The Anti–Packets Can Increase the Achievable Throughput of a Wireless Multi–Hop Network

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***Abstract*— This paper considers relaying techniques that increase the achievable throughput in multi–hop wireless networks by taking advantage of the bi–directional traffic flow. Such a relaying technique is termed relaying with Bi–directional Amplification of Throughput (BAT–relaying). The BAT–relaying is utilizing the concept of anti–packets, defined for bi–directional traffic flows. The relay node combines the anti–packets that are destined for different nodes and broadcasts the combined packet. Two BAT–relaying techniques have been proposed previously, Decode–and–Forward (DF) BAT–relaying and Amplify–and–Forward (AF) BAT–relaying. While in DF the relay node combines the packets by an `XOR` operation, AF BAT–relaying utilizes the inherent packet combining provided by the multiple access channel. In an errorless channel, AF has always higher achievable throughput than DF, but in noisy channels the noise amplification can severely degrade the performance of AF. In this paper we introduce a new scheme for BAT-relaying, termed Denoise–And–Forward (DNF) BAT–Relaying. The DNF BAT–relaying also makes use of the combining provided by the multiple access channel, but it removes the noise from the combined anti–packets before broadcasting to the destinations. While in the noiseless channel DNF and AF offer the same throughput performance which is superior to DF BAT–relaying, in large regions of the lower SNR values DNF BAT–relaying has the best throughput performance of all three schemes. Due to the unconventional nature of the BAT–relaying schemes, there are many open issues for further investigation. The design of a practical DNF scheme concerns several protocol layers, including modulation and coding.**

I. INTRODUCTION

The shared wireless medium is the chief factor that limits the capacity of wireless multi–hop networks [1]. On the positive side, the wireless broadcast medium enables enhanced interaction among the wireless transceivers and thereby an introduction of novel communication modes. Such is, for example, the *cooperative diversity* [2], where two or more wireless terminals cooperate to achieve a reliable reception at the destination. In a separate significant development, the emergence of network coding [3] has shifted the paradigm under which the network communication is designed. While the traditional routing replicates a packet from an incoming to an outgoing link at an intermediate network node, the network coding allows the intermediate nodes to process the packets in a more general way. Originally, the network coding has exhibited its benefits for multicast in wireline packet networks. Nevertheless, the unreliability and the broadcast nature of the wireless setting appear to be a fertile ground for developing network–coding solutions ([4] and references therein).

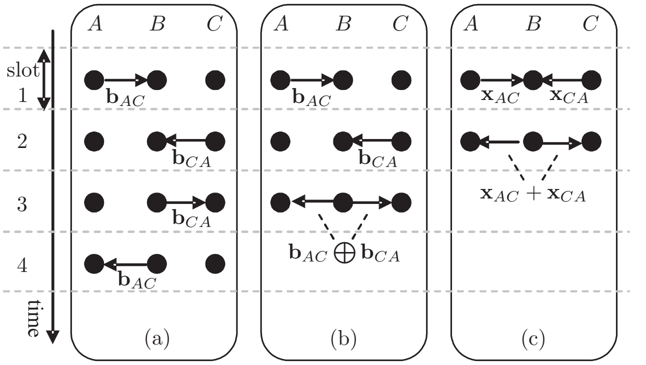

Fig. 1. (a) Conventional bi–directional relaying (b) Decode–and–Forward (DF) BAT–relaying (c) Amplify–and–Forward (AF) and Denoise–and–Forward (DnF) BAT–relaying

In this paper we consider wireless relaying with bi–directional unicast flows. In particular, we consider relaying techniques that take advantage of the traffic bi–directionality and increase the achievable throughput as compared to the conventional relaying. Therefore, the common term that we use to denote such a relaying is *relaying with bi–directional amplification of the throughput (BAT–relaying)*. The BAT–relaying methods take advantage of the packets $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$ that are relayed by the same node into opposite directions. We call $\mathbf{b}_{AC}$ an *anti–packet* for $\mathbf{b}_{CA}$ and vice–versa. There are two benefits from the utilization of the anti–packets. First, the *overall system throughput is increased*, as it takes less time to convey the same amount of data. Second, *the relay node saves energy* having less transmissions for the same amount of relayed data. The latter benefit has motivated us to use the term anti–packet through a relation to physics, where the collision of a particle and an anti–particle produces energy.

