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A low-complexity protocol for K-parallel-path multihop networks

Charlotte Hucher and Ghaya Rekaya-Ben Othman
TELECOM ParisTech, Paris, France
Email: {hucher,rekaya}@telecom-paristech.fr

***Abstract*— In this paper, a low-complexity protocol for the K-parallel-path multihop channel is proposed. This protocol is based on a smart path selection combined with a small space-time code. It is proven to achieve full rate and full diversity, and to reach the optimum diversity-multiplexing gain tradeoff $d^*(r) = K(1-r)^+$. Some implementation issues such as the frame length or interferences between paths are further discussed.**

I. Introduction

Since a few years, the multihop channel is intensively studied because of its interesting applications such as sensor networks. Different models have been proposed such as layered networks or K-Parallel-Path (KPP), and their theoretical performance have been analyzed. Multihop protocols have also been proposed to reach these theoretic performance. Diversity is usually brought by space-time coding [1]–[5]. However, this strategy induces a high decoding complexity. Thus some have considered the idea of selection. Antenna selection was already used in MIMO systems to bring some diversity [6], [7]. This idea has been generalized to relay or path selection in multihop cooperative networks [8], [9].

In this paper we propose a practical and low-complexity protocol for a KPP multihop network. The case of paths with equal lengths is first considered. The proposed protocol is based on the selection of a few amount of paths combined with a small MISO space-time block code (STBC). Three paths is proven to be a good choice to avoid backflow interferences. This protocol reaches full rate and full diversity, and achieves the optimum Diversity-Multiplexing gain Tradeoff (DMT) computed by Sreeram et al [2]. We then propose a generalization of this protocol to the case where the path lengths are different and to the use of decode-and-forward processing. Several implementation issues are further discussed. In order to achieve a good practical rate, the frame length has to be quite long. However, this does not increase the decoding processing because of the particular structure of the channel matrix. The influence of path interferences is also studied. The system is robust to small interferences between paths, but their power has to be much lower than the signal.

A. KPP channel model

We consider a network composed of one source, one destination, and several relaying nodes. The network is modeled by a K-Parallel-Paths (KPP) channel.

The length of the k^{th} path is denoted by n_k. Thus the k^{th} path contains $(n_k + 1)$ nodes. The first node of a path is the source S and the last one is the destination D. The i^{th} relay of the k^{th} path is noted R_i^k. A node can only broadcast information to its neighbors. The channel coefficient between node i and node $i+1$ of the k^{th} path is h_i^k. We can assume that the transmission between node $i+1$ and node i is submitted to the same attenuation with an opposite phase. Consequently, the corresponding channel coefficient is $(h_i^k)^*$. All the channel coefficients follow a Rayleigh distribution and vary very slowly. Thus they can be considered constant during the transmission of at least one frame. We also suppose a symmetric scenario, i.e. all the channel links are subject to the same average signal-to-noise ratio (SNR).

Considered terminals are half-duplex; they cannot receive and transmit simultaneously. They are equipped with a single antenna; the MIMO case is not considered in this work.

We assume that there is no interference between paths. This assumption is discussed further in section V-B.

Example 1: In the following, theoretical results are illustrated through the example of the 4-PP channel, where each path length $n_1 = n_2 = n_3 = n_4 = 3$ (see Figure 1).

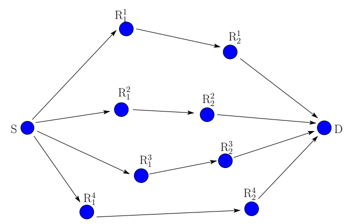


Fig. 1. 4-PP channel with path length $n = 3$

In the paper, following notation are used. Boldface lower case letters $\mathbf{v}$ denote vectors. Boldface capital letters $\mathbf{M}$ denote matrices. $\mathbf{M}^\dagger$ denotes the transpose conjugate of matrix $\mathbf{M}$. $\Pr$ stands for a probability. The symbol $\doteq$ and $\dot{\leq}$ denote the asymptotic behavior of the considered variable when the SNR grows to infinity.

