-STBC.

### A. D-TR-STBC with single and multiple relays:

For convenience, the two phase transmission of D-TR-STBC is presented only for the single relay. A similar explanation applies for the transmissions with $M$ relays using higher order OSTBCs or QOSTBCs.

#### Phase 1: During phase 1 transmission of frame $n$, the received signals at the relay and destination can be written as [cf. (1)]

$$\begin{align*}
[y_{D,1}^D, y_{D,2}^D] &= \sqrt{P_{PSD}} H_{SD} [s_1, s_2] + [w_{D,1}^D, w_{D,2}^D] \quad (2) \\
[y_{R,1}^R, y_{R,2}^R] &= \sqrt{P_{PSR}} H_{SR} [s_1, s_2] + [w_{R,1}^R, w_{R,2}^R] \quad (3)
\end{align*}$$

where $y_{R,i}^R = [y_{R,i}(P+1) \ldots y_{R,i}(Q)], w_{R,i}, i=\{1,2\}$ are of size $N \times 1$. The superscript 1 and the subscript $i$ in $y_{R,i}^R$ corresponds to the phase and the symbol block index respectively. Before re-transmitting the received signals during phase 2, the relay terminal normalizes the received signal power by a factor of $\gamma = \sqrt{|y_{R,i}^R(n)^2|} = P_{SR} + N_0$ to meet the transmit power constraints (more details can be found in [10]).

#### Phase 2: During phase 2, $D$ receives signals from $S$ and $R$ based on the underlying $2 \times 2$ OSTBC. $D$ will thus receive

$$\begin{align*}
y_{D,1}^D &= \sqrt{P_{PSD}} H_{SD} s_2 + \sqrt{P_{PSR}} H_{RD} H_{SR} s_1 + w_{D,1}^D \quad (4) \\
y_{D,2}^D &= \sqrt{P_{PSD}} s_1 - \sqrt{P_{PSR}} H_{RD} H_{SR} s_2^* + w_{D,2}^D \quad (5)
\end{align*}$$

where $w_{D,1}^D = w_{D,2}^D + \sqrt{P_{PSR}} H_{RD} w_{R,1}^R$, $w_{D,2}^D = w_{D,2}^D - \sqrt{P_{PSR}} H_{RD} w_{R,2}^R$ and $P_T = P_{PSR}/(P_{SR} + N_0), \quad P_N = P/(P_{SR} + N_0)$

The received signal vectors during phase 2 are normalized for the total noise power, $P_N$ and we have then

$$\begin{align*}
[y_{D,1}^D, y_{D,2}^D] &= \sqrt{\frac{1}{\gamma}} [\sqrt{\frac{1}{\gamma}} H_{RD} H_{SR} s_1 + \sqrt{\frac{1}{\gamma}} H_{RD} H_{SR} s_2] + [w_{D,1}^D, w_{D,2}^D] \quad (6)
\end{align*}$$

where

$$\gamma_1 = \frac{P_{PSR}}{P_{SR} + P|h_{RD}|^2 + N_0}, \quad \gamma_2 = \frac{P(P_{SR} + N_0)}{P_{SR} + P|h_{RD}|^2 + N_0}$$

$H$ is a block orthogonal matrix and allows for the decoding of circular correlation matrices in $S \to D$, $S \to R$, and $R \to D$ links respectively. Assume $P_{SD}=P_{R,D}=P, \forall i$. Let us consider the two phase transmission in frame $n$ for D-TR-STBC.
III. OPTIMAL DETECTION

This section discusses the optimal signal detection based on the VA and SD for the received signals in (8). \( \mathbf{Y} \) is a circulant and Hermitian matrix formed from the polynomial \( h(q^{-1}) = (P + \gamma_2)h_{SD}(q)h_{SD}(q^{-1}) + \gamma_1 h_{RD}(q)h_{RD}(q^{-1})h_{RD}(q^{-1})(P + \gamma_2)h_{SD}(q)h_{SD}(q^{-1}) \) of degree \( L = \max(L_{SD}, L_{RD} + L_{RD} - 2) \). E.g., the matrix \( \mathbf{Y} \) for \( L = 2 \) and \( N = 8 \) is shown below,

\[
\begin{bmatrix}
\lambda(0) & \lambda(-1) & \lambda(-2) & 0 & \lambda(2) & \lambda(1) \\
\lambda(1) & \lambda(0) & \lambda(-1) & \lambda(-2) & 0 & \lambda(2) \\
\lambda(2) & \lambda(1) & \lambda(0) & \lambda(-1) & 0 & 0 \\
0 & \lambda(2) & \lambda(1) & \lambda(0) & 0 & 0 \\
\lambda(2) & 0 & 0 & 0 & \lambda(0) & \lambda(-1) \\
\lambda(1) & \lambda(2) & 0 & 0 & \lambda(1) & \lambda(0) \\
\end{bmatrix}
\]

