Implementation of cooperative virtual MISO communication in underwater acoustic wireless sensor networks

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Abstract

In this paper, for the first time, virtual antennas are used in an underwater acoustic wireless sensor network and their effects on total system performance are studied. In multiple input single output (MISO) channels, spacial diversity is used to improve the system performance. In certain networks, especially in underwater networks, nodes are too small to have more than one antenna. Therefore, to achieve spacial diversity gain, cooperation between adjacent nodes can be a proper alternate method. For this purpose, each node of network tries to use its nearest adjacent node as a virtual antenna at some portions of time and with the aid of space time coding this new antenna profits from spacial diversity. It means that a cooperative virtual MISO scenario must be devised to determine the transmission and cooperation method in the network. Thus, the most frequently used cooperation schemes "decode and forward," and "amplify and forward," are applied, simulated and studied in an arbitrary underwater acoustic wireless sensor network and compared with the noncooperation mode. In this paper the alamouti space time coding, and the maximum ratio combiner are used to transmit, and combine data, respectively. Simulations show that virtual antenna in underwater wireless sensor networks can improve system performance up to 12.08%

Keywords: *Cooperative transmission, Underwater acoustic wireless sensor network, spacial diversity, Virtual MISO, Virtual antenna.*

1. Introduction

The first operational underwater acoustic (UWA) communication system was an underwater telephone, developed in 1945 in the United States, for communication with submarines. The underwater acoustic wireless sensor network (UWA-WSN) has recently become a hot topic in the field of acoustic communications. The major difference between this kind of sensor network and the traditional one is its special physical layer which affects acoustic waves. Acoustic waves are the best, and only means of achieving sufficient range and data transmission rate in underwater communications. Radio waves are soon absorbed in water and cannot support sufficient range and data rate. Light, experiences high dispersion in underwater environments and again, cannot support sufficient communication range and rate. However, new progresses achieved in underwater acoustic communications make reliable data transmission across several kilometres conceivable. So, the researchers are well encouraged to further investigate the underwater acoustic communications issues.

This strangely behaving physical layer has several influences on the channel parameters. Firstly, acoustic waves move slowly in water, about 1500 m/s, which is one fifth the speed of radio waves in the atmosphere [1]. So, acoustic waves have large delay spreads. In radio channels, Path loss only depends on link length. However, acoustic waves experience frequency and link length dependent Path losses in underwater environments. Therefore, the Link's carrier frequency affects its overall performance. Because of suspended particles and small bubbles, acoustic waves are dispersed widely in underwater environments. Furthermore, reflections from the water surface and sea bottom increase channel fading. All the points mentioned before, must be considered in the design of underwater acoustic wireless systems. The themes mentioned above show that, in UWA communications, as in radio communications, range and bandwidth are the important bottlenecks.

The noise generated in the ocean is categorized into two groups: man-made noise and ambient noise [2]. In the deep ocean, man-made noise is ignorable, whereas, in the presence of shipping activities or close to shore, man-made noise increases the overall level of noise intensity. On the other hand, geysers, earthquakes, heat, and some marine animals can be considered as major sources of ambient noise. Total noise in the underwater acoustic environment is related to signal carrier frequency. In part 2.1, there are further descriptions and statistical models of underwater acoustic noise.

Since path loss and noise power are frequency dependent, SNR in underwater acoustic communications is related to frequency. Also, in UWA channels, as in all wireless

