A SCALABLE COMMUNICATION ARCHITECTURE FOR THE SENSOR BROADCAST PROBLEM

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ABSTRACT

In our previous work, a time efficient data retrieval method was proposed for distributed data sources using the generalized group testing approach. In this work, we provide the physical-layer transmission and reception strategy that supports the implementation of the group testing method. The integration of the two protocols leads to a modified strategy that incorporates the errors occurring within the feedback channel. We propose a signal modulation scheme combined with the source and channel coding that was proposed using the concept of group testing. The numerical simulations show an improved performance with the proposed cooperative broadcasting scheme. Our methodology does not separate channel and source coding and can be implemented with a two layer architecture with low complexity.

1. INTRODUCTION

Standard communication and data compression models have been proven to be ineffective in solving the network broadcast problem when the number of sensors increases in the network [1]. In fact, in a shared medium, sensors' exchange of local information leads to either congestion or excessive interference. Expanding our previous work [2–5], we establish, in this paper, the physical layer transmission protocol that is suitable for the data exchange of a large scale sensor network.

In [3–5], we proposed a new class of multiple access methods for data exchange by generalizing the concept of group testing. We referred to these methods as the Group Testing Multiple Access (GTMA) schemes. GTMA allows the sensors with identical observations to share the same transmission time slot, thus, reducing the total number of channel accesses when the local observations are highly correlated. In fact, we have shown that, for relevant data models [3–5], GTMA requires a number of channel accesses that scales in the order of the joint entropy of the sensor observations, when the number of sensors increases. With GTMA, we are able to provide a combined solution for both the data transport problem and the data compression problem. As opposed to distributed source coding (DSC) schemes [6], GTMA achieves compression gains without encoding over the temporal dimension, thus, avoiding the large latency of DSC methods due to long codewords and the sequential decoding structure. More importantly, GTMA helps defining a novel architecture specifically tailored to sensor networks, which includes the *sensing layer*, *data collection layer* and *physical transmission layer* as shown in Fig. 1. In fact, the GTMA protocol proposed in [3–5] has exclusive exchanges of control information from the data collection functionality and feedback information from the physical layer functionality.

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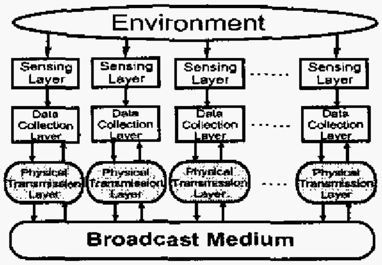


Fig. 1. Illustration of the data distribution structure.

In the specific strategies proposed in [3–5], the physical layer receiver was assumed to be able to decode, without error, the logic OR of individual boolean feedbacks from all nodes. The goal of this paper is to describe a complete physical layer architecture that is compatible with this model and that also incorporates noise and errors that arise in practice. We consider two options: (1) direct transmission links between each transmitting and receiving sensor; and (2) cooperative physical layer broadcasting, *i.e.* a revised version of the distributed cooperative technique which we call the Opportunistic Large Array (OLA) [2].

Prior to describing the physical layer, we first give a brief description of the GTMA strategy and specify the tree splitting algorithm that we will use throughout this work.

2. GROUP TESTING MULTIPLE ACCESS

Consider the set of sensors $\mathcal{S} = \{s_0, \cdots, s_{N-1}\}$ with binary observations $\mathbf{X} = [X_0, \cdots, X_{N-1}]$ (*i.e.* $X_i \in \{0, 1\}$ is the observation made by sensor s_i). The goal of GTMA is to design the scheduling and the transmission strategies of the sensors such that *the observation at each individual sensor is efficiently distributed to all the other sensors in the network.*

Assume that the binary field consists of large patches of 0's and large patches of 1's, such as the example shown in Fig. 5. In this case, a group of contiguous sensors will likely observe the same bit of information. As opposed to TDMA, which allocates a distinct channel to each individual sensor, GTMA allocates a single transmission period to a group of sensors with size greater or equal to 1. The scheduled transmissions in GTMA strategies are analogous to the testing of groups in classical group testing [7].

Specifically, let there be two orthogonal channels allocated for the transmission of each sensor group and let $U \subset \mathcal{S}$ be the group

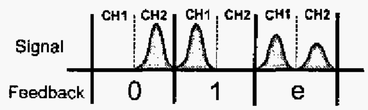


Fig. 2. The illustration of the responses that correspond to each feedback information.

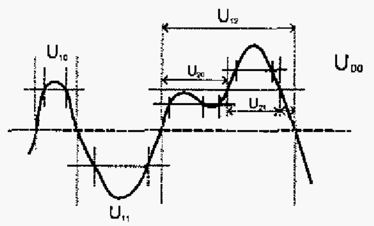


Fig. 3. Group Testing with multiple levels of quantization.

of contiguous sensors that is scheduled to transmit at the present time slot. In the first channel (CH1), all the nodes that observed 1 within the group U will emit their signals simultaneously which will form a positive signalling in CH1 if there is at least one sensor within the group that observed the symbol 1; otherwise, the channel will remain silent. Similarly, all nodes that observed 0 will respond in channel 2 (CH2). If the observations of the sensors in U are identical, only one channel will have a positive response and the feedback that is formed will be either 0 or 1, as shown in Fig. 2. However, if the observations of the sensors consists of different values, the feedback will result in an *erasure* (*i.e.* the e feedback shown in Fig. 2) and a subgroup of the sensors will be required to retransmit in the following time slot. By successively refining the size of the transmitting groups, the transmission will eventually be successful and a new group can be scheduled for the next transmission. Suppose that all the sensors have noiseless access to the two channels, the feedback given through the channel will provide each sensor with sufficient knowledge to determine the next test that is defined by the GTMA protocol and eventually allow each sensor to reconstruct the entire sensor field at its local site.

