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# Performance Comparison of Cooperative and Non-cooperative Relaying Mechanisms in Wireless Networks

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**Abstract**—Relaying is a known method for increasing coverage in wireless communication systems. In addition to coverage increase, new cooperative relaying methods have been proposed that may increase the wireless system capacity by taking advantage of higher data rates in intermediate cooperating relaying nodes. This paper investigates the performance of several of these relaying methods in terms of maximum achievable throughput at MAC service access point for single-frequency wireless ad-hoc networks. The simulation framework used is described, and the performance limitations of the relaying methods are analysed. We find that relaying, cooperative or not, does not significantly increase maximum achievable throughput for line-of-sight (LOS) propagation environments. The achievable throughput can be significantly increased for non-line of sight (NLOS) environments under specific conditions for source/destination and intermediate relaying nodes.

**Index Terms**—Relaying, cooperative relaying, wireless networks, MIMO.

## I. INTRODUCTION

As the demand for very high data rates increases, the need for new solutions that provide higher data rates for wireless networks increase as well. Some of the possible approaches are increased spectrum efficiency techniques, including intelligent relaying and cross-layer optimised solutions at PHY and MAC [1]. The spectrum that will be released for 4G systems will almost certainly be above 2 GHz that is currently used by 3G systems. The propagation environment for these bands is more vulnerable to non-line-of-sight conditions. On the other hand, deploying “dumb” relays is a solution that has been used for cellular networks in order to solve coverage problems [11]. In order to support higher data rates as well as increase coverage “smart” relaying algorithms will need to be implemented for next generation wireless networks.

The use of cooperative relaying schemas in future network scenarios has been studied extensively [2]-[6], [12]. In their study in 1998 Sendonaris *et al* [4] proposed a very simple and effective user cooperation technique to boost the uplink capacity. The technique basically uses spatial diversity; where two spatially separated Mobile Terminals (MTs) cooperate to

transfer the data to the base station (BS), in order to create a better uplink (higher data rate). Note that in their earlier work no distributed space-time coding has been considered. They improved the previous results in [5] and [6].

Laneman investigated relaying using space time block coding in [12], where he shows that cooperation reduces the individual MTs power consumption drastically, and also that the outage behaviour of the system improves compared to the direct link communication. The concept is taken further by Dohler [2] with multi-stage distributed-MIMO (also known as Virtual Antenna Arrays (VAA)) systems. These systems correspond to spatially adjacent MTs grouping into VAAs. The source VAA relays its traffic via the relaying VAAs towards the destination VAA. This system is referred as VAA multi-stage communication system.

Although there is a considerable amount of effort put into the analytical modelling of link performance of the cooperative relaying algorithms, their impact on the overall network system performance has not been investigated thoroughly; in particular the impact and interaction of relaying and routing have not been compared. In this paper we have focused on the simulation-based evaluation of the performance of different relaying algorithms in ad-hoc wireless networks. This performance is expressed in terms of best achievable throughput at MAC service access point.

This paper is organised as follows. First, a detailed description of the simulation framework created is given. The next section deals with performance evaluation of several relaying algorithms. In the third section, we point out the reasons for the performance limitations of the relaying methods. Finally we give the conclusions we draw from these results.

## II. SIMULATION FRAMEWORK

### A. Framework outline

The simulation set-up (Fig. 1) consists of two separate platforms. An 802.11a-compatible physical layer simulation model was created to generate BER performance curves for a VAA system, using Decode-and-Forward relaying algorithms. The model allowed for parameter configuration to ensure the

sameness of scenario (in particular node placement vs. each-other) in both the network model and the PHY layer model. The PHY layer simulation results are fed into a QualNet network model to get the performance metrics at MAC SAPs.

