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Performance Analysis of Binary Sensor-Based Cooperative Diversity Using Limited Feedback

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1. Introduction

The most important advantage of wireless sensor networks (WSNs) is their ability to bridge the gap between the physical and logical worlds by gathering certain useful information from the physical world and communicating that information to more powerful logical devices that can process it. If the ability of the WSN is suitably harnessed, it is envisioned that WSNs can reduce or eliminate the need for human involvement in information gathering in certain civilian and military applications (He et al., 2004).

It is a common belief that in the near future, many WSNs will be deployed for a wide variety of applications including monitoring and surveillance. Each sensor is powered by battery and is supposed to work for a relatively long time after deployment. The total energy cost of WSN includes all aspects of the sensor's actions. Transmission energy efficiency and reliability becomes important because wireless transceivers usually consume a major portion of battery energy (Akyildiz et al., 2002). This is true considering the severe channel fading and node failure in hostile environment (Ng et al., 2005).

Transmission energy conservation in WSN has two aspects. First, transmission protocols and algorithms should have high energy efficiency. Space-time coding and processing are helpful for enhancing transmission energy efficiency and reliability (Li & Wu, 2003). In particular, space-time block codes (STBCs) have attracted great attention because of their affordable linear complexity (Alamouti, 1998; Tarokh et al., 1999). Among the numerous STBC schemes, Alamouti's STBC (Alamouti, 1998) is probably the most famous one due to its simplicity. However, space-time techniques are traditionally based on multiple transmit antennas.

Due to insufficient antenna space, cost and hardware limitations, wireless sensors may not be able to support multiple transmit antennas. For the wireless sensors which have no multiple transmit antennas, STBC may still be used with cooperative transmission schemes (Li, 2005; Sendonaris, 2003a; Sendonaris, 2003b; Laneman & Wornell, 2003; Ohtsuki, 2006) where multiple sensors work cooperatively to form a virtual antenna array. Additional performance improvement can be achieved if limited feedback is available at the cooperating sensors. Two techniques are generally used for limited feedback; Sensor (relay) selection (SS) which selects n_1 out of n active sensor for cooperation ($n_1 \leq n$) and Extended Cooperative Balanced Space-Time Block Coding (ECBSTBC) which uses all active sensors (Eksim & Celebi, 2009a; Eksim & Celebi, 2010a).

Another important aspect of transmission energy conservation is that energy consumption rates in different parts of the WSN should be uniform or almost uniform so that the wireless sensors have approximately same lifetime. If the energy consumption rates are non-uniform, some parts of the WSN may die much sooner than the others. If these dying parts are critical for the WSN, this situation may lead to early dysfunction of the network, thus loosing Quality of Service (QoS), even if the other parts of the network still have a lot of residual energy. In the literature, this is called energy hole (Li & Mohapatra, 2007) problem.

Although SS schemes prolong the network life in uniform wireless channels, due to nature of the non-uniform wireless channels or location of the sensors, some of the sensors are more frequently selected for cooperation, so, there may be little or no energy left for their own use. Then, the energy hole problem occurs. For this problem not occurring in non-uniform wireless channels, the ideal communication protocol should distribute communication energy among the active sensors evenly without losing the QoS of the communication.

In (Ohtsuki, 2006), the performance of the statistical STBC cooperative diversity with observation noise and quantization noise is analyzed. In this work, the Alamouti`s code is used which is the only orthogonal code which achieves full diversity and full rate for two sensors, and the achievable diversity order is two when a single receive antenna is present at the fusion center. The use of the Alamouti`s code improves the bit error performance of the system when more than two active sensors are present in the transmitting side. The achievable diversity order can be increased via limited feedback. Since the limited feedback is not used in (Ohtsuki, 2006), the issue of how much feedback from a fusion center improves the performance when quantization and observation noise are present, is not analyzed. Additionally, the performance of binary sensors in non-uniform wireless channels and the impact of the energy hole problem in non-uniform wireless channels are not well investigated in the literature.

In this chapter, we show how to improve the performance of the statistical STBC with limited feedback. The effect of quantization and observation noise is also included in the analysis. Moreover, we show that SS schemes cause an energy hole problem in non-uniform wireless channels. The ECBSTBC provides an improvement to this problem since this scheme utilizes all available sensors to maintain equal power consumption among the available sensors and meets QoS of the communication until the end of the network lifetime. This increases the energy efficiency of the communication protocol in non-uniform wireless channels.

In addition, not only the ECBSTBC but also the SS schemes are adversely affected by the observation noise since it limits the bit error rate (BER) performance (Eksim & Celebi, 2010a). To improve upon this problem, we propose an ECBSTBC combined with SS scheme (Eksim, 2010b). In this scheme, an active sensor does not cooperate with other active sensors to transmit the observations if its observation is classified as "noisy". On the other hand, the sensors cooperate with each other using the ECBSTBC when their observation noise level is smaller than predefined threshold for transmission toward the fusion center. This hybrid technique yields improved performance at the fusion center compared to solely using the ECBSTBC or the SS methods.

In the following section, the system model is described, in the third section, the Extended Cooperative Balanced Space-Time Block Codes (ECBSTBCs) are explained, in the fourth

section, a performance analysis presented, and in the last section, the results of the our work and the conclusion are given.

The following notation used in this chapter: * denotes the conjugate operation; Re{.} and Im{.} are the real and imaginary part of the argument, respectively. The operator $\lceil . \rceil$ rounds to the smallest integer greater or equal than its argument.

2. System Model

The wireless sensor network consists of one source, one fusion center and N sensors which are located randomly and independently. Figure 1-2 show the wireless sensor network and its analytical model, respectively. All sensors are equipped with a single antenna and cannot communicate with each other. All channels are assumed frequency flat Rayleigh fading channel where channel gains are circularly complex Gaussian random variables and statistically independent from each other. The channels are quasi-static, namely, the fading coefficients remain constant over the duration of one frame and change independently in the following frame. h_{rid} is the channel gain from the ith active sensor to the fusion center where i=1, 2,.., n.

The fusion center is assumed to have perfect knowledge of the sensor-fusion center channels. This can be achieved via pilot tone training. However, the fusion center has no knowledge of the accuracy of the sensor measurements, since knowledge of the measurements at the fusion center requires considerable protocol overhead. Because of energy efficiency, only n sensors are active. Active sensors observe the environment. Due to the presence of the noise, the observation at each active sensor may be different. The observed data are binary quantized and transmitted by BPSK.