B. Existing works

1) Edge coloring strategy: In [1], [2], authors defined and studied the KPP channel from a theoretical point of view. In particular, the optimal DMT of such a channel is proven to be

$$d^*(r) = K(1-r)^+. \quad (1)$$

A transmission protocol is proposed to achieve these optimal performance using an edge coloring strategy. Let N be the cycle length for the protocol and $C = \{c_1, c_2, \dots, c_N\}$ be the set of colors. Each color in C represents a time slot. $\forall k \in \{1, \dots, K\}$ and $i \in \{1, \dots, n_k\}$, let C_i^k be the set of colors associated to the edge between relay R_i^k and relay R_{i+1}^k (the source is abusively noted R_0^k). Each color in C_i^k represents the time slots during which relay R_i^k is transmitting to relay R_{i+1}^k. The edge coloring has to respect the following constraints:

- at each time slot, the source is transmitting to only one path: $\forall (k, k') \in \{1, \dots, K\}^2, k \neq k', C_0^k \cap C_0^{k'} = \varnothing$;
- at each time slot, the destination is receiving from only one path: $\forall (k, k') \in \{1, \dots, K\}^2, k \neq k', C_{n_k}^k \cap C_{n_{k'}}^{k'} = \varnothing$;
- since the nodes are half-duplex, two neighbors cannot transmit simultaneously: $\forall k \in \{1, \dots, K\}, \forall i \in \{1, \dots, n_k - 1\}, C_i^k \cap C_{i+1}^{k'} = \varnothing$;
- each node on a path is transmitting during the same number of time slots T_k in order for all signals to reach destination: $\forall k \in \{1, \dots, K\}, \forall i \in \{1, \dots, n_k\}, Card(C_i^k) = T_k$.

Implemented with an approximately universal STBC [10], this protocol is proven to achieve the MISO bound.

2) End-to-end antenna selection: In [9], authors considered a layered network. Each layer l contains A_l nodes. A node in a layer l is connected to all nodes in layers $l-1$ and $l+1$. Authors proposed an end-to-end antenna selection (EEAS) designed to bring diversity with low decoding complexity. They considered both the full-duplex and half-duplex modes.

In the full-duplex mode, one path is selected so as to maximize the SNR at destination. This strategy allows to reach the optimum DMT of the system $d^*(r) = \alpha(1 - r)^+$, where $\alpha = \min_l \{A_{l-1} \times A_l\}$ is the maximum diversity.

In the half-duplex mode, two paths are selected: the first path is chosen according to the SNR at destination; the second one is then selected according to the same criteria but considering only the remaining nodes. The maximum diversity is limited by the choice of the second path to $\beta = \min_l \{(A_{l-1} - 1) \times (A_l - 1)\}$. Information symbols are sent alternatively on first and second paths, in order to reach a full rate of 1 symb. pcu. This strategy is proven to achieve a DMT of $d(r) = \beta(1 - r)$. The drawback of this strategy is that some diversity is lost, which degrades asymptotic performance.

II. Proposed protocol using an amplify-and-forward strategy

In order to achieve the theoretical limits of the KPP channel with a low complexity, we propose to combine the two diversity strategies: path selection and space-time coding. First we define our protocol for the case of equal path lengths ($\forall k \in \{1, K\}, n_k = n$) and generalize it to different path lengths in the sequel.

A. A smart combining of path selection and space-time coding

We propose to select S paths (S is not fixed yet). At each time slot, the source sends a signal to the first node of one of the selected paths. Meanwhile, all nodes that have received a signal in the previous time slot forward this signal to the next node in the path. Using this transmission strategy, a node is transmitting only $\frac{1}{S}$ of the time.

The paths are independent and thus can be selected independently. The first path is chosen to maximize the SNR at destination. The second one is selected using the same criterion but considering only the $(K - 1)$ remaining paths. And so on till the S^{th} path is selected.