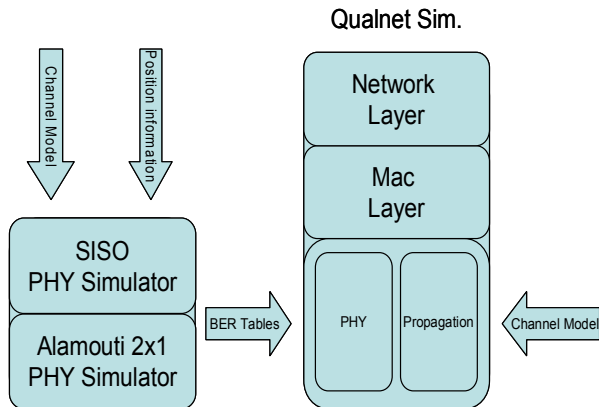


Fig. 1. Outline of the Simulation Framework.

### B. The PHY Layer Simulator

The first part of the platform consists of a PHY layer simulator which is based on the 802.11a standard [7] and can perform PHY layer simulations for SISO (Single Input Single Output) and Alamouti-based [8] D-STBC (Distributed-Space Time Block Codes) systems.

#### 1) The D-STBC PHY Layer Simulator

In D-STBC systems, intermediate MTs (relaying nodes) form a Distributed Virtual Antenna Array (VAA) system. The distributed relays transmit the space time coded frame at the same time towards the source, the destination, or another VAA. A 2x1 Distributed-MIMO communication system is shown below.

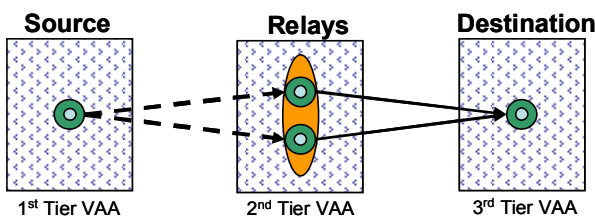


Fig. 2. A 2x1 Distributed-MIMO communication system.

The communication channel between the relaying MTs and destination is a 2x1 MISO channel, so it is possible to apply Alamouti coding on this channel [8]. It is also possible that there may be other intermediate VAA relays between (i.e. a 3<sup>rd</sup> intermediate VAA tier); in this case this is a MIMO channel.

We make two assumptions. First, the relaying MTs (the 2<sup>nd</sup> Tier VAA node above and any other possible intermediary nodes) are spatially close together, thereby experiencing approximately the same path loss from the source MT and towards the destination MT. And second, it is assumed that the relaying MTs are synchronised and the carrier frequency of the individual MTs is exactly the same in the same frequency band. If the signal that is transmitted by the source MT is decoded at both relaying MTs, the Alamouti-coded signals at the destination can be given as [8]:

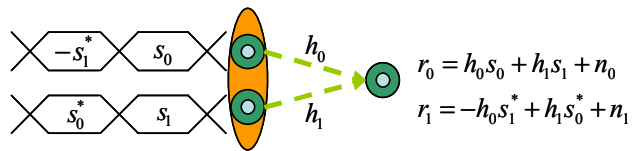


Fig. 3. Received Signals at the destination.

where  $h_0$  and  $h_1$  are the channels from relaying MTs to the destination,  $s_0$  and  $s_1$  are the transmitted signals that are received in the previous transmission period, and  $n_0$  and  $n_1$  are the complex Gaussian random variables that represents the noise added up to the received signal.

The PHY layer simulator can simulate the BER performance of the 2x1 MISO channel for all 802.11a standard modes.

#### 2) The SISO PHY Layer Simulator

A SISO channel can be thought to be a 1x1 MIMO channel. Hence it is possible to get BER performance for SISO systems from the same simulator, with slight modifications. The BER performance of the system is evaluated for both indoor Channel A model and the free space channel model, which are mentioned below.