2.1 Battery model

The Battery Model simulates the capacity and the lifetime of the sole energy source of the sensor. In reality, the battery behavior highly depends on the constituent materials and modeling this behavior is a difficult task. Present network simulation tools use linear model (Park et al., 2001). In the linear model, the battery behaves as a linear storage of current. The maximum capacity of the battery is achieved regardless of what the discharge rate is. The simple battery model allows user to see the efficiency of the user's application by providing how much capacity is consumed by the user. Knowing the current discharge of the battery and the total capacity in Ah (Ampere×Hour), one can compute the theoretical lifetime of the battery using the equation, $t = C_{bat}/I$, where t is the battery lifetime, C_{bat} is the rated maximum battery capacity in Ah, and I is the discharge current.

In this model, sensor user having an initial amount of energy diminishes its value when a packet is sent or received. In limited battery simulations, battery counter is added (Lim et al., 2005; Buttyan & Hubaux, 2003). It represents the battery power which is left to the sensors. When a sensor`s battery is consumed, further cooperation requests will not be accepted. In addition, many short range wireless networks generally consume the available energy for receiving which is approximately 2/3rd of the energy for transmitting (Lal et al., 2005).
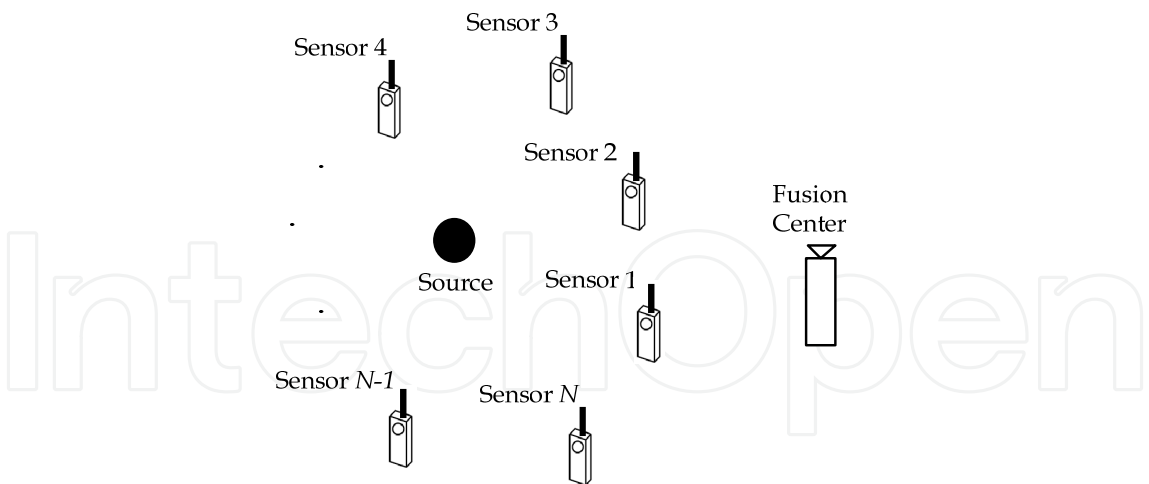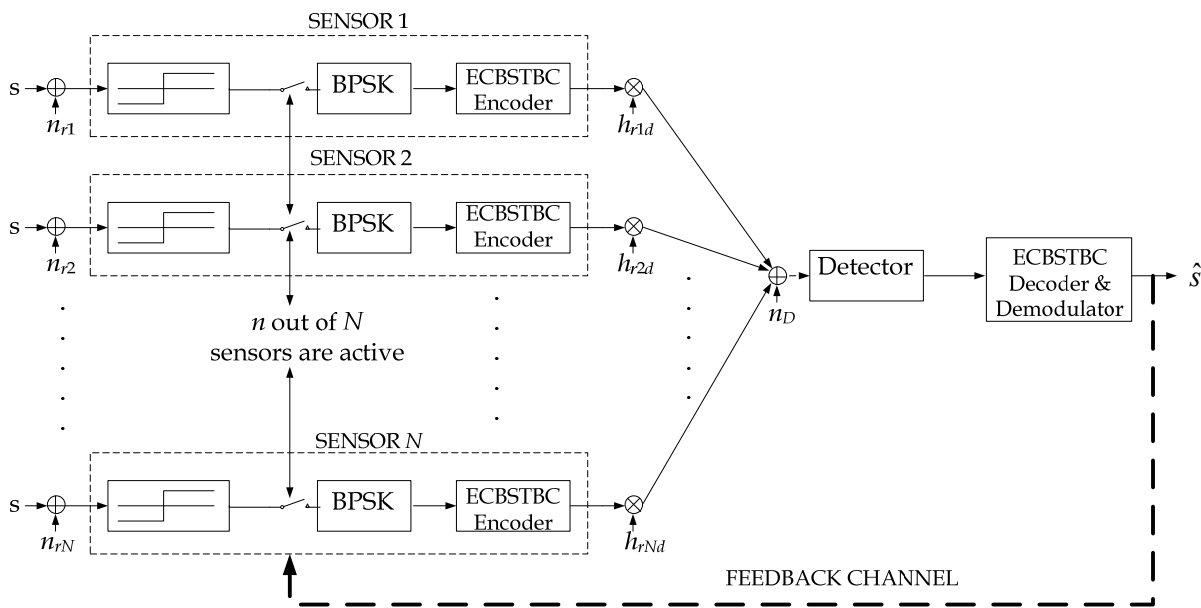
Fig. 1. Wireless sensor network

Fig. 2. Analitical model of wireless sensor network

2.2 Channel model

We assume that all parallel wireless channels are independent but they have statistically uniform paths with have identical means and variances (Cetinkaya, 2007). That is to say that the sensors-fusion center channels have equal variance and mean. This is not true for realistic scenarios, since some of the parallel channels have non-uniform statistical properties (Cetinkaya, 2007). In the non-uniform wireless channel simulations, the parallel channels may contain "better" or "worse" channels. When the ith active sensor-fusion center channel`s variance is much higher than the $j$th active sensor-fusion center channel`s variance ($\sigma_{rid}^2 >> \sigma_{rjd}^2$ where j=1,..,n and $j \neq i$), this channel can be considered as "better" channel. On the contrary, when the ith sensor-fusion center channel`s variance is much lower than the $j$th sensor-fusion center channel`s variance ($\sigma_{rid}^2 << \sigma_{rjd}^2$ where j=1,..,n and $j \neq i$), this channel can be called as "worse" channel (Ibrahim et al., 2008).