channels, SNR is a function of link length. Therefore, SNR is influenced by two major parameters: link length, and frequency. This means that, length changes can influence the optimum frequency of the system.
Because of considerable progresses made in radio communications, researches try to improve UWA systems by applying new schemes borrowed from radio communications. One of these methods is the cooperative communication which is suited to wireless sensor networks. In chapter 3 two schemes of cooperative communication, DF and AF, are adjusted, applied and simulated in UWA-WSN. Simulations show that Compared with no cooperation method, AF and DF methods can improve system performance up to 17 a nd 33.38 percents, respectively. (Authors of the paper published their First works on UWA cooperative WSN in [3] which are summarized in chapter 3). Using the results of previous chapters, a new method to improve UWA communication is proposed in chapter 4. In this method, which is called CUWA-MISO (cooperative UWA multiple input multiple output) communication, each node of network uses its nearest adjacent node as a virtual antenna in a co operation scenario and vice versa. Based on the results of chapter 5, decode and forward scheme is chosen and used as the cooperation scenario.
The reminder of this paper is organized as follows: Section 2 describes the UWA channel; the cooperative UWA wireless communication is described and simulated in section 3; in section 4 the CUWA-MISO scheme is proposed and simulated; and finally, the whole work is summarized and concluded in the last section. This paper's Simulations show that the CUWA-MISO communication scheme can improve performance of UWA-WSNs up to 12.08%.

2. UWA Channel

To specify a special wireless channel like the UWA channel several parameters must be defined. In this chapter, important parameters of the UWA channels such as the noise PSD, the path loss and the SNR are studied.

2.1 Noise in UWA Channels

Sources of Ambient noise in the UWA channels can be categorized and modeled in 4 g roups. The noise power spectrum density (PSD) in underwater channels is depended on frequency, f, and can be modeled as [4]:

$$N(f) = N_t(f) + N_s(f) + N_w(f) + N_{th}(f) \quad (1)$$

Where

$$N_s(f) = 40 + 20(s - 0.5) + 26\log_{10}(f) - 60\log_{10}(f + 3),$$
$$N_w(f) = 50 + 7.5\sqrt{\omega} + 20\log_{10}(f) - 40\log_{10}(f + 0.4),$$
$$N_{th}(f) = -15 + 20\log_{10}(f) \text{ and } N_t(f) = 17 - 30\log_{10}(f).$$

Where $N_t(f)$, $N_s(f)$, $N_w(f)$ and $N_{th}(f)$ are the noises caused by the turbulence, the shipping activities, the wind and the heat, respectively. s is the shipping activity factor, whose value ranges from 0 to 1 for low and high activities, respectively, and w is the wind velocity (0-10 m/s).
Figure 1 illustrates the simulated noise PSDs for 3 arbitrary cases, $s = 0\ w = 0$, $s = 0.5\ w = 5$ and $s = 1\ w = 10$, at frequencies less than 100 kHz. All other cases slide between these graphs.

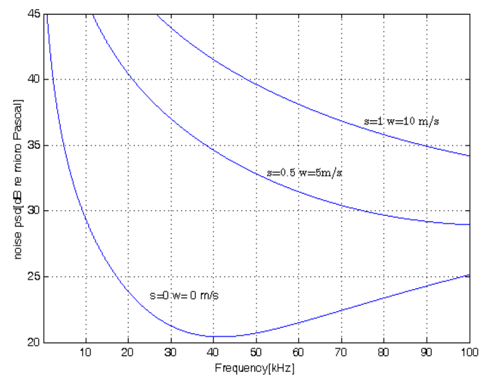

Fig. 1: Noise PSD versus frequency for 3 arbitrary selections of s and w.

2.2 Pathloss and SNR in UWA channels

Signals in the UWA Channels experience frequency and link length dependent path losses which are more complicated than those in the radio channels and can be modeled as:

$$T_\ell = 10\log_{10} r + 10^{-3}\alpha r \quad (2)$$

Where r is the link length, and the absorption coefficient, α, is a function of frequency.

$$\alpha(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f} + 2.75\times10^{-4} + 0.003 \quad (3)$$

Figure 2 shows $\alpha(f)$ in frequencies less than 100 kHz.

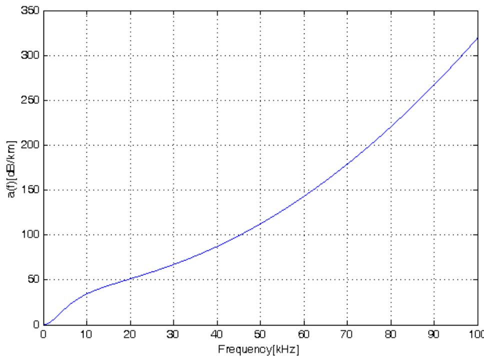

Fig. 2:Absorption coefficient $\alpha(f)$ in frequencies less than 100 kHz.