### C. Channel Models and Coding

For 802.11a, different channel models have been defined for the different propagation environments such as offices, industrial buildings, exhibition halls, etc.[13] To show the difference between LOS and NLOS propagation environments in terms of relaying, we have just focused on free space and office propagation environments that have different propagation characteristics. Different relay positions and channel models are used to generate BER results for both MIMO and SISO type communication systems.

Channel model A is typical for large office environments with NLOS (non-line-of-sight) propagation and is used to simulate indoor performance of the relaying systems. The path loss between the relaying MT(s) and the destination MT can be calculated with the propagation model given below:

$$L_p = 10 \log_{10} (4\pi d / \lambda)^2 + \alpha d \quad (1)$$

where  $d$  is the distance between the relaying MT(s) and the destination MT,  $\lambda$  is the wavelength and  $\alpha$  (dB/m) is the fading added to the line of sight path loss to model the shadowing effects.

Path loss for free space propagation model is given as:

$$L_p = 10 \log_{10} (4\pi d / \lambda)^2 \quad (2)$$

where  $d$  is the distance between the relaying MT(s) and the destination MT,  $\lambda$  is the wavelength.

The simulator uses a constraint length seven convolutional encoder with Viterbi decoding as required in 802.11a standard. The detailed information on 802.11a standard can be found in [7].

#### D. Network Simulation Environment

QualNet [14] has been used as the network simulator. QualNet is an event based simulator that is designed to evaluate network system performance and assist with the improvement of the network protocol design through simulation, with particular strengths in mobile ad-hoc network modelling.

We have modified the 802.11a PHY and MAC layer modules in QualNet to cater for the different types of relaying mechanisms chosen. The BER curves that are produced by the PHY layer simulator have been integrated into the system through these modifications. Also the channel models for the appropriate propagation environments have been incorporated to QualNet by modifying the propagation model module.

The network model is based on protocol module modifications done to the QualNet MAC and PHY modules so as (a) to match the relaying scenario requirements, and (b) to ensure compatibility of the scenarios for simulations between the relaying PHY model and the network model.

#### E. Simulation Scenario

The simulation scenario consists of a single or a pair of relaying nodes located in the middle of the source and the destination as shown in Fig. 4.

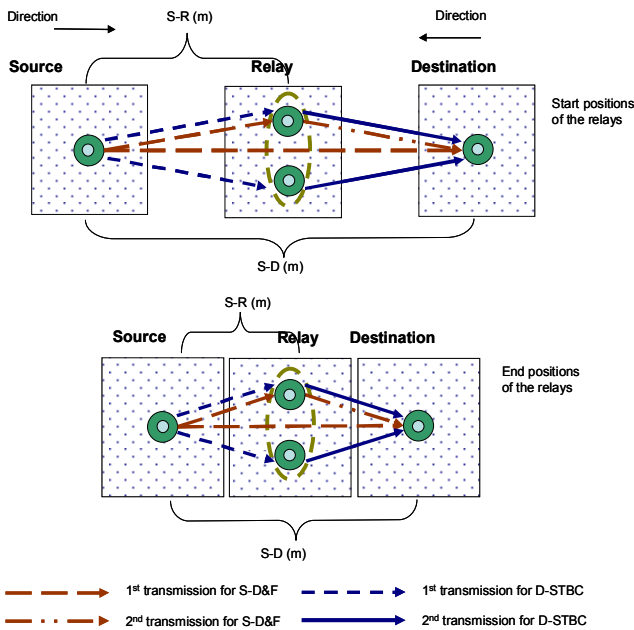


Fig. 4. Simulation Scenario.

For each run of simulation, the distance between the source-relay and relay-destination is reduced by a constant value, depending on the channel model used. An explicit minimum distance is used.

In all simulation scenarios a constant bit rate (CBR) traffic with 1800 bytes packet length is used in order to investigate the maximum achievable throughput. The nodes are placed in pre-determined locations and for each location the simulation is run for 60 seconds. The packet transmission interval at the application layer is chosen to be 800 microseconds. The node queues are assumed to be large enough that there is no packet

drop. The CBR traffic generated by the application is chosen to be always greater than the link throughput (saturation) so there is no idle time in the wireless medium.