The conventional relaying is depicted on Fig. 1(a). The packets, each of length N bits, $\mathbf{b}_{AC}, \mathbf{b}_{CA} \in \{0,1\}^N$ are destined from A to C and C to A, respectively. It takes 4 slots to relay $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$ by conventional relaying. The relying that is here referred to as *Decode–And–Forward (DF) BAT–relaying* is depicted on Fig. 1(b) and it has been previously proposed in [5], [6]. In DF BAT–relaying, after decoding $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$, the relay B applies a canonical network coding

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operation and broadcasts the packet $\mathbf{b}_B = \mathbf{b}_{AC} \oplus \mathbf{b}_{CA}$, where $\oplus$ denotes the bitwise `XOR` operation. Since the node A already has $\mathbf{b}_{AC}$, it extracts the required packet $\mathbf{b}_{CA}$ through $\mathbf{b}_{CA} = \mathbf{b}_B \oplus \mathbf{b}_{AC}$. Analogously, C extracts the anti–packet $\mathbf{b}_{AC}$. The relaying method on Fig. 1(b) requires only 3 slots to transfer the packets $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$, which means that the bi–directional throughput is "amplified" with respect to the conventional relaying. The *Amplify–and–Forward (AF) BAT relaying* has been introduced and analyzed in [7] and is different from the usual network coding, since it utilizes the inherent packet combining provided by the multiple access channel. This technique is illustrated by Fig. 1(c). Let $\mathbf{x}_{AC}$ and $\mathbf{x}_{CA}$ be the baseband representations of the packets $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$, respectively. If in the first slot both A and C are transmitting over the additive multiple access channel, then B receives the noisy version of the anti–packets sum $\mathbf{y}_B = \mathbf{x}_{AC} + \mathbf{x}_{CA} + \mathbf{z}_B$. If node B amplifies y_B and broadcasts the amplified βy_B, then A receives a noisy signal from which it can subtract $\mathbf{x}_{AC}$ and attempt to decode $\mathbf{x}_{CA}$ (analogously for C). In the absence of noise, A decodes $\mathbf{x}_{CA}$ ($\mathbf{b}_{CA}$) and C decodes $\mathbf{x}_{AC}$ ($\mathbf{b}_{AC}$) after only 2 slots, thus doubling the throughput compared to Fig. 1(a).

However, in the AF BAT–scheme, the relay node amplifies the noise. Under a low SNR, this produces excessive packet errors and deteriorates the obtainable throughput gain of AF BAT. In this paper we introduce the *Denoise–and–Forward (DNF) BAT* relaying. When receiving $\mathbf{y}_B$, in general, the relay node cannot decode the individual anti–packets[1]. Nevertheless, it can make an estimate $\hat{d}_{\mathbf{x}_{AC}+\mathbf{x}_{CA}}$ of anti–packet sum $\mathbf{x}_{AC} + \mathbf{x}_{CA}$ via a decision process that aims to eliminate the noise impact. To avoid confusion, such a decision process referred to as *denoising* instead of *decoding*. Fig. 1(c) can be used also to illustrate the timing for the DNF–BAT. In absence of channel errors, DNF–BAT and AF–BAT perform identically. However, there is a fundamental difference between them in presence of errors: DNF does not amplify the noise, as it broadcasts its estimate $\hat{d}_{\mathbf{x}_{AC}+\mathbf{x}_{CA}}$ to A and C. We will see that such an operation makes DNF–BAT superior to the other two BAT–strategies in terms of achievable throughput.

II. NOTATIONS AND DEFINITIONS

We will use $\mathbf{b} = (b[1], b[2], \dots b[N])$ where $b[n] \in \{0, 1\}$ to denote the string of N bits that represents a data packet. Through the application of certain modulation and coding technique, these N bits are mapped into M symbols $\mathbf{x} = (x[1], x[2], \dots, x[M])$, where $x[m] \in \mathcal{X}$ is a complex number and we assume that the expected values are $E\{x[m]\} = 0$ and $E\{|x[m]|^2\} = 1$. The latter implies that the average transmitted energy per symbol is 1. The duration of a time slot in which one packet can be accommodated is denoted by T_s. The nominal data rate for a packet of N bits is $R_s = \frac{N}{T_s}$ [bps] and both A and C are transmitting at rate R_s.

For DF BAT–relaying, let $x_B[m]$ denote the $m-$th symbol transmitted by the relay node B. Clearly, it is assumed that both packets $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$ have previously been received correctly, the packet $\mathbf{b}_{AC} \oplus \mathbf{b}_{CA}$ have been created and an appropriate modulation/coding have been applied to obtain $\mathbf{x}_B$. The $m-$th symbol received at A and C, respectively, can be expressed as:

$$\begin{aligned} r_A^{(DF)}[m] &= h_{AB} x_B[m] + z_A[m] \\ r_C^{(DF)}[m] &= h_{BC} x_B[m] + z_C[m] \end{aligned} \qquad (1)$$

where h_{AB} and h_{BC} denote the complex channel gains for the link $A - B$ and $B - C$, respectively. The values $z_A[m]$ and $z_C[m]$ represent the complex additive Gaussian white noise at the receiver of A and C, respectively. We assume that the noise level at A, B, and C is identical $\sigma_A^2 = \sigma_B^2 = \sigma_C^2 = \sigma^2$.