Let g_k be the product of the channel coefficients composing the k^{th} path. g_k can be expressed:

$$g_k = \left(\prod_{j=1}^{n-1} \sqrt{\rho} \beta_j^k h_j^k \right) h_n^k, \tag{2}$$

where β_j^k are the amplifying factors chosen so that the power of the transmitted signal is normalized

$$\forall j \in \{1, \dots, n-1\}, \beta_j^k = \frac{1}{\sqrt{1 + \rho |h_j^k|^2}}. \tag{3}$$

Let the g_{k_i} be the ordered channel products:

$$\forall (i, j) \in \{1, \dots, K\}^2, i > j, |g_{k_i}|^2 > |g_{k_j}|^2.$$

Then the selected paths are paths $(k_i)_{1 \leq i \leq S}$.

Once the S paths are selected, the space-time code to be used can be chosen. Since selection brings diversity, we do not need to take a large set of paths. A small value of S is sufficient and it allows to use a small STBC and thus to have a low decoding complexity.

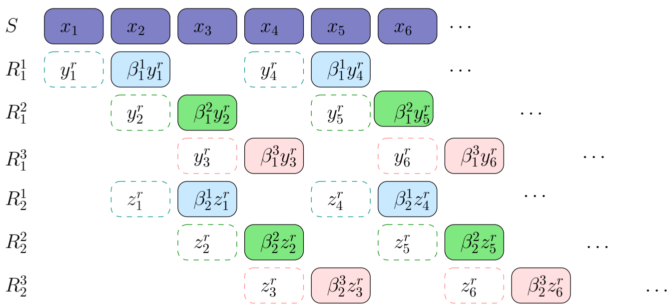


Fig. 2. Transmission frame of the path selection multihop protocol

The protocol illustrated in Figure 2 for the case of $S = 3$ is an orthogonal protocol. So the equivalent channel model is the same as the one of the MISO channel. DAST codes [11] or a diagonal of a perfect code can be used. These codes were proven to be universal in [12].

Coded symbols x_i can then be written as $\mathbf{x} = \mathbf{M}\mathbf{s}$, where $\mathbf{M}$ is a unitary matrix (rotation). $\mathbf{x}$ and $\mathbf{s}$ are the arrays of coded and information symbols respectively.

We consider again the network presented in Example 1. Figure 3 shows the performance obtained with and without a STBC when two or three paths are selected. Several remarks can be done considering this figure:

- The more paths, the lower performance. Indeed, according to the selection criterion, the additional paths have lower SNR at destination.

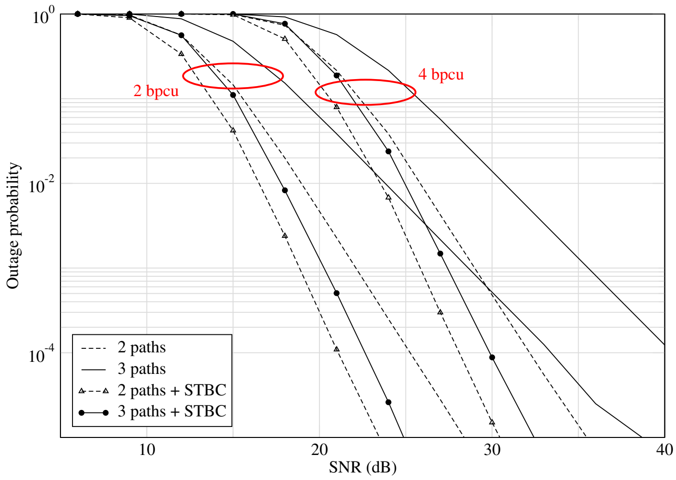


Fig. 3. Outage probability of the path selection multihop protocol with and without a distributed STBC

- As expected, space-time coding brings diversity and thus better asymptotic performance. We can observe diversity orders of 4 when an STBC is used, while the uncoded strategies bring diversity orders of 3 and 2 only for $S = 2$ and $S = 3$ respectively.
- The higher the number of selected paths, the larger the gain between the uncoded strategy and the one using a STBC. Indeed, more diversity orders are brought by the STBC.