### III. PERFORMANCE EVALUATION OF RELAYING MECHANISMS

A detailed analysis of relaying methods and their outage behaviours has been given in [9], where it is shown that the performance of relaying systems heavily depends on the inter-node channel characteristic. The outage probability of a relaying system also depends on the maximum overall mutual information that can be transmitted over the channels that are formed by the nodes to achieve the desired rate  $R$ .

We have chosen three different relaying methods, which are Decode and Forward (D&F), Selection Decode and Forward (S-D&F), and Distributed Space Time Block Codes (D-STBC) respectively [9], [2], to show the impact of the relaying methods on the throughput for a realistic scenario.

The selection of the above mentioned relaying algorithms is based on an analysis of their reported (expected) complexity and performance. The D&F schema is selected to be used as the base comparison case; the complexity of the schemas increases from D&F  $\rightarrow$  S-D&F  $\rightarrow$  D-STBC, while their performance is reported, analytically, to increase as well. From theoretical results in [3], [4] and [9], we know that the performance of the distributed relaying algorithms depends on the coding scheme and the diversity order. On the other hand, relaying schemas explicitly requiring extra resources for inter-relay node communications were not considered as applicable for the ad-hoc wireless network environment.

Two different types of channel models are used in the simulations. The details of channel models are given in section II.C. The simulation-based performance evaluation of the relaying algorithms for the selected channel models is given in the following sections.

#### A. Performance evaluation for AWGN Channel model

The performance of the selected relaying algorithms has been evaluated with the scenario described in section II.E. For the free space propagation model the source-relay and relay-destination distance can be more than 200 metres. Hence the distances between the source-relay and relay-destination pair were chosen to be 200 metres each for the start positions of the simulation scenario, with a step decrement in this scenario of 10 metres Fig. 5 shows MAC throughput performance for the selected relaying methods for an AWGN Channel.

The proposed relaying algorithms perform slightly better than the direct connection for larger distances (low SNR levels). But the throughput increase that is promised by the analytical models of these relaying methods is not observed for AWGN channel. Although the simulation results show the same trend with the analytical calculations that are given in [9], our results indicate that any improvement in the MAC layer performance of the relaying methods is not quite as significant. The main reason for the poor performance is the need of an extra transmission period needed for the retransmission of the packet at the relay node(s). This

decreases the useable system bandwidth by more than half due to the interframe spacing (SIFS, DIFS intervals) required for every transmit action. Any algorithm that uses extra transmission periods for cooperation would considerably decrease the efficiency of the system in any single-frequency ad-hoc network.

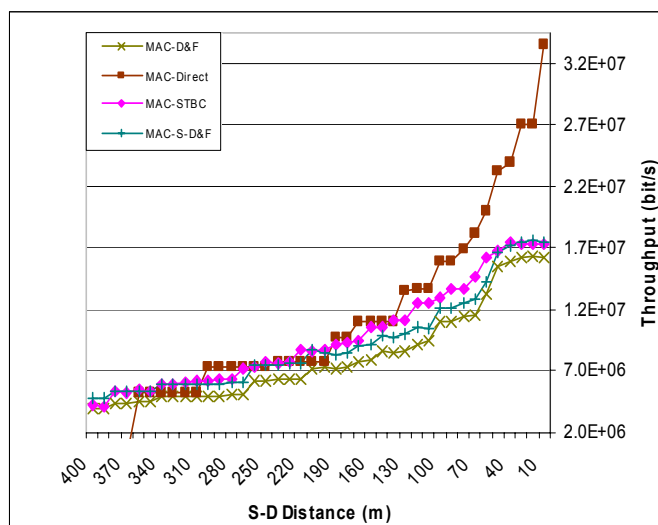


Fig. 5. MAC Throughput for AWGN Channel

As expected, though, the performance of the S-D&F method is better than the non-cooperative D&F relaying method for larger distances. The S-D&F method takes advantage of diversity for low SNRs and provides a more reliable communication link between the source and the destination. For high SNR values the performances of all three different relaying methods are quite close. This result proves that behaviour of D&F methods for large SNRs is the same as stated in [9]. The performance of D-STBC systems drops considerably in uncorrelated propagation environments. The non-cooperative Decode and Forward method is the worst performing relaying algorithms since it doesn't take advantage of any type of diversity.