The first part of relation (2) is similar to the radio channels and denotes the power consumptions by signals transmitted from source to destination in the wireless channels. The second part corresponds to the mechanical absorptions of traveling wave's power in the underwater environment it is caused by the mechanical nature of the acoustic waves and specifies the UWA channels.

For an arbitrary signal power, by substituting Eq. (3) into Eq. (2), the received power at the destination can be computed. Therefore, with the aid of Eq. (1), the following relation will be obtained:

$$SNR(d,f) = 10\log P_T - T_\ell - 10\log N \qquad (4)$$

Where P_T is the signal power, N is the total noise power in the transmission band and d is the link length.

In figure 3 relative SNRs for several link lengths from 5 to 100 km are simulated and plotted. It is obvious that the 3dB bandwidth is inversely related to the link length.

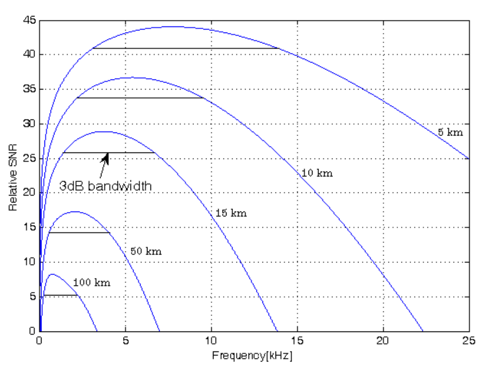

Fig. 3: Relative SNR versus Frequency in 5-100 km

Figure 3 is confirmation of the dependency of the optimum frequency on the link length. It proves that, a single optimum frequency cannot be found for all of the frequencies and ranges.

3. Cooperative communication schemes in UWA Networks

The concept of spacial diversity has attracted the attention of wireless communications researchers and has led to continuous and efforts to make use of it in WSNs. In a wireless channel several paths can exist between the transmitter and the receiver. If some of these paths are independent and have sufficient performance, the channel performance can be enhanced by sending copies of the data along these paths and combining them in the receiver. Since the paths are independent the total error probability decreases. Therefore, the channel and the system performance increase. Multiple input multiple output (MIMO) systems make use of spacial diversity by using several antennas in the transmitters and the receivers. These antennas must be separated far enough to make the corresponding paths independent. But in many applications of WSNs this becomes impossible, since network nodes maybe smaller than required in order to support such separated antennas. To solve this problem, the idea of cooperative communication is proposed. In cooperative communication systems, the transmitter sends one copy of data packets to the relay node. Then, the relay node, depending on the cooperation scheme, amplifies or decodes each data packet and retransmits it to the destination. If the relay has the proper position, the relay path will be independent from the direct path. The receiver uses and combines both received signals to estimate the transmitted data.

In figure 4 a simplified model of the one relay UWA cooperative channel, which will be used in continuation of the paper, is shown.

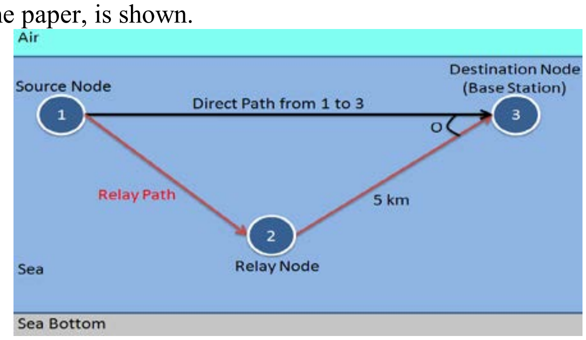

Fig. 4: UWA cooperative channel

In next part two frequently used cooperative schemes, DF and AF, in WSNs is defined and applied to an UWA cooperative WSNs.