\( \lambda(n) = \sqrt{\frac{2}{Q_{\mathbf{Y}}^2}} \left[ \mathbf{Y}_s \right]_n \). Assume the last \( P \) symbols that form the CP are set to zero, i.e., \( s = [0 \mathbf{CP}] \), and this results in \( \sqrt{\mathbf{Y}_s} = \sqrt{\mathbf{Y}} [0 \mathbf{CP}] = \sqrt{\mathbf{Y}} \mathbf{s} \), where \( \sqrt{\mathbf{Y}} \) corresponds to the first \( N \) columns of \( \sqrt{\mathbf{Y}} \).

Replacing \( \sqrt{\mathbf{Y}} \) with its QR decomposition \( \sqrt{\mathbf{Y}} = \mathbf{R} \), where \( \mathbf{Q} \) is an \( \times \) unitary matrix and \( \mathbf{R} \) is an \( \times \) upper triangular matrix. Expanding \( \sqrt{\mathbf{Y}} \) to have,

\[
\sqrt{\mathbf{Y}} = \begin{bmatrix} Q_{1} & Q_{2} \\ R_{1} & 0 \end{bmatrix}
\]

(15)

In other words,

\[
\|Q_{1} y - R_{1} x\|^2 \leq d^2 - \|Q_{2} y\|^2
\]

(16)

Define \( z = Q_{1} y, d^2 = d^2 - \|Q_{2} y\|^2 \). Hence SD is equivalent to a tree search through a tree with \( N \) levels and having \( (N-n)^{th} \) nodes at \( n^{th} \) level, where \( n = N \) to \( 1 \). We can re-write (17) as,

\[
\sum_{m=1}^{N} \left( z(m) - \sum_{n=m+1}^{Q} r_{m,n} x(n) \right)^2 \leq d^2
\]

(18)

where \( r_{m,n} \) is \( (m,n)^{th} \) entry of \( \mathbf{R}_{1} \). The signals are decoded recursively in the reverse order starting from the \( N^{th} \) symbol, \( (z(N) - r_{N,n} x(N)) \leq d^2 \). The search radius is updated for each symbol positions and is given as

\[
R_{n}^2 = d^2 - \sum_{m=n+1}^{Q} \left( z(m) - \sum_{n=m+1}^{Q} r_{m,n} x(n) \right)^2
\]

(19)

- In nulling and cancelling (NC), the ZF estimate of the 'strongest' entry is found and its effect is subtracted from the received signal \( y \). The procedure is repeated \( Q \) times up to the 'weakest' entry to get the signal estimate \( \hat{s}_{NC} \).

The sphere radius is, \( d_{SC} = \|y - \sqrt{\mathbf{Y}} \mathbf{s}_{SC}\|^2 \).

- Computational complexity, \( C_{sphere} \propto K^N \), \( \eta \in [0, 1] \) where \( \eta \) is a factor dependant on SNR and for the case of large SNR, \( \eta \leq 1 \) and hence the complexity does not vary much with \( K \) and \( L \) for moderate values of \( N \).

- In other words, the complexity of SD is proportional to the number of signal points inside the sphere of radius \( R \) or the number of nodes visited during search procedure.

C. Decoder Complexity Considerations

The complexity of SD and VA depends either linearly or exponentially on the following system parameters, the number of channel taps \( L \), signal modulation order \( K \), signal block length \( N \) and the SNR range of interest. In this paper, the average complexity of the algorithms is defined as follows.