B. Diversity-multiplexing gain tradeoff analysis

In order to compute the DMT of the proposed protocol, we study the asymptotic behavior of its outage probability. The system model can be written:

$$\mathbf{y}^{(S\times 1)} = \mathbf{H}^{(S\times S)}\mathbf{x}^{(S\times 1)} + \mathbf{z}^{(S\times 1)}, \tag{4}$$

where $\mathbf{y}^{(S\times 1)}$ contains the set of received signals, the equivalent channel matrix $\mathbf{H}^{(S\times S)}$ is diagonal and its diagonal elements are the channel products $g_{k_i}, i \in \{1, ..., S\}$ of the S selected paths, $\mathbf{x}^{(S\times 1)}$ contains the set of coded symbols and $\mathbf{z}^{(S\times 1)}$ is an array of colored noise since it contains all noises accumulated at each relaying node.

It was proven in [1, Theorem 2.3] that the DMT is the same if the noise is colored or white. So the noise can be considered as white in the scale of interest and the DMT of the proposed protocol is the same as the one of the new system model:

$$\tilde{\mathbf{y}}^{(S\times 1)} = \mathbf{H}^{(S\times S)}\mathbf{x}^{(S\times 1)} + \mathbf{w}^{(S\times 1)}, \tag{5}$$

where $\mathbf{w}^{(S\times 1)}$ is an array of AWGN.

The outage probability of the new system is given by:

$$p_{out}(r\log\rho) = \Pr\left\{\frac{1}{S}\log\det\left(\mathbf{I}+\mathbf{H}\mathbf{H}^{\dagger}\right) \leq r\log\rho\right\}. \tag{6}$$

Replacing the channel matrix by its expression, we obtain:

$$p_{out}(r\log\rho) = \Pr\left\{\log\prod_{i=1}^{S}\left(1+|g_{k_i}|^2\right) \leq Sr\log\rho \;\middle|\; \forall(i,j)\in\{1,...,K\}^2, i>j, |g_{k_i}|^2 > |g_{k_j}|^2\right\}.$$

A straight upper bound to the outage probability is:

$$p_{out}(r\log\rho) \leq \Pr\left\{\log\prod_{i=1}^{S}|g_{k_i}|^2 \leq Sr\log\rho \;\middle|\; \forall i\in\{S+1,...,K\}, \log(|g_{k_i}|^2)^S \leq Sr\log\rho\right\}.$$

The channel paths are independent. Thus the previous upper bound can be rewritten as a product of probabilities:

$$p_{out}(r\log\rho) \leq \Pr\left\{\log\prod_{i=1}^{S}|g_{k_i}|^2 \leq Sr\log\rho\right\} \times \prod_{i=S+1}^{K}\Pr\left\{\log|g_{k_i}|^2 \leq r\log\rho\right\}.$$

Replacing the g_{k_i} by their expression (2), we obtain:

$$p_{out}(r\log\rho) \leq \Pr\left\{\log\prod_{i=1}^{S}\prod_{j=1}^{n}\rho|\beta_j^{k_i}h_j^{k_i}|^2 \leq Sr\log\rho\right\} \times \prod_{i=S+1}^{K}\Pr\left\{\log\prod_{j=1}^{n}\rho|\beta_j^{k_i}h_j^{k_i}|^2 \leq r\log\rho\right\}.$$

$\forall j \in \{1, ..., n-1\}$, we have the asymptotic behavior:

$$\rho|\beta_j^{k_i}h_j^{k_i}|^2 = \frac{\rho|h_j^{k_i}|^2}{1+\rho|h_j^{k_i}|^2} \doteq 1.$$