3.1 DF and AF in UWA Cooperative WSNs

The basic idea behind DF is that, one copy of data which is sent to the receiver must also be sent to the relay. In the relay, this message is decoded, corrected, coded and retransmitted to the destination. At the destination, the data which is received from both paths are decoded, corrected, and combined to figure out the transmitted message. With this approach, the achievable bit rate is [5]:

$$R_{df} = \sup_{P(\chi_1\chi_2)} \max\{I(X_1;Y_2|X_2), I(X_1,X_2;Y_3)\} \quad (5)$$

It means that the relay decodes the message, perfectly, and retransmits it to the destination. In Gaussian channels, if the transmitter and relay send their data coherently, the above rate will be achievable.

In figure 4 the transmitter, the relay and the receiver nodes are called 1, 2 and 3, respectively. In Gaussian relay channels, the channel gain between nodes i and j ($i, j = 1,2,3$, $i \neq j$) is termed h_{ij} . The received signals in the relay and the receiver experience additive white Gaussian noise with unit power. Moreover power constraints in the transmitter and the receiver are, $E\left[|X_1|^2\right] \le P_1$ and $E\left[|X_2|^2\right] \le P_2$, respectively. By computing relation (5), for the Gaussian channel the following will be obtained [6]:

$$R \le \max_{0\le\beta\le1} \min\{\log(1+(1-\beta)|h_{21}|^2 P_1), \quad (6)$$

$$\log(1+|h_{31}|^2 P_1 + |h_{32}|^2 P_2 + 2\sqrt{\beta|h_{31}|^2 |h_{32}|^2 P_1 P_2})\}$$

β is a real constant and showing the correlation between X_1 and X_2 Which are the transmitted data from the transmitter and the relay, respectively. If the transmitter (1) and the relay (2) cannot transmit coherently, the correlation is unusable and $\beta = 0$. Therefore we have

$$R \le \max_{0\le\beta\le1} \min\{\log(1+|h_{21}|^2 P_1), \quad (7)$$

$$\log(1+|h_{31}|^2 P_1 + |h_{32}|^2 P_2)\}$$

In the AF scheme, the relay node amplifies and retransmits the received signals without decoding them. The relay receives $y_2(b)$ at time b. Then, by considering the power constraints, it multiplies $y_2(b)$ by γ .

$$R \le \max_{0\le\beta\le1} \min\{\log(1+|h_{21}|^2 P_1), \quad (8)$$

$$\log(1+|h_{31}|^2 P_1 + |h_{32}|^2 P_2)\}$$

A Gaussian relay channel is considered and modeled using the following expressions:

$$Y_2(i) = h_{21}X_1(i) + Z_2(i)$$
$$Y_3^1(i) = h_{31}X_1(i) + Z_3^1(i) \quad (9)$$
$$Y_3^2(i) = h_{32}X_2(i) + Z_3^2(i)$$

Where Y_3^1 and Y_3^2 are the received signals from the relay and transmitter. If all the noise powers are unit and the power constraints in the transmitter and receiver are P , the following relation will be obtained:

$$\gamma = \sqrt{\frac{P}{|h_{21}|^2 P + 1}} \quad (10)$$

And the AF scheme can achieve the following bit rate:

$$R = \log\left(1 + P(|h_{31}|^2 + \frac{|h_{32}|^2 |h_{21}|^2 P}{1+|h_{21}|^2 P + |h_{32}|^2 P})\right) \quad (11)$$

If the system works in the low SNR regime which meaning, $P \to 0$, the bit rate will be:

$$R = \log\left(1 + P|h_{31}|^2\right) \approx \frac{|h_{31}|^2 P}{\ln 2} \quad (12)$$

In such a situation, the relay channel cannot help improving system performance and is useless; because in the AF scheme, both noise and power are amplified and in the low SNR, the AF cannot help with data estimation in the receiver.

In figure 5 performances of one relay cooperative UWA AF and DF channels are simulated and compared with the noncooperation mode. In this figure the horizontal axis is the distance between transmitter and receiver and vertical axis is the bit error rate (BER) which is representative of the system performance. Relay position is same as figure 4 and $\hat{O}$, the angle between the relay path and the direct path in the receiver, is $15°c$. Channel experiences additive white Gaussian noise (AWGN).