For AF BAT–relaying, in the first slot, both A and C transmit their packets to B, such that the $m-$th received symbol at B is:

$$y_B[m] = h_{AB} x_A[m] + h_{BC} x_C[m] + z_B[m] \qquad (2)$$

In the second slot, the relay B amplifies $y_B[m]$ for a factor β and broadcasts it to both A and C. The signal received by A can be written:

$$\begin{aligned} &y_A^{(AF)}[m] = \beta h_{AB} y_B[m] + z_A[m] = \\ &\beta h_{AB}^2 x_A[m] + \beta h_{AB} x_C[m] + \beta h_{AB} z_B[m] + z_A[m] \end{aligned}$$

The average transmitted signal energy over one symbol period at node B should also be 1, such that:

$$\beta = \sqrt{\frac{1}{|h_{AB}|^2 + |h_{BC}|^2 + \sigma_B^2}} \qquad (3)$$

Having that A knows $x_A[m]$ and assuming that A knows the values β and h_{AB}, then A can subtract $\beta h_{AB}^2 x_A[m]$ from $y_A^{(AF)}[m]$ and thus receive the symbols of C through an equivalent AWGN channel, represented by:

$$r_A^{(AF)}[m] = \beta h_{AB} h_{BC} x_C[m] + \beta h_{AB} z_B[m] + z_A[m] \qquad (4)$$

In analogous manner we can obtain:

$$r_C^{(AF)}[m] = \beta h_{AB} h_{BC} x_A[m] + \beta h_{BC} z_B[m] + z_C[m] \qquad (5)$$

In case of DNF, the received signal after the simultaneous transmission of A and C is identical to the one in the case of AF, given by (2). If not stated otherwise, in this paper we will assume that the relay node B makes a *per–symbol denoising decision*. An alternative to per–symbol denoising decision is *per–codeword denoising decision*, discussed in Section IV. In per–symbol denoising decision, for each received symbol $y_B[m]$ the relay B produces a symbol $d[m] \in \mathcal{X}$ by using the following two steps:

(1) By knowing h_{AB} and h_{BC}, the relay node can find the pair or set of pairs $(\hat{x}_A[m], \hat{x}_C[m]) \in \mathcal{X} \times \mathcal{X}$ such that

$$(\hat{x}_A[m], \hat{x}_C[m]) = \underset{(x_A, x_C) \in \mathcal{X}^2}{\arg\min} \; |y_B[m] - (h_{AB} x_A + h_{BC} x_C)| \qquad (6)$$

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[1] When the power of the received anti–packet differs significantly, e. g. $\mathbf{x}_{CA}$ is received with much more power than $\mathbf{x}_{AC}$, then B treats $\mathbf{x}_{AC}$ as a noise and decodes $\mathbf{x}_{AC}$ from $\mathbf{y}_B$.

(2) Having $(\hat{x}_A[m], \hat{x}_C[m])$, the relay can produce the $m-$th denoised symbol by using the *denoise mapping*:

$$d[m] = \mathcal{D}(\hat{x}_A[m], \hat{x}_C[m]) \tag{7}$$

where the mapping $\mathcal{D} : \mathcal{X}^2 \mapsto \mathcal{X}$ has the following properties:

$$\mathcal{D}(x_A, x_C) = \mathcal{D}(x'_A, x_C) \quad \Rightarrow \quad x_A = x'_A \tag{8}$$

$$\mathcal{D}(x_A, x_C) = \mathcal{D}(x_A, x'_C) \quad \Rightarrow \quad x_C = x'_C \tag{9}$$

However, it can happen that:

$$\mathcal{D}(x_A, x_C) = \mathcal{D}(x'_A, x'_C) \text{ when } x_A \neq x'_A \text{ and } x_C \neq x'_C \tag{10}$$

In the second slot, B transmits the packet $\mathbf{d}$, which represents a denoised combination of the anti–packets $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$. The $m-$th received symbol at A and C, respectively, is:

$$\begin{aligned} r_A^{(DNF)}[m] &= h_{AB} d[m] + z_A[m] \\ r_C^{(DNF)}[m] &= h_{BC} d[m] + z_C[m] \end{aligned} \tag{11}$$

Let A correctly decode $d[m] \in \mathcal{X}$. Since A knows $x_A[m]$ then due to the property (9), the node A can uniquely determine $x_C[m]$. Considering (8), the same observation holds for C.