**Definition 1:** The average complexity of the VA is equal to the product of the signal block length, \( N \) and the number of states visited, which is a fixed value equal to \( K^L \). The average complexity of SD is the expected number of nodes visited in the tree search for decoding a signal block, where the tree has \( N \) levels starting with a node, ending with \( N^{th} \) nodes and \( K \) branches emanating from each node. The number of operation required per state or node is not considered, since it is relatively less cumbersome and involves few linear calculations. The expected number of nodes visited per symbol
L(y_i|s_i) = \sum_{k=1}^{N} L(y_i(k)|s_i(k)) = \min_{s_i} \text{Re} \left\{ \sum_{n=1}^{N} s_i^*(n) \left( 0.5\lambda(0)s_i(n) + \sum_{l=1}^{L} \lambda(l)s_i(n-l) - z_i(n) \right) \right\} + \text{const.} \quad (12)

and \quad \mu_{a_i}(n) = \mu_{a_i}(n-1) + \text{Re} \left\{ s_i^*(n) \left( 0.5\lambda(0)s_i(n) + \sum_{l=1}^{L} \lambda(l)s_i(n-l) - z_i(n) \right) \right\}, \quad \text{where } i = 1, 2 \quad (13)

block for SD is obtained through numerical simulations. We adopt the following notation for the average complexity,

\begin{align*}
C_{VA} &= \log(N(NK)^L) \\
C_{SD} &= \log(N(E[N_{SD}]))
\end{align*}

(20)

where \(N_{SD}\) is the expected number of nodes visited for SD.

The direct transmission link \(S\rightarrow D\) has \(L_{SD}\) taps and the transmission link through the relay \(R_i\) is equivalent to the convolution of channel impulse responses \(h_{SR_i}\) and \(h_{R_iD}\). The resultant end-to-end channel between \(S\) and \(D\) for D-TR-STBC has \(L = \max(L_{SD}, L_{SR} + L_{RD})\) taps. \(L\) depends on the number of channel taps in both the direct and relay-assisted transmission links and is lower bounded by \(L_{SD}\), i.e., \(L \geq L_{SD}\). Assuming the frequency selective links between the nodes have equal number of taps and this results in relay-assisted transmission having twice the number of channel taps compared to that of direct transmission, which will increase the average complexity of the decoder. The problem of interest is when the values of \(L\) and \(K\) are large. The complexity of VA is proportional to the number of states which grows exponentially with \(L\) and \(K\). E.g., Assume \(K = 8\) and \(L_{SD} = L_{SR} = L_{RD} = 5\), which results in \(L = 6\). The number of states will be equal to \(8^6 = 262,144\). Hence the use of VA becomes prohibitive for the above D-TR-STBC scenario. On the other hand, for a large SNR the complexity of SD is a low-degree polynomial in the block length and does not vary significantly with \(L\) and \(K\). This offers a significant computational reduction over VA for such scenarios over the SNR range of interest.

IV. Simulation Results

In this section, we show the simulation results of SD and VA evaluated using Monte-Carlo simulations for the system setups explained in section II and present the average complexity (per symbol block decoding) for different values of SNR, \((P/N_0)\). The main aim of the results is to show the advantage of SD over Viterbi decoder from the average complexity point of view. Simulations are done for variety of system parameters including different signal modulation orders, channel taps, length of symbol block and also for different number of relay terminals. The average complexity of VA and SD are plotted based on the average number of nodes visited as given in (20).

No power control or coding is assumed at the source or relays. Relay terminal employs AF based protocol. For D-TR-STBC, the transmit power is shared among the participating terminals in phase 2 to maintain a fairness in comparison with the transmit power used in conventional STBC system with collocated antennas. A total of 50,000 blocks is considered for different values of SNR to obtain the results. Except for the results in Table II, the value of \(P_{SR}/N_0\) is set to 20 dB. For simulations with 4-PSK and 8-PSK signal constellations, the SD radius is obtained using the ZF and the NC estimates respectively. A similar assumption is made for the simulations with \(N = 10\) and \(N = 20\) respectively.

Fig. 2 compares the average complexity of VA and SD for a D-TR-STBC transmission with multiple relay terminals. For \(M = 1\) and \(M = 2\), 2×2 and 3×3 OSTBCs respectively are used. For \(M = 3\), 4×4 OSTBC and 4×4 QOSTBC are used. The simulations are done for \(L = 4\) channel taps, 4-PSK constellation and a symbol block length, \(N = 10\). The complexity of VA for OSTBC and QOSTBC are given by \(\log_{10}(10\cdot4^4)=3.4\) and \(\log_{10}(20\cdot4^4)=4.7\) respectively. The average complexity of the SD is significantly reduced due to the spatial diversity at the destination terminal from the MRC of individual channel matrices given in (12), which reduces the probability of ill-conditioned channel matrices or equivalently too many tree searches from a larger sphere radius. At high SNR, SD starts to behave more like decision feedback equalizer (DFE) and the average complexity converges to the complexity of searching one path (or \(N\) nodes) down the tree to yield the ML solution with high probability. Thus clearly outperforming the VA which has a fixed complexity for all SNR. Unlike OSTBC which allows for a full de-coupling of signal blocks, QOSTBC does not achieve full decoupling and works with the decoding of a pair of symbol blocks of size \(2N\). This results in a tree search over \(2N\) levels for SD. Hence it results in higher average complexity as shown in Fig. 2.