Figure 5 shows that UWA cooperative schemes can improve performance of UWA-WSNs. Maximum improvement is at 7500m where the BER decreases from 0.2596 in the noncooperation mode to 0.0927 in the DF mode and 0.1755 in the AF mode which means 33.38% and 17%, respectively. (Note that the maximum bit error rate is 0.5 and the vertical axis in figure 5 is graphed logarithmic). Costs of such improvements are relay establishment and corresponding source usages.

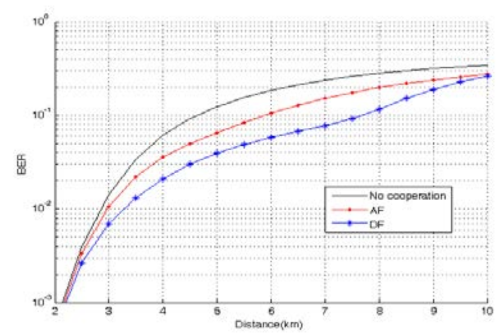

Fig. 5: Performance of one relay UWA channel with and without cooperation with AWGN

As it can be seen in figure 5, if the length of direct path decreases, the performance improvement of cooperative schemes decreases too. When the direct path decreases less than 5 km, the relay path will be longer than it. Therefore, the relay path experiences larger Pathloss and the cooperative channel tends to the weak relay channel. As was mentioned in the last part, if the relay channel is weak which means that it experiences low SNR, it will not help improving system performance and will be unusable. Based on the results of this part the DF cooperation method is chosen to use as cooperation scenario in the reminder of work.

4. CUWA-MISO Communication System

The As was mentioned in part 3, in MIMO systems, the performance of communication is improved by using spatial diversity. In many cases, it is impossible to have more than one antenna for each node in the network. Thus, a cooperative communication can be a g ood alternate method. In the previous part, a cooperative UWA channel with passive relay was modeled and simulated. In such a system, the relay just retransmits the received data and cannot work like the source node to transmit its own data. Therefore, although a passive relay helps improve system performance, it imposes supernumerary nodes on an underwater sensor network and increases system costs. But if network designers omit these nodes, how can they benefit from spatial diversity? This concern is addressed in the following part.
To solve the problem, the authors tried to combine the cooperative underwater acoustic schemes with multiple input single output communication. The combined method is referred to as the cooperative underwater acoustic MISO (CUWA-MISO) in this paper. In the CUWA-MISO method, each node works in a cooperative scenario with an adjacent node and uses its antenna as a second antenna to retransmit data, and vice versa. This means that each node works as the second antenna of its adjacent node for a portion of time and sends its own data in the remainder of time, and vice versa. So, each node has a virtual antenna and uses it to improve the system performance with the help of spatial diversity.
In figure 6, a CUWA-MISO communication system is shown. Obviously, in this method, supernumerary nodes are omitted and each node uses its adjacent node as a virtual antenna in a cooperative transmission path. Therefore, without any extra nodes or antennas, spatial diversity can be used to improve the system performance. In this scenario, the destination does not differ from that of section 3 and has just one antenna.