III. DF AND AF TRANSMISSION OF ANTI–PACKETS

A detailed analysis on the impact of channel errors on the DF and AF BAT relaying can be found in [7], where the assumption is that the channels h_{AB} and h_{BC} are static. In this section we describe the operation of the conventional, DF BAT and AF BAT relaying methods.

In the conventional relaying, B polls A and A (re)transmits the $\mathbf{b}_{AC}$ packet until B receives it. Then B (re)transmits the $\mathbf{b}_{AC}$ packet to C until C receives it.

Let p_{e1}, p_{e2} denote the packet error rate (PER) for the link $A-B, B-C$, respectively. The operation of DF BAT–relaying can be described as follows:

1) The buffer of B is *empty* if B has delivered all received $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$ packets. With an empty buffer, B polls A to retrieve a new $\mathbf{b}_{AC}$ packet. A retransmits $\mathbf{b}_{AC}$ consecutively until it is correctly received at B.
2) If B has $\mathbf{b}_{AC}$, but not $\mathbf{b}_{CA}$ packet in the buffer, then B polls C to retrieve a new $\mathbf{b}_{CA}$ packet. C retransmits $\mathbf{b}_{CA}$ consecutively until it is correctly received at B.
3) If B has $\mathbf{b}_{CA}$, but not $\mathbf{b}_{AC}$ packet in the buffer, then B polls A to retrieve a new $\mathbf{b}_{AC}$ packet. A retransmits $\mathbf{b}_{AC}$ consecutively until it is correctly received at B.
4) If B has both $\mathbf{b}_{AC}$ and $\mathbf{b}_{CA}$ packet in the buffer, then B creates the packet $\mathbf{b}_B = \mathbf{b}_{AC} \oplus \mathbf{b}_{CA}$ and transmits it. Due to the channel errors, the following can occur:
    a) With probability $(1-p_{e1})(1-p_{e2})$, the packet $\mathbf{b}_B$ is received correctly by both A and C. Then the buffer of B is empty.
    b) With probability $(1-p_{e1})p_{e2}$, the packet $\mathbf{b}_B$ is received correctly by A and erroneously by C. Then the buffer of B contains $\mathbf{b}_{AC}$ packet.
    c) With probability $p_{e1}(1-p_{e2})$, the packet $\mathbf{b}_B$ is received correctly by C and erroneously by A. Then the buffer of B contains $\mathbf{b}_{CA}$ packet.
    d) With probability $p_{e1}p_{e2}$, the packet $\mathbf{b}_B$ is received erroneously by both A and C. Then B retransmits the packet $\mathbf{b}_B$ in the next slot.

We use the following scheme for AF BAT–relaying. We again assume that A and C are backlogged with packets and each of them has a new packet whenever requested by B. Here is a simple variant of the AF BAT–relaying:

1) In the odd slots, both A and C transmit to B packets simultaneously.
2) In an even slot, B amplifies and retransmits the signal that it has received in the previous odd slot. At the end of an even slot, A is informed via B whether its packet has been received by C and C is informed whether its packet has been received by A. If A and/or C gets negative acknowledgement, it retransmits the same packet to B in the next odd slot.

The bit errors that occur when A receives the (amplified–and–forwarded) transmission from B are not independent from the bit errors that occur at C which receives the same transmission from B. This is because, for the $m-$th transmitted symbol from B, there is an identical noise component $z_B[m]$ which present in both received symbols $y'_A[m]$ and $y'_C[m]$, though with different amplification. Consequently, packet errors at A are dependent with the packet errors at C.

IV. DENOISE–AND–FORWARD (DNF) BAT–RELAYING

We first consider the denoising in case of BPSK modulation with a modulation set $\mathcal{X} = \{-1, 1\}$. Let us assume that $h_{AB} = h_{BC} = 1$, such that the received signal at B becomes:

$$y_B[m] = x_A[m] + x_C[m] + z_B[m] \tag{12}$$

Fig. 2 depicts the decision regions and the per–symbol denoise mapping applied by B for a received signal given by (12). For this particular example, the transmissions of $(x_A, x_C) = (-1, 1)$ and $(x_A, x_C) = (1, -1)$ are indistinguishable at B. This implies that in the relation (6) the $\arg\min$ function will output two pairs whenever the received y_B is in the shaded region. The selected denoise mappings are

$$\mathcal{D}(-1,-1) = \mathcal{D}(1,1) = 1 \quad \mathcal{D}(-1,1) = \mathcal{D}(1,-1) = -1 \tag{13}$$

In general, h_{AB} and h_{BC} are uncorrelated complex numbers. Without loss of generality, we can assume that h_{AB} is a positive real number, while h_{BC} has an arbitrary phase. The node B knows both h_{AB} and h_{BC} from the channel estimation. The decision region and the denoise mapping are depicted on Fig. 3 where e. g. B broadcasts $d[m] = -1$ when $y_B[m]$ falls in the shaded region.