3. Extended Cooperative Balanced Space-Time Block Codes

The ECBSTBCs can be obtained from an OSTBC multiplied by an extension matrix. Since Alamouti`s code is the only orthogonal code with rate one and minimum delay, the ECBSTBCs can be obtained as an extension of the Alamouti`s code (Alamouti, 1998) as

$$C=XW. \tag{1}$$

Here X is the Alamouti`s code matrix, W is a 2xn ($n>2$) matrix whose columns are 2x1 standard basis vectors, and the rank of W must be 2. The following example shows how to generate the ECBSTBCs for three active sensors. Consider the ECBSTBC pair with transmission matrix

$$C_1 = \begin{bmatrix} s_1 & s_2 & as_2 \\ -s_2^* & s_1^* & as_1^* \end{bmatrix} \tag{2}$$

where $a=e^{j2\pi m/q}$, q is the extension level and $m=0, 1,…q$-1. The columns and rows of C_1 denote symbols transmitted from three active sensors in two signaling intervals, respectively. C_1 is obtained from the Alamouti code using Equation (1) where

$$X = \begin{bmatrix} s_1 & s_2 \\ -s_2^* & s_1^* \end{bmatrix} \quad W = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & a \end{bmatrix}. \tag{3}$$

In this fashion, arbitrary number of the ECBSTBCs can be generated by increasing the extension level. For that reason, the fusion center needs $n+d$ feedback bits ($n \geq 3$) to select any possible ECBSTBCs where $d = \lceil (n-2)\log_2 q \rceil - 1$ (Eksim & Celebi, 2009b; Eksim, 2010b). n-2 feedback bits are needed to achieve full diversity as in Cooperative Balanced Space-Time Block Codes (CBSTBC) (Eksim & Celebi, 2007). The rest of the d+2 feedback bits provide additional coding gain.

The ECBSTBCs can be used in WSN. The ECBSTBC contains two phases: Measurement and cooperation. There are many measurement and cooperation phases respectively within a frame. Additionally, each frame includes an initialization phase. In the initialization phase, which occurs at the beginning of the each frame, the fusion center informs the active sensors about which ECBSTBC would be utilized within the frame using feedback channel. The selected code is fixed over one frame. In the measurement phase, each cooperating sensor makes two consecutive observation and binary quantization. The observation at each sensor is assumed to be Gaussian random variable with mean ±m and variance σ^2. In the cooperation phase of the ECBSTBCs, the fusion center receives the signal, r_D,

$$r_D = \sqrt{\frac{P}{N}} Ch_{rd} + n_D . \tag{4}$$

Here h_{rd} is the channel coefficient vector that contains path gains from the sensors to the fusion center, n_D is additive white Gaussian noise vector whose components are complex zero-mean with variance σ_D^2, P is the average total transmit power of the active sensors and C is the ECBSTBC matrix.

3.1 Three active sensors

Due to energy efficiency, when three sensors are active in the wireless environment, then, C_1, C_2 and C_3 are available ECBSTBC matrices. These matrices are

$$C_1 = \begin{bmatrix} s_1 & s_2 & as_2 \\ -s_2^* & s_1^* & as_1^* \end{bmatrix} C_2 = \begin{bmatrix} s_1 & s_2 & as_1 \\ -s_2^* & s_1^* & -as_2^* \end{bmatrix} C_3 = \begin{bmatrix} s_1 & as_1 & s_2 \\ -s_2^* & -as_2^* & s_1^* \end{bmatrix}. \tag{5}$$

Here a is the coefficient as defined previously. The fusion center selects the ECBSTBC C_j, $j=1,2,3$ and the feedback bit a that gives the maximum coding gain. In this case, two bits of feedback is needed to select the ECBSTBC matrices and k bit of is needed to select the feedback bit a where $k = \lceil \log_2 q \rceil$.

The decoding of the ECBSTBCs is similar to CBSTBCs (Eksim & Celebi, 2007). Assume that the C_1 matrix gives maximum coding gain. The received signals at fusion center are given as

$$r_{D,1} = \sqrt{\frac{P}{3}} \left[h_{r1d}\bar{r}_{1,1} + h_{r2d}\bar{r}_{2,2} + ah_{r3d}\bar{r}_{3,2} \right] + \eta_1$$

$$r_{D,2} = \sqrt{\frac{P}{3}} \left[-h_{r1d}\bar{r}_{1,2}^* + h_{r2d}\bar{r}_{2,1}^* + ah_{r3d}\bar{r}_{3,1}^* \right] + \eta_2. \tag{6}$$

Here $\bar{r}_{ri,j}$ is the observed data which includes observation and quantization noise by the ith active sensor at the jth symbol interval. Here η_1 and η_2 are noise at the fusion center. The fusion center estimates s1 and s2 by linear processing

$$\hat{s}_1 = h_{r1d}^* r_{D,1} + (h_{r2d} + ah_{r3d})r_{D,2}^*$$

$$\hat{s}_2 = (h_{r2d} + ah_{r3d})^* r_{D,1} - h_{r1d}r_{D,2}^* . \tag{7}$$

Substituting $r_{D,1}$ and $r_{D,2}$ in Equation (7),

$$\hat{s}_1 = \sqrt{\frac{P}{3}} \left[\left(\begin{array}{c} |h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2 \\ +2\max\left(\mathrm{Re}\{ah_{r2d}^* h_{r3d}\}, \mathrm{Re}\{ah_{r1d}^* h_{r3d}\}, \mathrm{Re}\{ah_{r1d}^* h_{r2d}\} \right) \end{array} \right) \right] s_1 + \varphi_1$$

$$\hat{s}_2 = \sqrt{\frac{P}{3}} \left[\left(\begin{array}{c} |h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2 \\ +2\max\left(\mathrm{Re}\{ah_{r2d}^* h_{r3d}\}, \mathrm{Re}\{ah_{r1d}^* h_{r3d}\}, \mathrm{Re}\{ah_{r1d}^* h_{r2d}\} \right) \end{array} \right) \right] s_2 + \varphi_2 \tag{8}$$

where φ_1 and φ_2 are the noise terms which include both observation and quantization noise at the active sensors and the noise at the fusion center. The contribution of the $2\max\left(\mathrm{Re}\{ah_{r2d}^* h_{r3d}\}, \mathrm{Re}\{ah_{r1d}^* h_{r3d}\}, \mathrm{Re}\{ah_{r1d}^* h_{r2d}\} \right)$ term in Equation (8) will always be positive and the gain will be greater than the sum of the magnitude squares of all path gains $\left(|h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2 \right)$. If the observation noise is very low, then, the diversity order

approaches to 3. It can be easily shown that the diversity order of the ECBSTBC approaches to n if n sensors are active when the observation noise is very low. A proof can be found in Appendix A.