The coverage increase is clearly apparent from the simulation results since after a certain distance direct communication is not possible between the source and destination node.

### B. Performance evaluation for Channel A model

The performance of the selected relaying algorithms with a Channel A model has been evaluated with the SNR values collected from the PHY layer simulator. The maximum distance for the Channel A model cannot be more than 50 metres. As a result, the source-relay and the relay-destination distances were chosen to be 30 metres, and the step decrement used was 2 metres for the simulation scenario described earlier.

All the evaluated relaying algorithms perform better with a Channel A model as compared to the AWGN channel with free space propagation. The main reason is the NLOS (non-line-of-sight) propagation environment in which the signal degrades very rapidly compared to LOS (line-of-sight) environments. This indicates clearly that deploying relays

helps to increase the throughput of the network for NLOS environments with fast fading, even if the relaying method that is used doesn't take advantage of cooperation. The simulation results for the selected relaying algorithms are given in Fig. 6.

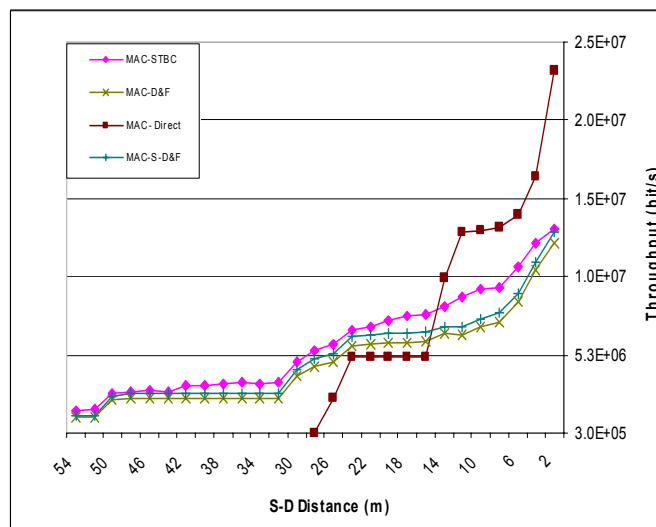


Fig. 6. MAC Throughput for Channel A

Results in Fig. 6 indicate that D-STBC is the best performing relaying algorithm for channel model A. This is expected since space time block code algorithms perform better in correlated environments. Performance of the S-D&F relaying is worse than D-STBC mainly due to the fact that the diversity offered by the channel is not fully exploited, but still performs better than the non-cooperative D&F relaying. It is to be noted that even though the cooperative relaying algorithms offer better throughput for NLOS environments, the improvement is not substantial, mainly due to reasons that are covered in Section IV.

The distance when relaying methods perform significantly better than the direct communication is in the region between 15 – 30 metres. In this simulation scenario the relaying algorithms perform better than the direct link for distances up to approximately 14 metres; for smaller distances the channel performance for the direct transmission is, at worst, similar to that of a single-hop relay node, hence the direct transmission performs better due to requiring only one frame transmission period instead of two.

Also to be noted is the significant increase in coverage that all relaying methods provide in this scenario (Channel A model). At the same time, their performance is very similar, and the same benefit can be achieved with the lowest complexity relaying method amongst them.

### C. Multi Stage D-STBC Cooperation

If the source packet travels through more than one intermediate VAA, it is possible to form a multi-stage D-STBC system. A two-stage D-STBC system is given in Fig. 7.