The modulation mapping is denoted as:

$$\mathbf{x} = \mathcal{A}(\mathbf{b}) \tag{14}$$

In BPSK N bits are mapped to N symbols and by reusing the notation we can define $\mathcal{A}(0) = -1, \mathcal{A}(1) = 1$. With the denoise mapping chosen as (13), the decision $d[m]$ of the relay node is in fact a modulation map of `XOR` operation $b_{AC}[m] \oplus b_{BC}[m]$. The bit domain representation of $d[m]$ is denoted by $b_d[m]$ and is determined as follows:

$$b_d[m] = \mathcal{A}^{-1}(d[m]) \tag{15}$$

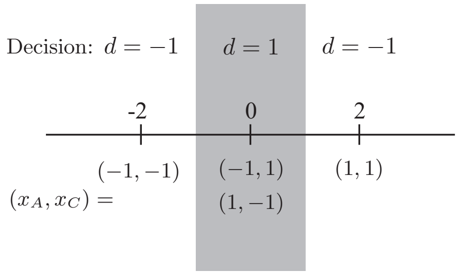

Fig. 2. Decision regions and denoise mapping for the case of BPSK and $h_{AB}=h_{BC}=1$. The relay node transmits the symbol $d[m]=1$ whenever $y_B[m]$ falls in the shaded interval.

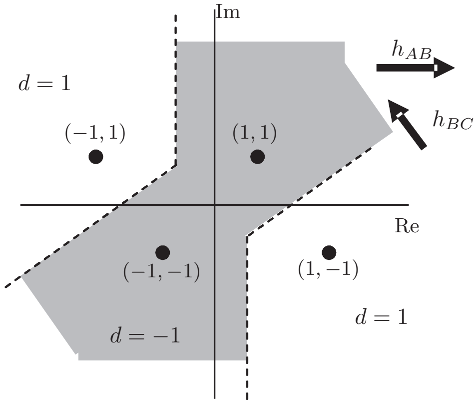

Fig. 3. Decision regions and denoise mapping for the case of BPSK with arbitrary uncorrelated h_{AB} and h_{BC}. The relay node transmits the symbol $d[m]=-1$ whenever $y_B[m]$ falls in the shaded region.

where $\mathcal{A}^{-1}$ is inverse mapping of $\mathcal{A}$, defined by (16). In short, for each symbol B makes decision about $b_{AC}[m]\oplus b_{BC}[m]$, such that in absence of channel errors, B can create the packet:

$$\mathbf{b}_d=\mathbf{b}_{AC}\oplus\mathbf{b}_{BC} \tag{16}$$

Note that in case of BPSK the relay node is always able to obtain this packet, irrespective of the values of h_{AB} and h_{BC}.

With such definitions of modulation and denoise mapping, there are implications regarding error detection and error correction that the relay can perform when DNF BAT relaying is used. Let us assume that A and C are using linear error detection codes e. g. CRC codes. Then $\mathbf{b}_{AC}\oplus\mathbf{b}_{BC}$ represents a valid codeword, such that after obtaining $\mathbf{b}_d$, the relay can run an error detection check and verify if there are errors in the denoising process. Similar observation is valid regarding the error correction codes. The relay can create the packet $\mathbf{b}_d$ and use *hard decoding* to find the valid codeword $\mathbf{b}_{AC}\oplus\mathbf{b}_{BC}$ which is closest to $\mathbf{b}_d$ in terms of Hamming distance.