Thus, the asymptotic behavior of the outage probability can be upper-bounded:

$$\begin{aligned}
&p_{out}(r\log\rho)\\
&\dot{\leq}\Pr\left\{\log\prod_{i=1}^{S}\rho|h_n^{k_i}|^2 \leq Sr\log\rho\right\} \times \prod_{i=S+1}^{K}\Pr\left\{\log\rho|h_n^{k_i}|^2 \leq r\log\rho\right\}\\
&\dot{\leq}\Pr\left\{\prod_{i=1}^{S}|h_n^{k_i}|^2 \leq \rho^{-S(1-r)}\right\}\prod_{i=S+1}^{K}\Pr\left\{|h_n^{k_i}|^2 \leq \rho^{-(1-r)}\right\}\\
&\dot{\leq}\rho^{-S(1-r)^+} \times \prod_{i=S+1}^{K}\rho^{-(1-r)^+}\\
&\dot{\leq}\rho^{-K(1-r)^+}.
\end{aligned}$$

So finally the DMT is lower-bounded by $K(1-r)$ which is the MISO upper-bound. Thus the DMT of the proposed protocol is optimal:

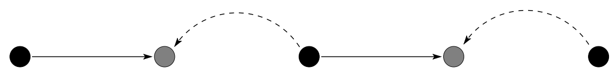
$$d^*(r) = K(1-r)^+. \tag{7}$$

C. Choice of S: influence of backflow interference

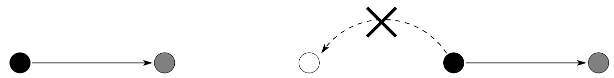
In [9], authors pointed out that two paths are necessary to achieve full rate in the half-duplex case. Indeed, because of the half-duplex constraint, nodes can transmit only half of the time. Thus, to achieve a rate of 1 symb. pcu, signals have to be sent on at least two paths alternatively.

In a wireless network, nodes usually ignore other nodes positions. Thus beam antennas cannot be used and the signals are broadcasted in all directions, and in particular, the signal is also sent backward to the previous node. The presence of these backflow interferences cannot be neglected. In [1], [2], authors show that these backflow interferences do not impair the DMT.

To see the influence of backflow on performance, we have simulated the 4-PP channel of Example 1 for two selected paths. In order to simplify implementation, we assume that backflow occurs once every two transmissions. Thus it is a lower bound for the case where backflow is happening at each transmission. We can remark in Figure 5 that in this case the 4-PP channel experiences a 5 dB loss for a outage probability of 10^{-5} compared to the case without backflow.



(a) Backflow



(b) No backflow

Fig. 4. How to avoid backflow interferences: black nodes are transmitting, gray nodes are listening, and white nodes are inactive

Avoiding backflow interferences would then be a great improvement for the protocol. This can be done quite easily by leaving an inactive node (neither transmitting nor listening) between each listening and transmitting ones (see Figure 4). With this strategy, a node is transmitting only once in three time slot. In order to get full rate, at least three paths have then to be selected instead of two.

Figure 5 shows that it is more efficient to use a 3 paths selection where no backflow can occur, rather than a 2 paths selection with backflow. The gain loss is twice smaller for a spectral efficiency of 4 bits pcu and is also reduced for 2 bits pcu.

Selecting $S > 3$ paths would also achieve full diversity of K. However adding some more paths decreases performance. Thus we can limit the number of selected paths to $S = 3$.

Remark 1: For a two-hop network ($n = 2$, one relay per path), there is no possible backflow. In this case, two paths are sufficient.

Remark 2: Even in the full-duplex mode, three paths are necessary to avoid backflow interferences. The same protocol has to be used in both full and half-duplex modes.

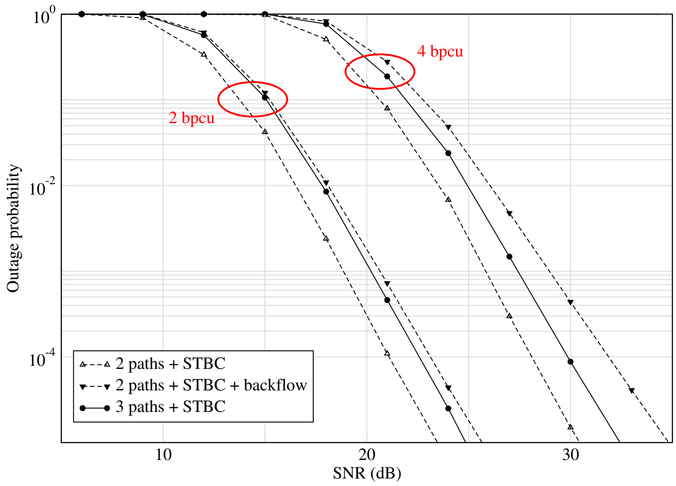


Fig. 5. Influence of backflow on the outage probability of the path selection multihop protocol