The source packet travels from the source node to the destination node through two groups of relays that use D-STBC cooperative relaying. As it can be seen from Fig. 7, the

2<sup>nd</sup> tier VAA and 3<sup>rd</sup> tier VAA form a “combined 2x1 MIMO channel”. Therefore, the system can take advantage of being able to transmit cooperative packets in both directions. For the source-1<sup>st</sup> tier VAA and the 3<sup>rd</sup> tier VAA-destination links, D-STBC cooperation is not possible in both directions.

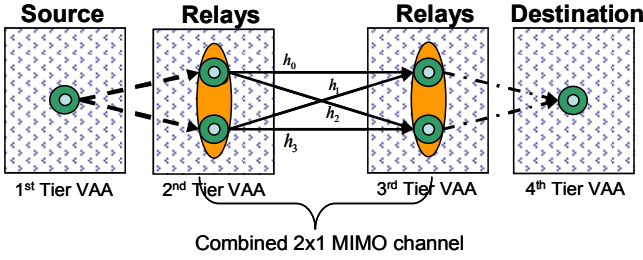
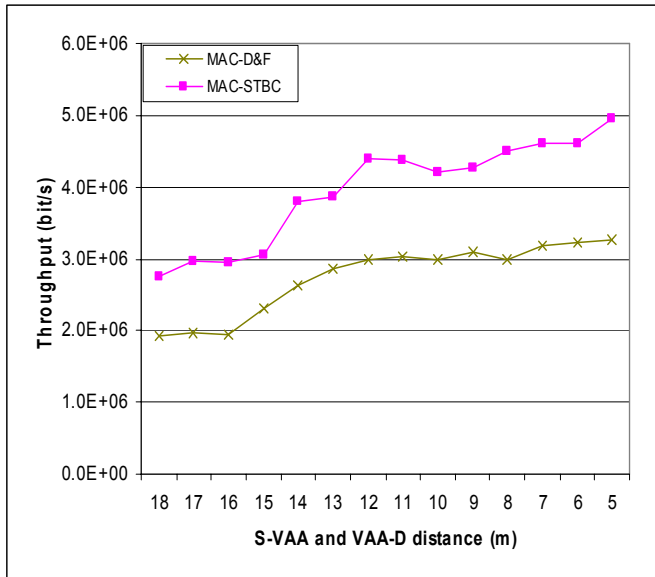


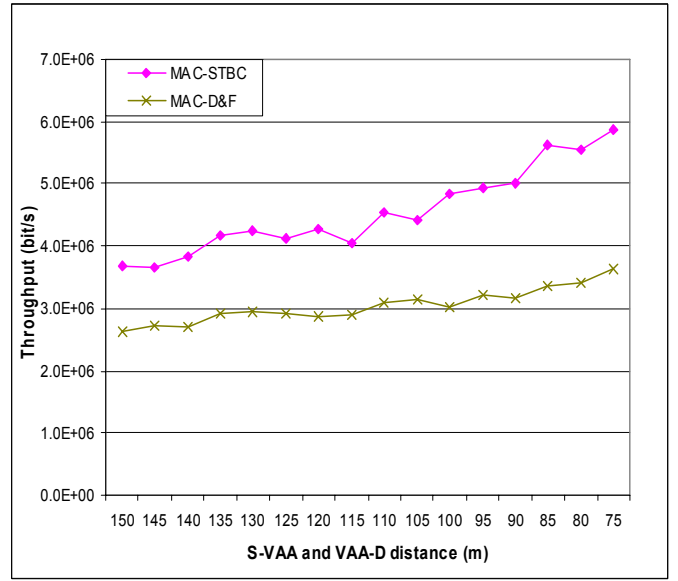
Fig. 7. A two stage D-STBC system

The simulation scenario consists of two pairs of relaying nodes located in the middle of the source and the destination as shown in Fig. 7. The distance between relay nodes is kept constant during the simulation. For each run of the simulation, the distance between the source-to-2<sup>nd</sup> Tier VAA and 3<sup>rd</sup> Tier VAA-to-destination is reduced by a constant value. The simulation is repeated until the source and destination reach a pre-determined distance from the relays. The performance of the two-stage D-STBC system is given below.