When a higher–order modulation is used, the definition of the denoise mapping $\mathcal{D}$ depends on the channel gains h_{AB} and h_{BC}. Let us illustrate this fact by considering QPSK. Let first $h_{AB}=h_{BC}=1$. The received signal y_B is given by (12). Four possible symbols can be sent, denoted by $0,1,2,3$, respectively, and the mapping of these four symbols in the complex plane is given by (see also Fig. 4):

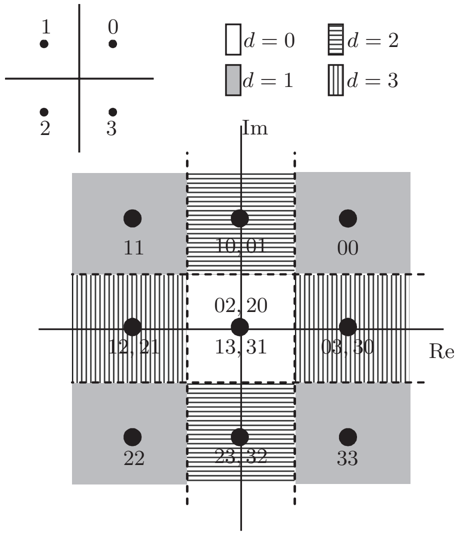

Fig. 4. Decision regions and denoise mapping for the case of QPSK and $h_{AB}=h_{BC}=1$. The used QPSK constellation is given in the left upper corner. The string x_Ax_C associated with each constellation point denotes the transmitted symbols that produce that point in absence of noise.

$$\begin{array}{ll} 0\mapsto 1+j & 1\mapsto -1+j \\ 2\mapsto -1-j & 3\mapsto 1-j \end{array} \tag{17}$$

In the absence of noise, y_B can obtain 9 different values. As illustrated on Fig. 4, these values correspond to 9 decision regions used for the denoise mapping. For this example, the denoise mapping $\mathcal{D}(x_A,x_C)$ is defined $\mathcal{D}(1,0)=\mathcal{D}(0,1)=2$, $\mathcal{D}(0,2)=\mathcal{D}(2,0)=\mathcal{D}(1,3)=\mathcal{D}(3,1)=0$, etc. When receiving $y_B=0$, the relay cannot distinguish which pair from the set $(x_A,x_C)\in\{(0,2),(2,0),(1,3),(3,1)\}$ has been transmitted, so it has to map all of them to the same value in the denoising process. Now let the channel gains be $h_{AB}=1$ and $h_{BC}=j$. One can easily check that when $y_B=h_{AB}x_A+h_{BC}x_C=0$, the relay node cannot distinguish among the four of the following pairs $(x_A,x_C)\in\{(0,1),(1,2),(2,3),(3,0)\}$. Hence we cannot use the denoise mapping Fig. 4 and either the QPSK mapping or the denoise mapping should be changed due to the change in $h_{BC}=j$.

If per–codeword denoising decision is used, then the relay B observes the set of samples $\mathbf{y}_B=h_{AB}\mathbf{x}_{AC}+h_{BC}\mathbf{x}_{CA}+\mathbf{z}_B$ and attempts to find a pair of codewords $(\mathbf{x}_{AC},\mathbf{x}_{CA})$ such as to minimize the Euclidian distance $\|\mathbf{y}_B-h_{AB}\mathbf{x}_{AC}-h_{BC}\mathbf{x}_{CA}\|$. Again, the definition of the denoise mapping will, in general, depend on h_{AB} and h_{BC}. The search for a codeword pair that minimizes the Euclidian distance may be prohibitively complex and the investigation of the codeword design/denoising is an interesting topic for future work.

The protocol for DNF BAT–Relaying is specified as follows:

1) With an empty buffer, B polls both A and C and they transmit simultaneously to B. After receiving the noised sum of anti–packets, B performs denoising and does error check for the obtained packet $\mathbf{b}_d$. In case of error, both A and C retransmit in the next slot and this is

repeated until B has a correct denoised packet.

2) If B has a correct denoised packet, it broadcasts to A and C. B retransmits the denoised packet until both A and C have received it.

As in [7], this protocol can be modelled by using an appropriate Markov chain and thus derive the achievable throughput when the links $A-B$ and $B-C$ have arbitrary, but stationary gains. Let p_d denote the probability that the denoised packet at B is incorrect. In the case when the links $A-B$ and $B-C$ have the same SNR i. e. $|h_{AB}| = |h_{BC}|$, then PER for the two links is identical $p_{e1} = p_{e2} = p_e$, such that the throughput is:

$$R_{DNF} = R_s \frac{2(1-p_d)(1-p_e)^2(1+p_e-p_e^2)}{2-p_e p_d - p_d - p_e^2 + p_e^2 p_d} \tag{18}$$

Nevertheless, it is more interesting to see the performance of DNF BAT relaying for a time–variant channel, since the decision regions depend on the actual pair of values h_{AB}, h_{BC}.