4. Performance Evaluations

In the cooperative communication, transmitting only from selected relays is called distributed transmit antenna selection (DTAS) (Michalopoulos et al., 2008) which may be seen as an alternative approach to the ECBSTBCs. The criterion in selecting a single active sensor is the best instantaneous sensor-fusion center channel gain (Luo et al., 2005), and this is called as sensor selection (SS n:1) (Eksim & Celebi, 2009a; Eksim & Celebi, 2010a). To maximize signal-to-noise ratio (SNR) at the fusion center, two active sensors are chosen out of all active sensors and then the selected sensors transmit the received signals using the Alamouti scheme (Gore & Paulraj, 2002). In the simulations, the best active sensor pair which has the best instantaneous sensor-fusion center channel pair is selected. This is called as the sensor selection with Alamouti (SS n:2) (Eksim & Celebi, 2009a; Eksim & Celebi, 2010a).

The bit error probabilities of the ECBSTBC, SS, SS with Alamouti and statistical STBC cooperative diversity (Ohtsuki, 2006) are evaluated by computer simulations. A frame of 100 symbols is used. For meaningful comparison, the total transmission power and bandwidth are fixed, namely, the power is divided equally among cooperative active sensors. Each active sensor is assumed to observe either of two events H_0 and H_1 with equal probability. The observation at each sensor is assumed to be Gaussian random variable with mean $\pm m$ and variance σ^2. The noisy observation is quantized by the active sensors independently. Then, the quantized observation is transmitted according to selected transmission scheme.
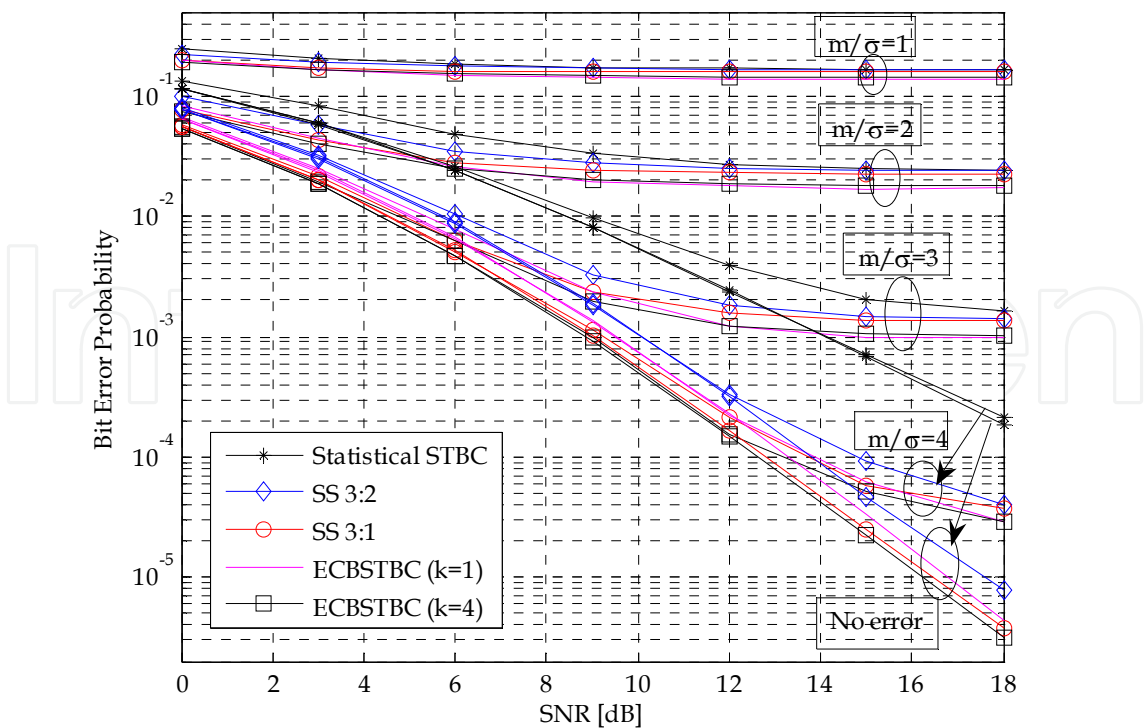

Fig. 3. The BER of three active sensors.

In Figure 3, the bit-error probability curves are shown for three active sensors. It is assumed that the ratio between the mean and the standard deviation of the observation in each active sensor (m/σ) is in the range of 1 and 4, and for comparison purposes no observation noise in each active sensor is also included in Figure 3. When m/σ is equal to 1 and 2, all transmission protocols give approximately similar performance since the observation noise limits the diversity gain. When m/σ is equal to 3, compared to the statistical STBC cooperative diversity (Statistical STBC), the SS with Alamouti's scheme (SS 3:2) provides an SNR advantage of approximately 3.73dB for a bit error rate (BER) value of P_b=2x10^{-3}. The SS scheme, the ECBSTBCs with one bit extension of feedback (ECBSTBC (k=1)), and the ECBSTBCs with four bit extension of feedback (ECBSTBC (k=4)) give additional 1.27dB, 1.77dB and 2.5dB SNR gains, respectively, compared to the SS with Alamouti's scheme. If the value of m/σ increases, the diversity order of the statistical STBC cooperative diversity approaches to 2. However, the limited feedback schemes´ diversity order approaches to 3.