III. Generalization to the Decode-and-Forward Strategy

A DF protocol can be used only if relaying nodes are able to correctly decode the signals. Usually in literature, when all source-relay links were in outage, non-cooperation is used, i.e. signals were sent through the source-destination link (SISO).

However, in the KPP channel, source and destination are considered too far away and there is no direct link. Thus we propose to use a selection between DF and AF strategies: a relaying node decodes the signal only when it is able to according to the outage criterion, i.e. when the equivalent channel at this node is not in outage.

Let $y_i^k = f_i^k x_k + w_i^k$ be the received signal at relay R_i^k, where f_i^k is the equivalent channel, x_k is the sent signal and w_i^k is AWGN.

Suppose relay R_i^k is not able to decode the signal, i.e. the equivalent channel is in outage: $\log(1 + |f_i^k|^2) < R$, where R the spectral efficiency of the protocol. An AF strategy is then used and the received signal at relay R_{i+1}^k is:

$$\begin{aligned} y_{i+1}^k &= \sqrt{\rho} h_i^k \beta_i^k y_i^k + w_{i+1}^k \\ &= \sqrt{\rho} h_i^k \beta_i^k f_i^k x_k + (\sqrt{\rho} h_i^k \beta_i^k w_i^k + w_{i+1}^k), \end{aligned}$$

where the amplifying factor is chosen so that the power is normalized: $\beta_i^k = \frac{1}{\sqrt{1+|f_i^k|^2}}$.

In order to determine if it can decode, we compute its instantaneous capacity:

$$\log\left(1 + \frac{\rho |h_i^k|^2 (\beta_i^k)^2}{1 + \rho |h_i^k|^2 (\beta_i^k)^2} |f_i^k|^2\right) < \log(1 + |f_i^k|^2) < R.$$

The equivalent channel at relay R_{i+1}^k is also in outage, thus this relay is not able to decode the signal neither. Applying this reasoning again, we prove that if a relaying node is not able to decode, the following nodes on the same path (except for the destination) will not be neither.

Consequently, the selection criterion does not have to be checked at each node and the strategy can be simplified:

- as long as decoding at relays is possible, a DF strategy is used;
- once a relay is not able to decode, an AF strategy is used till the end.

This way, noise accumulated during the transmission is reduced and performance is improved.

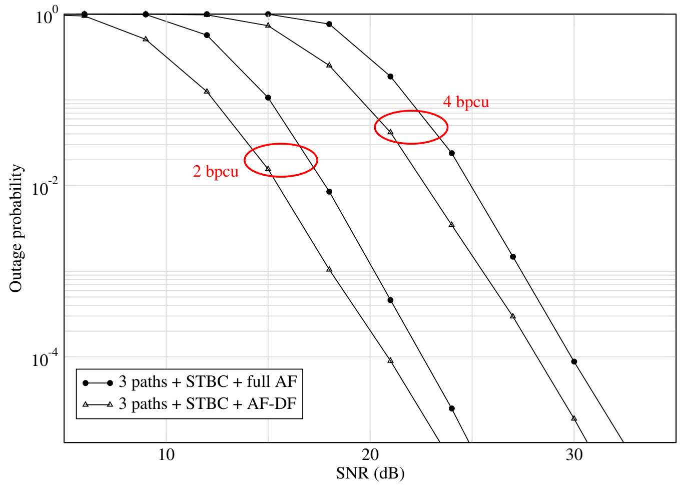


Fig. 6. Outage probability of the path selection multihop protocol using a combination of DF and AF strategies

Figure 6 represents the outage probability of this DF-AF strategy compared to the full AF strategy. As expected, decoding and re-encoding the signals at relaying nodes induces an improvement of performance. We can observe a 2 dB gain for both 2 and 4 bits pcu spectral efficiencies.