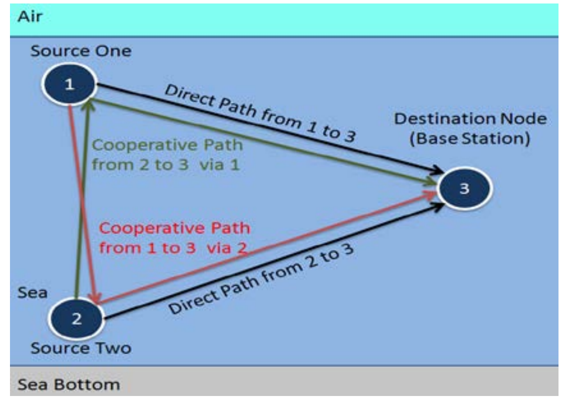

Fig. 6: CUWA-MISO communication system

4.1 Space time codes
Because of multiple antennas in transmitters which are placed far enough, the MISO systems benefit from spatial diversity. Several coding schemes have been proposed up to now. One of the most frequently used space time codes is the Alamouti space time block code (STBC) which is shown in figure 7.
In [7] the Alamouti STBC in MISO channels is described as follows:
1) The Encoding and Transmission Sequence: At a given symbol period, two signals are simultaneously transmitted from the two antennas. The signal transmitted from antenna zero is denoted by s_0 and from antenna one by s_1. During the next symbol period signal ($-s_1^*$) is transmitted from antenna zero, and signal s_0^* is transmitted from antenna one where * is the complex conjugate operation. The encoding is done in space and time (space–time coding).
2) The channel at time t may be modelled by a co mplex multiplicative distortion $h_0(t)$ for transmit antenna zero and $h_1(t)$ for transmit antenna one. Assuming that fading is constant across two consecutive symbols, we can write

$$h_0(t) = h_0(t+T) = h_0 = \alpha_0 e^{j\theta_0} \quad (13)$$

$$h_1(t) = h_1(t+T) = h_1 = \alpha_1 e^{j\theta_1}$$

Where, T is the symbol duration. The received signals can then be expressed as

$$r_0(t) = r(t) = h_0 s_0 + h_1 s_1 + n_0 \quad (14)$$

$$r_1(t) = r(t+T) = -h_0 s_1^* + h_1 s_0^* + n_1$$

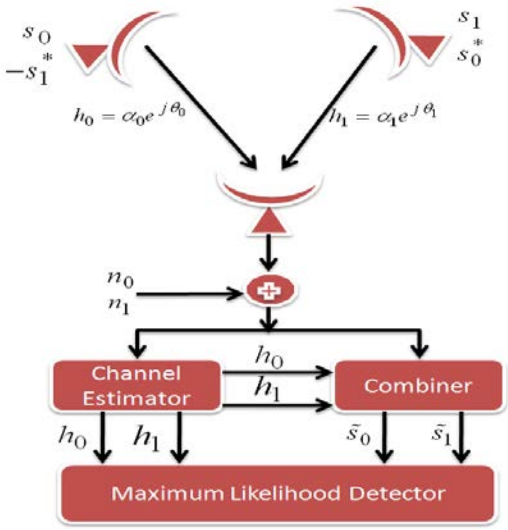

Fig. 7: Alamouti MISO transmition diversity model

Where r_0 and r_1 are the received signals at time t and $t+T$ and n_0 and n_1 are complex random variables representing receiver noise and interference.

2) The Combining Scheme: The combiner shown in Fig. 7 builds the following two combined signals that are sent to the maximum likelihood detector:

$$\tilde{s}_0 = h_0^* r_0 + h_1 r_1^* \quad (15)$$

$$\tilde{s}_1 = h_1^* r_0 - h_0 r_1^*$$

It is important to note that this combining scheme is different from the MRRC. Substituting (13) and (14) into (15) we get

$$\tilde{s}_0 = (\alpha_0^2 + \alpha_1^2) s_0 + h_0^* n_0 + h_1 n_1^* \quad (16)$$

$$\tilde{s}_1 = (\alpha_0^2 + \alpha_1^2) s_1 + h_1^* n_0 - h_0 n_1^*$$

The resulting combined signals in (16) are equivalent to that obtained from two-branch MRRC [7]. The only difference is phase rotations on the noise components which do not degrade the effective SNR. Therefore, the resulting diversity order from the new two-branch transmit diversity scheme with one receiver is equal to that of two-branch MRRC. Further comments can be found in [7].

UWA-MISO Communication System and simulations

In the previous part, the Alamouti STBC was described. In this part, based on the Alamouti STBC, the CUMA-MISO communication scheme will be proposed and compared with the noncooperation method via simulations.