In Figure 4, the bit-error probability curves are shown for four active sensors. It is assumed that the ratio between the mean and the standard deviation of the observation in each active sensor (m/σ) is in the range of 1 and 4. When m/σ is equal to 1, all transmission protocols give approximately similar performance. For m/σ is being equal to 2, the statistical STBC cooperative diversity (Statistical STBC), the SS with Alamouti's scheme (SS 4:2) and the SS scheme (SS 4:1) reach to an error floor at BER value of P_b=2.3x10^{-2}. On the other hand, the ECBSTBCs with one bit extension of feedback (ECBSTBC (k=1)) and the ECBSTBCs with four bit extension of feedback (ECBSTBC (k=4)) reach to an error floor at BER value of P_b=7.65x10^{-3} and P_b=5.97x10^{-3}, respectively. When m/σ is equal to 3, compared to the
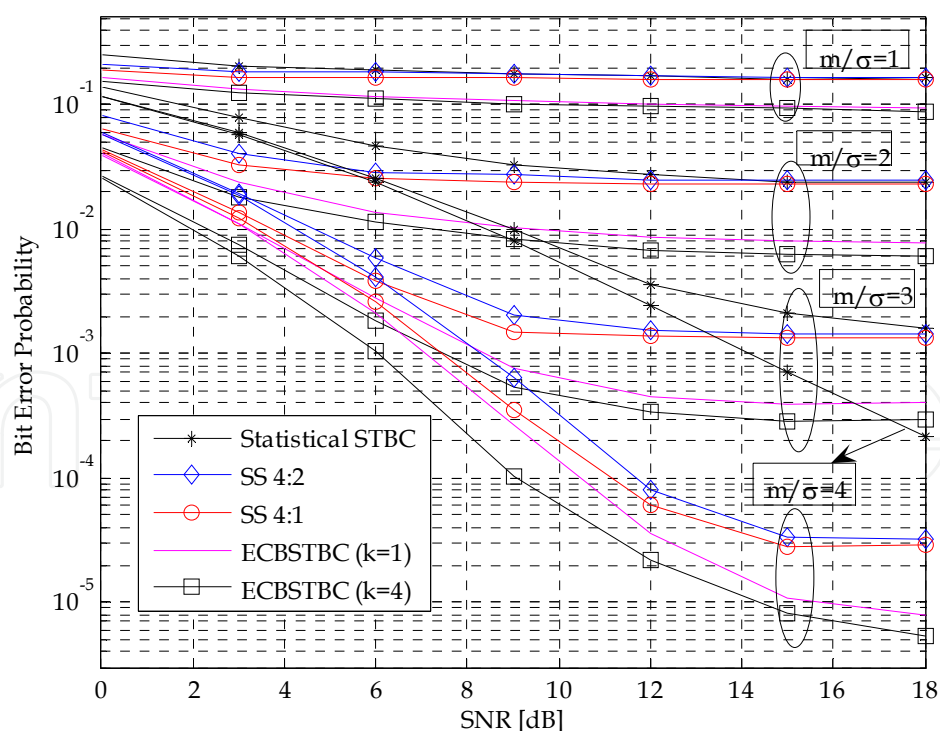

Fig. 4. The BER of four active sensors.

statistical STBC cooperative diversity, the SS with Alamouti's scheme (SS 4:2) provides an SNR advantage of approximately 6.26dB for a BER value of P_b=2x10^{-3}. The SS scheme (SS 4:1), the ECBSTBCs with one bit extension of feedback (ECBSTBC (k=1)) and the ECBSTBCs with four bit extension of feedback (ECBSTBC (k=4)) give additional 1.19dB, 2.54dB and 3.46dB SNR gains, respectively, compared to the SS with Alamouti´s scheme. When the value of m/σ increases, again, the diversity order of the statistical STBC cooperative diversity approaches to 2 because it utilizes only 2 active sensors. However, the diversity order of the limited feedback schemes approaches to 4.

In Figures 5-6, it is assumed that the sensor`s battery is limited. The linear battery model which is described in Section 2.1 is used. Four sensors are present in the wireless environment and all of them are active. It is assumed that the ratio between the mean and the standard deviation of the observation in each active sensor is equal to 3 (m/σ=3) and the sensors-fusion center channels´ SNR are 10dB. In Figure 5, four uniform sensor-fusion center channels are present in the wireless environment and their variances are equal to 1. Statistical STBC yields a BER value of P_b =7x10^{-3}. However limited feedback schemes such as the SS with Alamouti's (SS 4:2) and the SS (SS 4:1) yield BER values of P_b=1.8x10^{-3} and P_b=1.4x10^{-3}, respectively. The ECBSTBCs with one and four bit extension of feedback generate the BER values of P_b=5.74x10^{-4} and P_b=4.36x10^{-4}, respectively. Since the channels are uniform, all schemes sustain the QoS until the lifetime of the WSN.