The selection does not change the asymptotic analysis and the DMT of this DF-AF strategy is still the optimum one: $d^*(r) = K(1-r)^+$.

IV. Generalization to different path lengths

In previous sections, we have considered that all the paths have the same length n. In practical systems, this is not always the case.

The proposed protocol can be easily generalized to the case where the path lengths are equal modulo $S = 3$. Let $n - 3q_i$ be the length of path $k_i, i \in \{1, 2, 3\}$. For each path k_i, the transmission is delayed by $3q_i$ time slots to compensate the delay due to the longest path.

If path lengths are not equal modulo 3, a delay has to be created in the shorter paths. Without loss of generality, we can assume that the difference between the lengths of the different paths is lower than 3. The delay cannot be introduced by the source, because it is already transmitting at each time slot. Thus this has to be done at relays. As a node is transmitting once in 3 time slots, a relay cannot add more than one time slot of delay.

Example 2: On Figure 7 is represented the transmission for a 3PP network with path lengths $n = n_1 = 5$, $n_2 = 4$ and $n_3 = 3$.

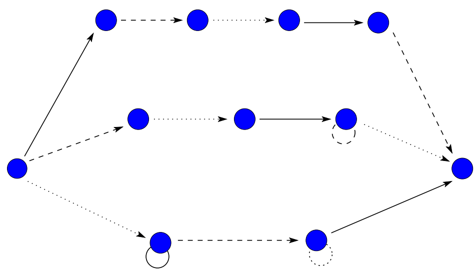


Fig. 7. Transmission in a KPP network with different path lengths: continuous, dashed and dotted arrows represent transmissions on time slots 3T, 3T+1 and 3T+2 respectively.

V. Implementation issues

A. How long should the frame be?

The full rate of 1 symb. pcu is a theoretical rate that is reached when the frame length is infinite, which is obviously not the case in practical applications. The achievable rates are of the form $\frac{T}{n+S(T/S-1)+S-1} = \frac{T}{n+T-1}$ where T is the number of symbols in a frame. $n + T - 1$ is then the transmission length for $S = 3$.

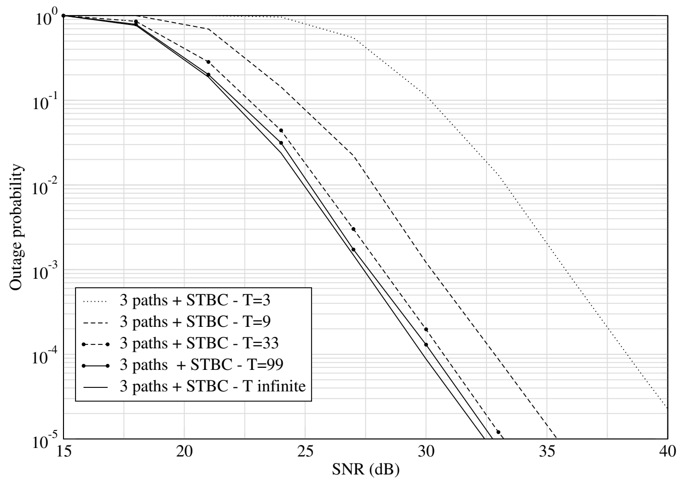


Fig. 8. Outage probability of the path selection multihop protocol for different rate/frame length: T is the number of symbols to sent, thus the rate is $\frac{T}{n+T-1}$.