As it can be seen from the graphs in Fig. 8, for smaller distances between the source-2<sup>nd</sup> Tier VAA and the 3<sup>rd</sup> Tier VAA-destination, the throughput differential increase is noticeable as compared to non-cooperative D&F method. This is mainly due to the fact that the first hop (source-2<sup>nd</sup> Tier VAA) and last hop (last tier to destination node) are the bottlenecks in this system, because the channel between the cooperating relaying VAAs can support much higher throughputs compared to the source-2<sup>nd</sup> Tier VAA and the 3<sup>rd</sup> Tier VAA-destination channels. This limiting factor is discussed further in Section IV.



a) Channel A



b) AWGN Channel

Fig. 8. MAC throughput of the Multi stage D-STBC vs D&F

Looking at the graph trends in Fig. 8-a indicates that the performance of the non-cooperative D&F method is better for Channel A model compared to AWGN model, since deploying relays in highly correlated multi path channels improves the inter-node channel characteristics considerably.

#### IV. PERFORMANCE LIMITATIONS

##### A. Distributed Space Time Cooperation

According to Kramer [10], the following rate is achievable for two level relay systems:

$$R_{DF} : \max_{p(x_1, x_2)} \min \{I(X_1; Y_2 | X_2), I(X_1 X_2; Y_3)\} \quad (3)$$

Where  $X_i, Y_i$  represent channel input and channel output respectively. The first term ( $I(X_1; Y_2 | X_2)$ ) in (3) represents the rate at which the relay node can decode the source message reliably, and the second term ( $I(X_1 X_2; Y_3)$ ) represents the maximum rate at which the destination node can reliably decode the source message taking account repeated transmissions from the source and relay.

If the signal transmitted in the first transmission period is ignored at the destination node then the formula in (3) can be rewritten as:

$$R_{DF} : \max_{p(x_1, x_2)} \min \{I(X_1; Y_2 | X_2), I(X_2; Y_3)\} \quad (4)$$

The maximum mutual information is always limited by the individual channel throughput. The relay-destination channel performance depends on the channel capacity of the source-relay channel. For D&F relaying systems the main limiting factor for the throughput is the source-relay channel capacity [9].

The maximum mutual information for D-STBC systems can be modelled using a similar approach, since the relaying nodes

can be assumed to be a single node if the signal transmitted in the first transmission period is ignored at the destination node (no cooperation between source and destination). With this assumption the system can then be modelled as in Fig. 9.

For a wireless network that implements any form of acknowledgement, a bi-directional relaying is required (destination-source as well as source-destination). Any form of STBC used in such system will create a non-reciprocal channel between the source and relay nodes, and also between the relay and destination nodes, because the uplink (see Fig. 9) cannot use space-time cooperation since inter-relay node communication is not desirable in single-frequency ad-hoc wireless network environment due to resource usage.

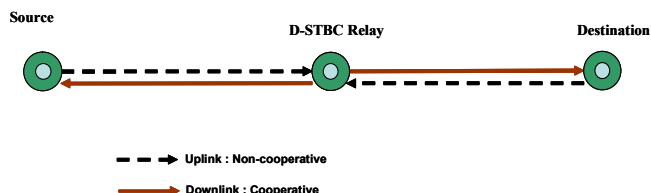


Fig. 9. A Single stage D-STBC system

On the other hand it is possible to use D-STBC type cooperation for the relay-source and relay-destination link (downlink), if the relay nodes are strictly synchronised and use exactly the same carrier frequency. Thus, the links that can take advantage of cooperation will support higher data rates than that of non-cooperative links; the overall throughput will be limited by the non-cooperative links