V. NUMERICAL RESULTS

In this section we provide simulation results that compare the achievable throughput of the different relaying schemes. Fig. 5 depicts the normalized throughput of the different schemes when BPSK transmission is used. We consider a slotted channel where a packet consisting of 100 bits can be transmitted over single slot. Each point represents the average throughput obtained when the SNR of both links $A-B$ and $B-C$ is identical and fixed throughout the simulation run. That is, for given SNR equal to γ we have:

$$\gamma_{AB} = \frac{|h_{AB}|^2}{\sigma^2} = \frac{|h_{BC}|^2}{\sigma^2} = \gamma_{BC} \tag{19}$$

The relation between the phases of h_{AB} and h_{BC} does not affect the error probability of the conventional, DF and AF scheme. Note that for the case of AF, the node A uses (4) to decode x_C and it is clear that the equivalent SNR available for the decoding does depend on $|h_{AB}h_{BC}|$, which removes the dependence on the phases of h_{AB} and h_{BC}. This is not true for DNF BAT relaying, where the phase between h_{AB} and h_{BC} determines the decision regions used for denoising. Therefore, in each simulation run for DNF we have kept $|h_{AB}|$ and $|h_{BC}|$ constant, but we have selected random phases prior for each slot in which A and C have transmitted simultaneously to B. It can be seen that the throughput of DNF is always superior to AF, as DNF prevents amplification of the noise, while still utilizing the simultaneous transmission of A and C. At lower SNR, the throughput of DNF is lower than DF and even the conventional relaying. This is because of the increased error rate when B denoises the transmission of A and C.

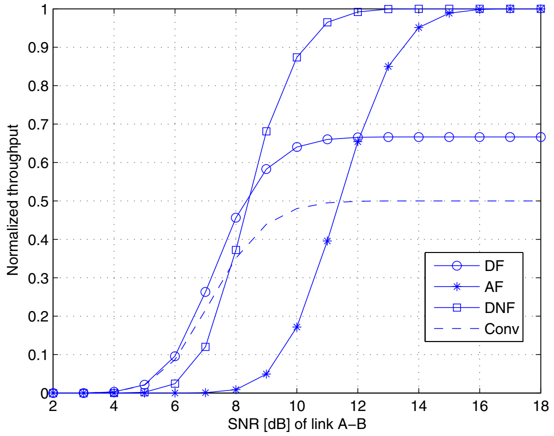

Fig. 5. Normalized throughput of DF, AF, DNF BAT–relaying and the conventional relaying versus the SNR γ_{AB} for the link $A-B$. The SNR for the link $B-C$ is chosen to be equal $\gamma_{BC} = \gamma_{AB}$.

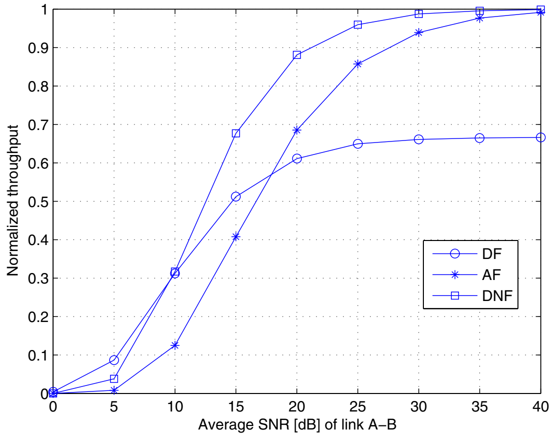

Fig. 6. Normalized throughput of DF, AF and DNF BAT–relaying versus the average SNR $\bar{\gamma}_{AB}$ for the link $A-B$. For each point, the average SNR for the link $B-C$ is chosen to be equal $\bar{\gamma}_{BC} = \bar{\gamma}_{AB}$. The packet size is $N = 100$ bits.

Fig. 6 compares the throughput performance of DF, AF and DNF BAT–relaying schemes for a Rayleigh fading channel. The abscissa shows the average SNR. For each point in the graphs, the average SNR is identical for both links $A-B$ and $B-C$, but the instantaneous values may differ $|h_{AB}| \neq |h_{BC}|$. We keep the channel constant over 2 slots, as this is the maximal possible channel variability that still ensures correct operation of AF BAT relaying. Understandably, here the throughput of all three schemes grows slower with SNR as compared to Fig. 5, but the relations among the throughput of different schemes remain unchanged.

The price for such a superior performance of DNF BAT Relaying is its complexity. When the SNR is fairly high, it is more convenient to use AF BAT relaying, as it does not require any significant processing at the relay. The denoising may be a very demanding operation in terms of processing, especially if the relay performs error detection/correction before broadcasting the denoised packet. Alternatively, B can choose to do hard per–symbol decision for denoising and forward the denoised packet without checking the errors in the combined packet and such an operation will require a DNF BAT protocol different from the one described in the previous section. Although this can degrade the performance of DNF BAT–relaying, we expect that it will still offer a better performance than AF BAT relaying at the lower SNRs.