In the Figure 6, two uniform, one "better" and one "worse" sensor-fusion center channels present in the wireless environment. The channel variances are 1, 10 and 0.1, respectively.
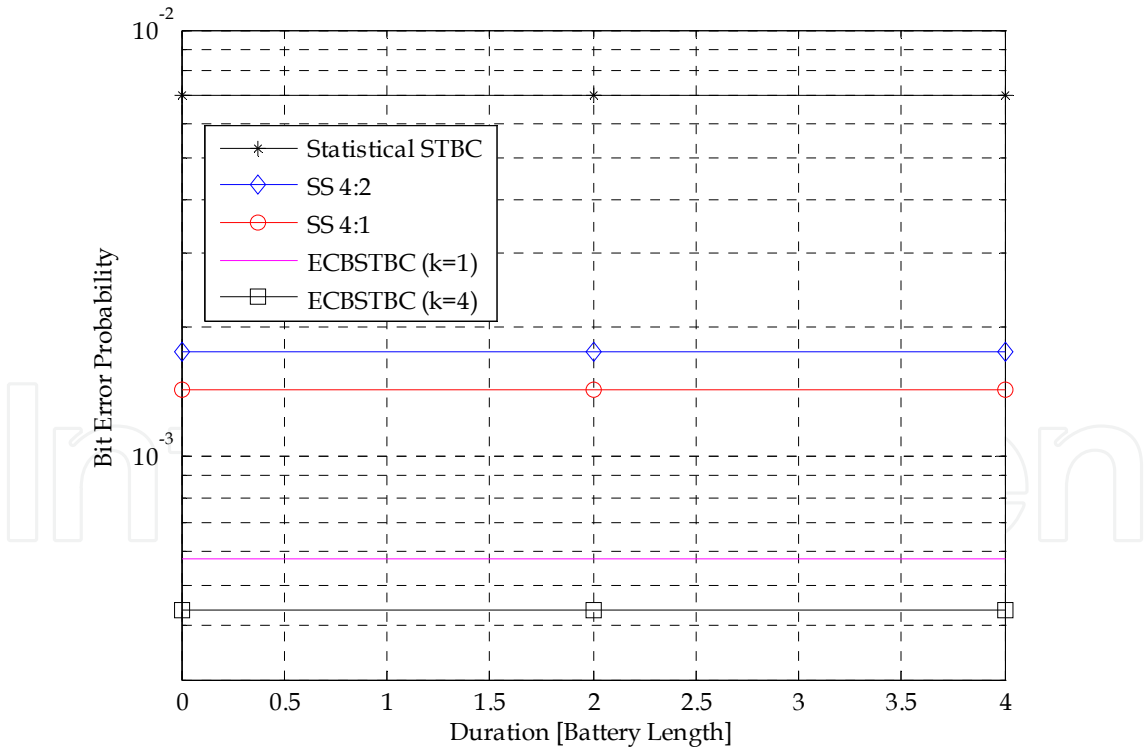

Fig. 5. The BER of four active sensors. The sensor-fusion center channels are 10dB and the parallel channels are uniform.

The SS scheme generally selects the active sensor which is present in the "better" sensor-fusion center channel. For this reason, the SS generates a BER value of P_b=1.3x10^{-3} until first sensor`s battery runs out. For this reason, the energy hole problem occurs. Then, the SS scheme generally selects two active sensors which are present in the uniform sensor-fusion center channels and the BER value increases to $P_b$=3.7x10$^{-3}$. Finally, the last active sensor`s battery runs out that is present in the "worse" sensor-fusion center channel. In this case, the BER value increases to P_b=0.1477. Due to the energy hole problem, similar scenario is valid for the SS with Alamouti's scheme. Statistical STBC generates a BER value of P_b=1.4x10^{-2}. The ECBSTBC with one and four bit extension of feedback result in BER values of P_b=1.2x10^{-3} and P_b=1.1x10^{-3}, respectively. In the non-uniform wireless parallel channels, the ECBSTBCs support QoS requirements until all sensors` batteries run out. This can be achieved via optimal distribution of transmission power among active sensors.

In Figures 7-8, four active sensors are present in the wireless environment and each active sensor transmits 1 feed forward bit to the fusion center (Eksim & Celebi, 2008). In this case, hybrid scheme which is proposed in (Eksim, 2010b) can be applied. This feed forward bit informs the fusion center that the observation noise at the active sensor is lower or higher according to a specified threshold value. When the active sensor´s observation noise is lower than the threshold, this active sensor will be selected for cooperation (Eksim, 2010b). When two active sensors observation noise is lower than the threshold, two active sensors employ Alamouti´s code to transmit their observations. If all active sensors observation noise is higher than the threshold, all active sensors are selected for cooperation. The selected ECBSTBC information is transmitted to the selected active sensors and they transmit their observations according to the selected ECBSTBC throughout the frame. Similar to the hybrid scheme, 1 feed forward bit can be utilized by the SS schemes. In this case, the SS schemes lead to lower BER values at the fusion center.
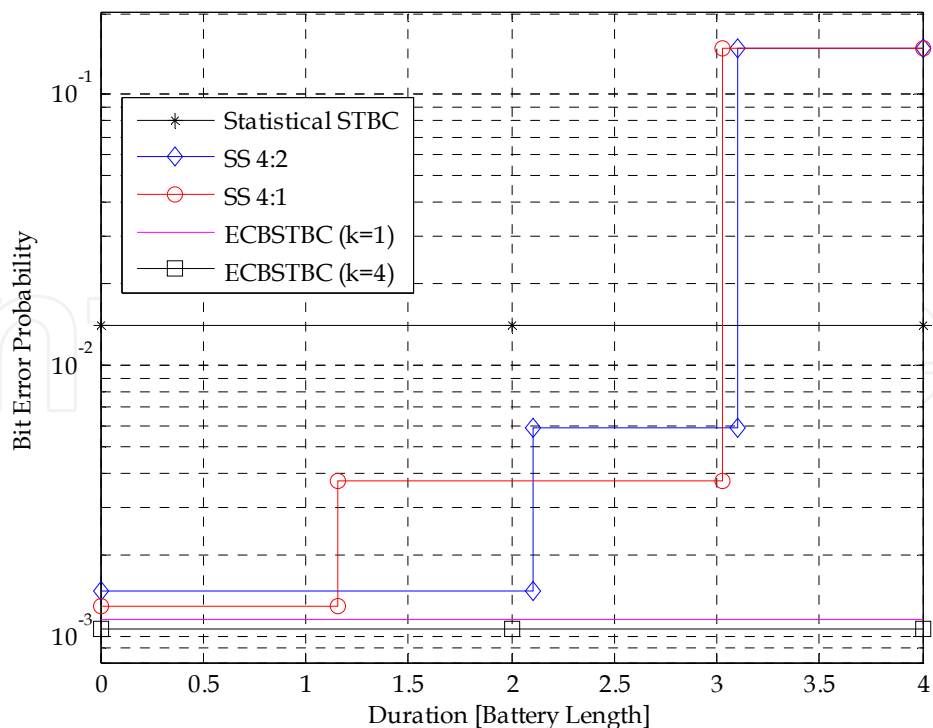

Fig. 6. The BER performances of four active sensors. The sensor-fusion center channels are 10dB and the parallel channels are non-uniform.