### B. Multi-stage D-STBC Relaying

The main performance limiting factor for multi-stage D-STBC systems is the requirement to retransmit the packet along the source-destination link, which will cause delay in the link and drop the efficiency. The efficiency of the system in terms of transmission time can be given as;

$$E_{i,j} = \frac{\sum_{i,j} Td_{i,j}}{\sum_{i,j} (Td_{i,j} + Tack_{i,j} + Tifs_{i,j})} \quad (6)$$

where  $Td_{i,j}$  is the period that is used for actual data transmission from the node  $i$  to the node  $j$ ,  $Tack_{i,j}$  is the period for ACK packets, and  $Tifs_{i,j}$  is the period that the node waits for other nodes to transmit their packets. It is assumed that there is no packet drop in the communication link. As it can be seen from the above formula, the efficiency of the link drops as the number of hops that the packet travels increases. This is a significant drawback for multi-stage D-STBC systems, since the source node needs to be close to the first stage VAA in order to establish a communication link that can support the higher data rates achievable by the second-tier (and beyond) links. This is because, as shown in Section IV.A, the channel between source and the first stage VAA cannot take advantage of D-STBC cooperation on both directions. This is also true for the link from the last stage

VAA to the destination. Also it needs to be noted that forming multistage relaying systems may require the involvement, through management, of the upper layers of the communication system.

## V. CONCLUSIONS AND FURTHER WORK

Relaying has been considered as a method that mainly increases coverage in cellular systems. It has also been proposed that selected relaying algorithms can increase the capacity of wireless networks. In this paper we have evaluated a set of relaying algorithms (D-STBC, S-D&F and D&F algorithms) using a combined simulation environment that enabled us to perform different sets of simulations and check their performance, in terms of maximum achievable throughput, at MAC service access points. We have also looked at the problems involved with using relaying algorithms and their performance limitations.

Our simulation results show that, qualitatively, cooperative use of relays forming virtual antenna arrays to exploit the spatial diversity inherent to multi-hop communication networks can increase the capacity, as well as coverage, of wireless ad-hoc networks, which agrees with reported analytical modelling of such systems. The downside, however, is that the capacity increase is not very significant for the chosen relaying algorithms.

For free space communication environment (no multi-path propagation), the proposed relaying methods provide almost no advantage over direct communication in terms of throughput increase. In multi-path fading environments all relaying schemas performed considerably well; D-STBC cooperative relaying was found to be the best candidate for these environments.

Single-stage D-STBC provided the best performance for two hop scenarios. It is interesting to note that the greater achievable throughput is seen in a clearly defined range in the system, which specifies when relaying is actually beneficial as compared to a direct-link based system.

The results indicate that the multi-stage D-STBC relaying provides better throughput than D&F relaying for certain scenarios; the maximum throughput differential, compared to non-cooperative D&F method, is about 30%. This throughput increase is limited by the channel conditions between the source and the first stage VAA or the last stage VAA and destination.

In summary, we have shown that relaying technologies for wireless ad-hoc networks can provide some capacity increase. On the other hand, the complexity involved in setting up a multi-stage cooperative relaying to attain the capacity promised by these relaying methods is expected to be high. This includes methods to detect conditions under which cooperative relaying is beneficial, mechanisms to invoke relaying selectively, as well as other practical problems such as the synchronisation of the distributed nodes and frequency matching of the cooperating nodes. The simulation of the relaying algorithms in this paper highlights the importance of further research that takes into account the complexity issues

in the area of virtual antenna arrays and new diversity schemes, as well as multiple access and radio resource management protocols for multi hop networks. Also, comparison of the overall network performance for systems with combined relaying and routing remains an interesting issue.

## VI. ACKNOWLEDGMENTS

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