Fig. 3 compares the average complexity of VA and SD for a D-TR-STBC transmission with and without relay selection (RS), using 2×2 OSTBC. The simulations are done for 8-PSK constellation and for \(N = 10\). For the relay selection, a relay is selected out of the available \(M = 3\) relay terminals that has the maximum product of channel powers in the individual \(S\rightarrow R_i\rightarrow D\) links. It is assumed that the selection is only among the relay assisted links and doesn’t include the \(S\rightarrow D\) link. Since the SD radius calculation using ZF and NC estimate
involves channel inverse, the relay selection results in lesser probability of ill-conditioned channel matrix and hence results in smaller SD search radius (fewer node search) and average complexity compared to that of no relay selection. From the results in Fig. 3, the average complexity of SD with relay selection is approximately four times lesser than that of no relay selection for $P/N_0 < 12$ dB.

Table II compares the average complexity of VA and SD for D-TR-STBC transmission with $M=1$ using $2 \times 2$ OSTBC for $P_{SR}/N_0=5$, 10 and 25 dB. It is evident from the MRC channel in (12) that for low values of $P_{SR}/N_0$, the noise power forwarded from the relay is large enough such that $\gamma_s \approx P_{SR}$ and hence the diversity is decreased to one [10]. Thus (12) depends solely on the channel matrix of the direct link $H_{SD}$. Reduced diversity increases the probability of ill-conditioned combined channel matrix $\mathbf{Y}$ and this could result in a larger SD search radius. The average complexity of the SD varies by four fold between $P_{SR}/N_0=5$ and $P_{SR}/N_0=25$ dB as shown in Table II. For the case of high $P_{SR}/N_0$, the decoding complexity resembles to the results given in Fig. 2.

Finally, Fig. 4 presents the average complexity for VA and SD for variations in the signal block length, $N=20$. The simulations are done for D-TR-STBC with single relay terminal, $M=1$ having $L=3$ and $L=4$ channel taps and for 4-PSK constellation. Since the complexity of VA is linearly proportional to the block length, it results in just a small increase of $\log_{10}(2)=0.301$ with $N$ increased from 10 to 20, whereas the average complexity of SD is increased by around 10 times. For $P/N_0>12$ dB, the complexity of SD starts to be lower that that of the VA.

Table II compares the average complexity of VA and SD for D-TR-STBC with single relay assisted frequency selective links.

<table>
<thead>
<tr>
<th>$P_{SR}/N_0$ (dB)</th>
<th>VA and SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>05 dB, $C_{SD}$</td>
<td>3.65</td>
</tr>
<tr>
<td>10 dB, $C_{SD}$</td>
<td>3.40</td>
</tr>
<tr>
<td>25 dB, $C_{SD}$</td>
<td>3.40</td>
</tr>
<tr>
<td>$C_{VA}$</td>
<td>3.40</td>
</tr>
</tbody>
</table>

Fig. 3. Average Complexity of VA and SD for D-TR-STBC with $N=10$ and $K=8$. Comparison between no relay selection ($M=1$) and relay selection (RS) by choosing the best relay from $M=3$ available relays.

Fig. 4. Average Complexity of VA and SD for D-TR-STBC for two different signal block lengths, $N=10$, 20 with $M=1$ and $K=4$.

V. CONCLUSION

To sum up, we have investigated the complexity of VA and SD for D-TR-STBC with frequency selective links. Although VA has linear increase in complexity for higher block size, its complexity is prohibitive for higher channel memories in the relay-assisted transmission link and for higher modulation orders. The main advantage of using SD is that for a moderate block size and medium SNR, it has relatively lesser complexity compared to that of VA for different channel memory lengths and modulation orders. From the simulation results, it is clear that the SD is set to be a better candidate for the D-TR-STBC with single carrier relay-assisted frequency selective links.

REFERENCES