In Figure 7-8, it is assumed that the ratio between the mean and the standard deviation of the observation in each active sensor (m/σ) is equal to 2 and 3. In Figure 7, it can be observed that when m/σ is equal to 2, the statistical STBC cooperative diversity (Statistical STBC), the SS with Alamouti's scheme (SS 4:2) and the SS scheme (SS 4:1) reach to an error floor at BER value of P_b=2.3x10^{-2}. The ECBSTBCs with four bit extension of feedback (ECBSTBC (k=4)) reach to an error floor at the BER value of P_b =7.65x10^{-3}. On the other hand, the hybrid scheme with threshold 0.5m, not only the ECBSTBC with four bit extension of feedback (ECBSTBC (k=4, Th=0.5m)) but also the SS scheme (SS 4:1 (Th=0.5m)) and the SS scheme with Alamouti (SS 4:2 (Th=0.5m)) have error floors at lower BER values. In Figure 8, it can be observed that when m/σ is equal to 3, the statistical STBC cooperative diversity (Statistical STBC), the SS with Alamouti's scheme (SS 4:2) and the SS scheme (SS 4:1) cannot reach to the BER value of P_b =1x10^{-3}. The ECBSTBCs with four bit extension of feedback (ECBSTBC (k=4)) reach to an error floor at BER value of P_b =3x10^{-4}. On the other hand, the hybrid scheme with threshold 0.4m, the ECBSTBC with four bit extension of feedback (ECBSTBC (k=4, Th=0.4m)), the SS scheme (SS 4:1 (Th=0.4m)) and the SS scheme with Alamouti (SS 4:2 (Th=0.4m)) do not reach to an error floor even if signal-to-noise ratio is equal to 18dB.
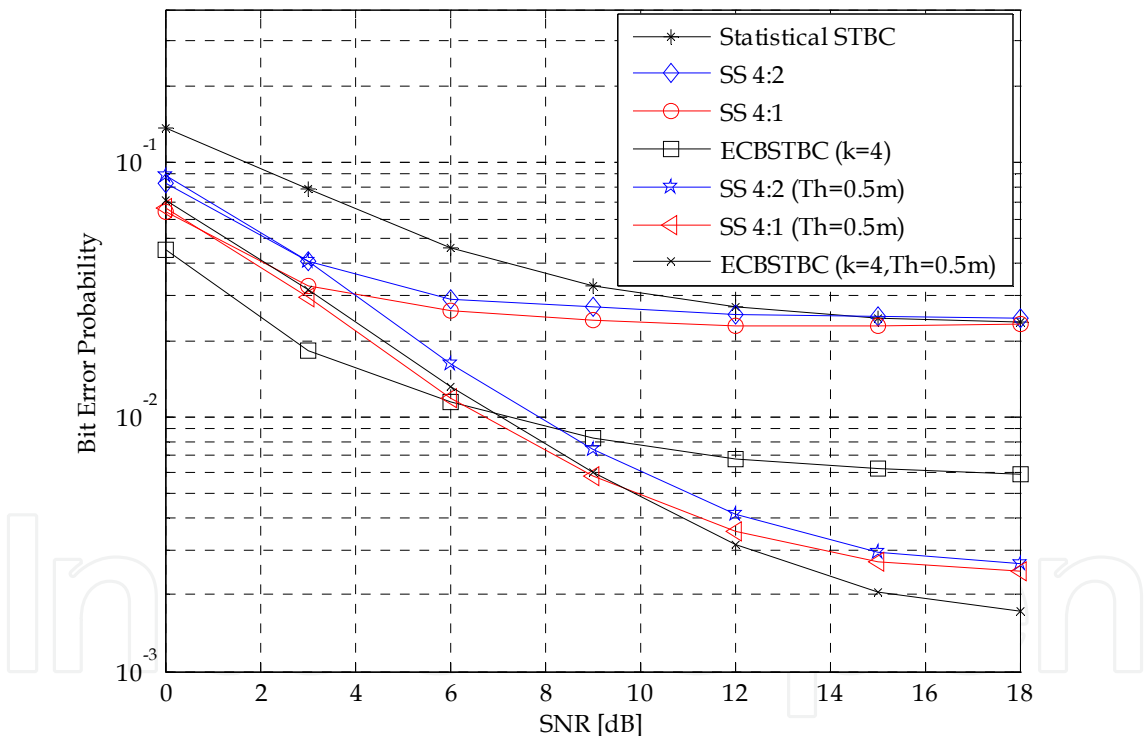

Fig. 7. The BER of four active sensors when m/σ=2.

5. Conclusions

In this chapter, methods increasing reliability of communications in WSNs are suggested. They are based on statistical cooperative diversity generating space-time block codes with limited feedback. It is shown that both SS schemes and ECBSTBC improve the performance of the statistical STBC with limited feedback, but the ECBSTBC have better signal-to-noise

ratio improvement compared to the SS schemes. Binary quantization is used and the quantization and the observation noise are taken into account. It is well known that the observation noise limits the BER performance. To diminish the effects of the observation noise, the ECBSTBC combined with SS scheme is proposed to improve the BER performance (Eksim, 2010b). This hybrid technique yields improved performance at the fusion center compared to solely using the ECBSTBC or the SS methods.