VI. DISCUSSION AND FURTHER INVESTIGATIONS

The practical implementation of the BAT–relaying strategies requires careful consideration of the communication protocols. In this section we outline some important issues regarding the implementation aspects. In case of DF BAT, the node A needs to know only the Channel State Information (CSI) for the link $A - B$ i. e. the channel gain h_{AB}, while C needs to know only h_{BC}. Obtaining such a knowledge does not put any additional burden to the system, as A and C need to have that CSI to be able to communicate coherently with B. However, in case of AF and DNF, both nodes A and C need to know both gains h_{AB} and h_{BC}. This is critical for DNF if a modulation of higher order is used, as the denoise mapping needs to be changed and such change should be conveyed to A and C. The efficient methods for determining the denoise mapping and disseminating that information to the nodes that are communicating with anti–packets represent an interesting topic for further study. It is also important to see the robustness of the AF and DNF schemes to the CSI errors. In order to obtain additive multiple access channel in case of AF and DNF, the transmissions of A and C should be synchronized at B. It is viable to assume that such synchronization can be achieved if B broadcasts an *anti–packet poll message*. That message contains the information "A and C should transmit their packets to each other", upon which A and C get synchronized and transmit to B. Another problem occurs when the anti–packets have different lengths, such that an appropriate padding scheme is needed for the shorter packet so as to have consistent anti–packet combining at the relay.

Many new problems appear when we consider the scenarios with multiple nodes and communication over multiple (> 2) hops. Let us consider the case with multiple nodes that communicate with each other via a relay node B. The polling problem for node B is not "which node to poll such as to retrieve a packet with high probability", but rather a generalization of it "which pair of nodes should be polled, so that they have anti–packets with high probability". If DF BAT is applied, such nodes send the packets to B sequentially (e. g. lower address sends first). When B is forwarding the combination of anti–packets, it should add a signalling to provide information which packets (in terms of source/destination address and sequential number) are contained in the combined packet. For example, in case of AF, a preamble can be added before transmitting the amplified symbols. While DF BAT scheme is amenable to practical implementation for multiple users and multiple hops [8], the implementation of AF or DNF is much more involved because the usual ARQ protocol which ensure hop–by–hop reliable transmission can not be applied straightforwardly. The potential of the AF BAT scheme in multiple hops is discussed in [7].

The DNF scheme opens questions related to the modulation/coding aspects. For example, from the shape of the decision regions on Fig. 3 it can be inferred that when the channel gains on the two links are largely different, say $|h_{AB}| > |h_{BC}|$, then the relay can apply successive interference cancellation and decode first the packet $\mathbf{b}_{AC}$ and then the packet $\mathbf{b}_{BC}$. This practically means that the relay can switch to a form of DF BAT–relaying. Finally, an open issue is the selection of modulation/denoise mappings to have low–complexity error detection/correction at the relay node.

VII. CONCLUSION

We have considered relaying techniques that increase the achievable throughput by taking advantage of the bi–directional traffic flows. Such a relaying technique is termed relaying with Bi–directional Amplification of Throughput (BAT–relaying). The BAT–relaying is utilizing the concept of anti–packets, defined for bi–directional traffic flows. The relay node combines the packets (anti–packets) that are destined for different nodes and broadcasts the combined packet. Two BAT–relaying techniques have been proposed previously. The first variant, Decode–and–Forward (DF) BAT–relaying, combines the packets by using the XOR operation, which makes such proposal closely related to the network coding approaches. The second variant is Amplify–and–Forward (AF) BAT–relaying, which utilizes the inherent packet combining that emerges from simultaneous use of a multiple access channel. In an errorless channel, AF BAT–relaying is always superior to DF, but in noisy channels the noise amplification can severely degrade the performance of AF compared to DF. In this paper we have proposed a new scheme for BAT-relaying, termed Denoise–And–Forward (DNF) BAT–Relaying. The DNF BAT–relaying also makes use of the combining provided by the multiple access channel, but it removes the noise from the combined anti–packets before broadcasting to the destinations. While in the noiseless channel DNF and AF offer the same throughput performance which is superior to DF BAT–relaying, in large regions of the lower SNR values DNF BAT–relaying has the best throughput performance of all three schemes. Due to the unconventional nature of the BAT–relaying schemes, we have provided a separate section in the paper to outline the issues that need further investigation.

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