Figure 8 shows the influence of rate on the performance for a spectral efficiency of 4 bits pcu. The network of Example 1 is once again considered ($n = 4$). Three paths are selected and a space-time code is used to achieve full diversity. Frames of at least 30 symbols have to be sent in order to limit the loss compared to the theoretical full rate to less than 1 dB. Transmitting a longer frame however does not increase the decoding complexity. Indeed, the equivalent MIMO channel is a diagonal matrix. Thus the message can be decoded every three slots and an STBC of dimension 3×1 is sufficient to achieve full diversity. Only some coding gain would be loss.

B. Discussion on path interferences

The DMT is proven in [1], [2] to be optimal even in presence of interference between paths. However we can show

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by simulation that these interferences have a strong influence on the performance.

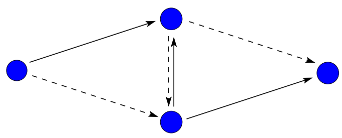

Fig. 9. Two-hop two-relay single-antenna channel model

Let's consider the simple example of a two-hop two-relay single-antenna network, also known as the diamond channel [13], [14] (see Figure 9). We assume that the two paths are not isolated: there are interferences between the two relays. However, as the relaying nodes are smartly chosen so that the interferences are limited, the SNR between the two relays is lower than between the nodes of a same path.

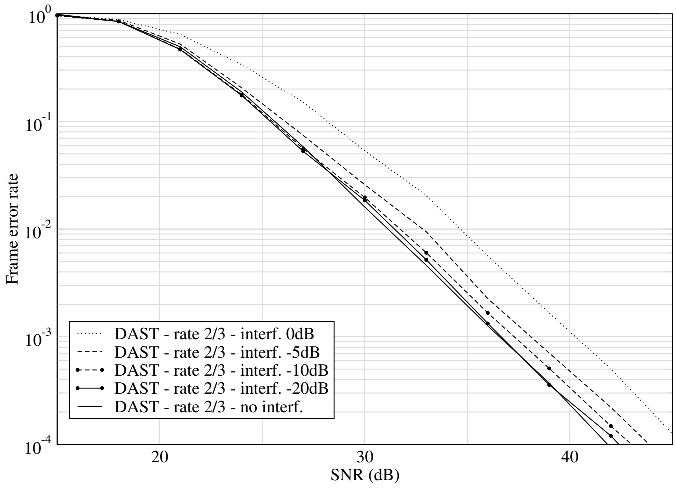

Fig. 10. Influence of path interference on the performance of the path selection multihop protocol

In Figure 10 are represented the performance with different interference powers and a spectral efficiency of 4 bits pcu. If interferences have the same power than the signal, we observe a 3 dB loss compared to the ideal case where paths are isolated. If the power of the interference is 5 dB lower than the signal, this loss is reduced to 2 dB. Finally, if the power of the interference is 20 dB lower than the signal, the performance are very close to the perfect case, so paths can be considered as isolated.

This case can occur if there is an obstacle between the two relays. In an indoor environment, the two relays could be set in different rooms for example. In an outdoor environment, the two relays could be separated by a building.

VI. Conclusion

In this paper, we provide a simple and low-complexity protocol for the KPP multihop network. The three best paths are selected considering their SNR to destination. Symbols are coded with a 3×1 STBC and sent successively on the three paths. The choice of three paths allows to considerably improve the performance by avoiding backflow interferences. This strategy is proven to achieve full rate of 1 symbol per channel use, as well as full diversity K. Moreover, this protocol reach the optimum DMT $d^*(r) = K(1-r)^+$. A generalization of this protocol using decode-and-forward processing when possible is proven to increase performance.

Some implementation issues are further discussed. In order to have a practical rate the nearest to 1, the frame length has to be quite long. However, the structure of the channel matrix allows to decode signals every 3 time slots. Thus the decoding complexity is not increased by the length of the frame. The problem of interferences between the paths is also pointed out. It is shown on an example that if the link between the paths is submitted to a strong fading (more than 10 dB), the loss in performance is limited (less than 1 dB).

This kind of protocol is of particular interest in sensor networks. However in such a context, several nodes want to transmit their information. Therefore, in a future work, we plan to propose a generalization of this protocol to the case of multiple sources.

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