It is always assumed that when all of the sensor-fusion center channels are uniform or the sensors have unlimited battery. Then, the energy hole problem does not occur in WSN. This situation cannot be realized all the time in wireless environment and the energy hole problem occurs if the SS schemes are utilized. This problem is very significant in WSNs, since, in that case, the QoS cannot be maintained during the network lifetime. As opposed to the SS schemes, the ECBSTBC is a useful tool to alleviate the energy hole problem inherently. Since the ECBSTBC utilizes all active sensors to distribute transmission power among active sensors evenly when all active sensors present in non-uniform wireless channels.
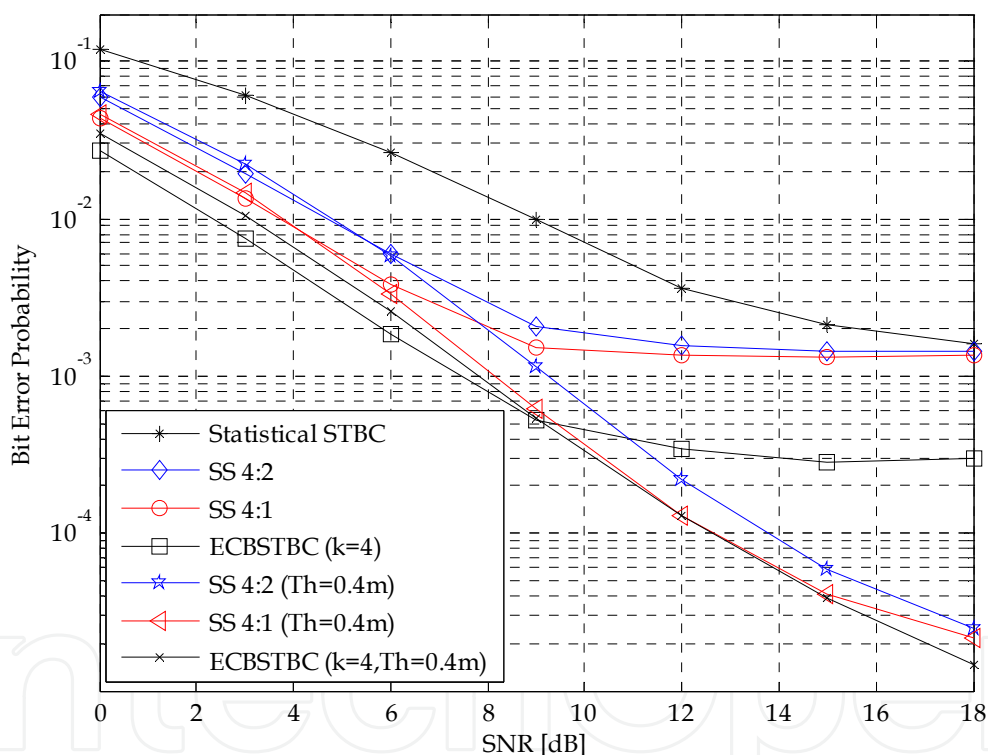

Fig. 8. The BER of four active sensors when m/σ=3.

6. Acknowledgement

Appendix A: Derivation of BER Upper Bound for ECBSTBC and Diversity

When three sensors are active, the value of m/σ is high and BPSK is used modulation scheme; Instantaneous signal-to-noise ratio at the fusion center, SNR_{fc}, can be written as follows

$$SNR_{fc} = SNR \frac{\left(|h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2 + 2\max\left(\text{Re}\left\{ah_{r2d}^* h_{r3d}\right\}, \text{Re}\left\{ah_{r1d}^* h_{r3d}\right\}, \text{Re}\left\{ah_{r1d}^* h_{r2d}\right\}\right)\right)^2}{3\left(|h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2\right)} \tag{A.1}$$

Here $SNR = E_b/N_o$ is the signal-to-noise ratio per bit without fading. To find an upper bound, Equation (A.1) can be re-written as follows

$$SNR_{fc} \geq \frac{SNR}{3}\left(|h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2\right) \tag{A.2}$$

The bit error probability of BPSK is given in (Proakis, 2001).

$$P_b = Q\left(\sqrt{2SNR}\right) \tag{A.3}$$

where $Q(x)$ is the Q-function. Then, Put Equation (A.2) in place of Equation (A.3), the bit error probability is upper bounded by Q-function.

$$P_b \leq Q\left(\sqrt{2\frac{SNR}{3}\left(|h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2\right)}\right) \tag{A.4}$$

As it is well-known, the Q-function is upper bounded with exponential, thus, the BER can be upper bounded as follows

$$P_b \leq \exp\left(-\frac{SNR}{3}\left(|h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2\right)\right) \tag{A.5}$$

The BER upper bound averaged over channel statistics is given as

$$P_b \leq E\left\{\exp\left(-\frac{SNR}{3}\left(|h_{r1d}|^2 + |h_{r2d}|^2 + |h_{r3d}|^2\right)\right)\right\}. \tag{A.6}$$

Since the fading statistics h_{r1d}, h_{r2d} and h_{r3d} are independent; Equation (A.6) can be written as follows

$$P_b \leq E\left\{\exp\left(-\frac{SNR}{3}|h_{r1d}|^2\right)\right\} E\left\{\exp\left(-\frac{SNR}{3}|h_{r2d}|^2\right)\right\} E\left\{\exp\left(-\frac{SNR}{3}|h_{r3d}|^2\right)\right\}. \tag{A.7}$$

Evaluating Equation (A.7), we obtain the BER upper bound at the fusion center

$$P_b \le \left(\frac{3}{(SNR + 3)} \right)^3 . \tag{A.8}$$

Above equation can be expanded to arbitrary number of active sensors, thus, the BER upper bound for n active sensors is given as

$$P_b \le \left(\frac{n}{(SNR + n)} \right)^n . \tag{A.9}$$

From Equation (A.9), the diversity is n when the value of m/σ is high.

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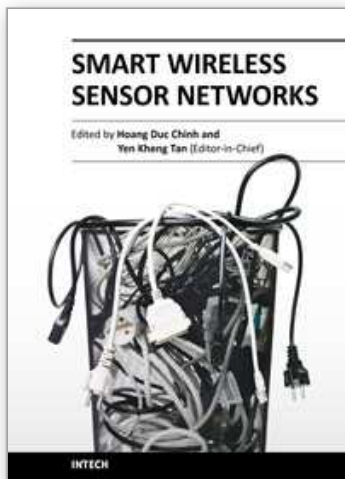
Smart Wireless Sensor Networks

Edited by Yen Kheng Tan

The recent development of communication and sensor technology results in the growth of a new attractive and challenging area â€" wireless sensor networks (WSNs). A wireless sensor network which consists of a large number of sensor nodes is deployed in environmental fields to serve various applications. Facilitated with the ability of wireless communication and intelligent computation, these nodes become smart sensors which do not only perceive ambient physical parameters but also be able to process information, cooperate with each other and self-organize into the network. These new features assist the sensor nodes as well as the network to operate more efficiently in terms of both data acquisition and energy consumption. Special purposes of the applications require design and operation of WSNs different from conventional networks such as the internet. The network design must take into account of the objectives of specific applications. The nature of deployed environment must be considered. The limited of sensor nodesâ€™ resources such as memory, computational ability, communication bandwidth and energy source are the challenges in network design. A smart wireless sensor network must be able to deal with these constraints as well as to guarantee the connectivity, coverage, reliability and security of networkâ€™s operation for a maximized lifetime. This book discusses various aspects of designing such smart wireless sensor networks. Main topics includes: design methodologies, network protocols and algorithms, quality of service management, coverage optimization, time synchronization and security techniques for sensor networks.

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