In the CUWA-MISO communication system, like the Alamouti scheme, each source node has 2 antennas, 0 and 1. But the difference with the CUWA-MISO system is that Antenna 1 is a virtual antenna which is set on the adjacent node. If the source node wants to send data by its virtual antenna, it must send the data packet to that adjacent node. The adjacent node will send the received packet to the destination, and for a time interval, it will lend its antenna to the source, and vice versa. In two consecutive signal intervals, the source node transmits s_0 and $-s_1^*$ within antenna 0 and s_1 and s_0^* within virtual antenna 1, respectively. Another difference between these methods is in their complex multiplicative distortion $h_1(t)$. When the source node uses its virtual antenna, it must send s_1 and s_0^* to its adjacent node. Therefore s_1 and s_0^* experience an extra distortion compared with s_0 and $-s_1^*$. In other words, the distance between source node and its virtual antenna will have some effect on the transmitted data from antenna 1. On the other hand, in the DF cooperation scheme, which is used in CUWA-MISO, the relay node (adjacent node) decodes, estimates, recodes, and then retransmits the received data. Therefore, for the adjacent node, the following relations can be written:

$$r_1' = h' s_1 + n' = \alpha' e^{j\theta'} s_1 + n' \quad (17)$$

$$r_0'^* = h'' s_0 + n'' = \alpha'' e^{j\theta''} s_0 + n''$$

Where r_1' and $r_0'^*$ are the s_1 and s_0^* which are influenced by the complex multiplicative distortions h' and h'', respectively. n' and n'' are complex random variables representing the received noise and interference in the relay node.

After s_1' and $s_0'^*$ are received they will be decoded, estimated and recoded. As a result, $\tilde{s}_1'$ and $\tilde{s}_0'^*$ which are made from s_1' and $s_0'^*$, will be sent to receiver. Thus, for the receiver , the following expressions will be defined:

$$\tilde{s}_0 = (\alpha_0^2 + \alpha_1^2) \tilde{s}_0'^* + h_0^* n_0 + h_1 n_1^* \quad (18)$$

$$\tilde{s}_1 = (\alpha_0^2 + \alpha_1^2) \tilde{s}_1' + h_1^* n_0 - h_0 n_1^*$$

In figure 8 the performances of the CUWA-MISO system is simulated and compared with the noncooperation mode. The system model is shown in figure 6. The distance between source 1 and the destination ranges from 1km to 8km (horizontal axis). The distance between source 2 and the destination is 5km (constant). The angle between paths 1 to 3 (13) and 2 to 3 (23) is 15°. The channel experiences Rayleigh fading. Figure 8 shows that the CUWA-MISO communication schemes can improve performance of UWA-WSNs. Maximum improvement is at 7000m where the BER decreases from 0.1738 in the noncooperation mode to 0.1132 in the CUWA-MISO which means 12.08%.

5. Conclusion and summery

In this paper implementation of cooperative virtual MISO communication in UWA-WSNs is studied. For this purpose, after describing the UWA channel and its parameters, two frequently used cooperative transmission schemes, AF and DF, are studied and implemented in UWA channel and compared with the noncooperation mode via computer simulations. Simulations show that the DF scheme works better than the AF in UWA-WSNs. Therefore the DF is chosen to use in virtual MISO system. Then the alamouti STBC in MISO channels is described and adapted to virtual MISO systems. And finally the CUWA-MISO system is proposed, simulated and compared with the noncooperation mode. In figure 8, simulations show that the CUWA-MISO scheme can improve performance of UWA-WSNs by up to 12.08%

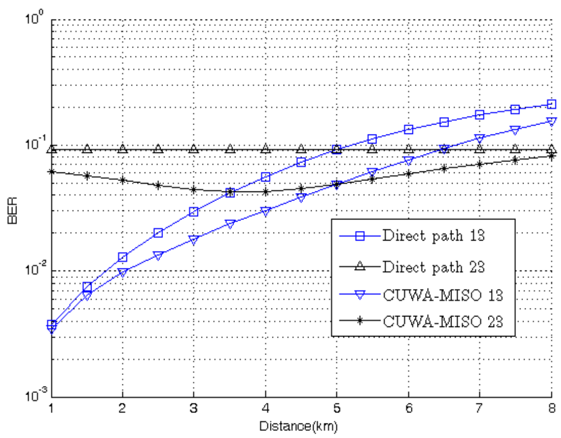

Fig. 8: CUWA-MISO in compare with noncooperative scheme in Rayleigh fading

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