Suppose the sensor observes a deterministically smooth and continuous field quantized with B bits of information, *i.e.* $X_i = [b_0, b_1, \cdots, b_{B-1}]$ where $b_l \in \{0, 1\}$. With low spatial frequency or high sensor density, we shall expect large sets of close-by sensors to observe identical symbols at the most significant bit (b_0), such as the groups U_{10}, U_{11} and U_{12} shown in Fig. 3. Since the groups consist of contiguous sensors, the sensor field corresponding to the area of these groups are also smooth and continuous.Therefore, one can impose a similar group testing scheme on each of these individual groups. With the methodology that efficiently acquires information from a binary sensor field, we can iterate this procedure to determine the bits of the quantized samples in the order of significance.

In the following, we introduce the tree splitting protocol with the 0, 1, e feedback as a special case of group testing.

2.1. Tree Splitting Protocol with 0, 1, e feedback

In the tree splitting protocol, we initiate the process by scheduling a transmission on the group $U \equiv S$. When the feedback results is an erasure, the tested group will be divided into two sub-

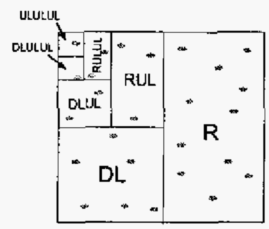


Fig. 4. The location-based splitting of tested groups.

groups where each subgroup is transmitted separately in the subsequent transmission periods. The splitting process continues until the feedback is either 0 or 1 in which case the content of their observations are resolved and the smallest group (defined through the previous splitting) that is not yet resolved is scheduled to transmit in the subsequent time slot. The set of groups constitute a binary tree where each parent node has two children nodes that represent the two divided subgroups as mentioned above. In this case, each node within the tree represents a group that contains all sensors within its own subtree. The scheduling of group transmissions are governed by the tree structure and the feedbacks. These are the functionalities that are referred to by the data collection layer.

In practice, the splitting of groups can be performed according to the location of the sensors. More specifically, let the set of sensors S be randomly distributed within the $d \times d$ square area and let the sensors be grouped in the order shown in Fig. 4. When the initial group S results in an erasure, we first split the network into the (L)eft and (R)ight groups according to their locations by equally partitioning the square area. If the testing of group L results in an erasure, we split the L group into the (U)p-L group and (D)own-L group and test each of them individually in the subsequent periods. However, if the feedback is either 0 or 1, we proceed on testing the next smallest group that is not yet resolved which is R in this case. Assuming that the feedbacks continue to be erasures, we proceed on splitting the nodes, as shown in Fig. 4, into the Left of UL and Right of UL, then Up of LUL and Down of LUL ... *etc.*

The advantage of the proposed algorithm is that no knowledge of the sensor field is required at the sensors, nor is the location of other sensors.

3. PHYSICAL TRANSMISSION MODEL

In GTMA, each tested group of sensors are allocated a distinct transmission period in which they convey their collective feedback, as shown in Fig. 2. By ensuring a reliable distribution of the feedback, each sensors will be able to reconstruct the entire sequence of observations. In this section, we consider two options for the physical transmission layer: (1) the Non-Cooperative Transmission scheme; and (2) the Cooperative Transmission scheme. Both of these strategies are realized with a simple on-off pulse transmitter and an energy detector at each individual receiver.

3.1. Non-Cooperative Transmission

Assume that the allocated transmission period of each test is synchronized among sensors[1] and that each sensor $s_i \in S$ has knowl-

[1]The synchronization can be obtained by using the distributed synchronization protocol proposed in [8].

edge of their own location. For each tested group of sensors U, we allocate two channels using the orthogonal waveforms $p_1(t)$ and $p_2(t)$, *e.g.* the orthogonal FSK with $p_1(t) = e^{j2\pi ft}$ and $p_2(t) = e^{j2\pi(f+k/2T)t}$, where T is the duration of each transmission period. For each sensor $s_j \in U$, a signal

$$a_j(t) = X_j p_1(t) + \bar{X}_j p_2(t) \quad (1)$$

is transmitted according to the observation X_j and its complement $\bar{X}_j$. Without transmitter cooperation, each sensor $s_i \in \mathcal{S}$ receives the mixture of signals emitted directly from the sensors in U. Denoting by $\langle a(t), b(t)\rangle$ the inner product between the two functions $a(t)$ and $b(t)$, in AWGN, a sufficient statistic for the observation is given by

$$\mathbf{r}_i = [\langle r_i(t), p_1(t)\rangle, \langle r_i(t), p_2(t)\rangle] = [r_{i1}, r_{i2}] \quad (2)$$

$$= \left[\sum_{\substack{k\neq i:\\ s_k\in U}} \frac{h_{ik}}{d_{ik}} X_k e^{-jd_{ik}/c} + n_{i1}, \sum_{\substack{k\neq i:\\ s_k\in U}} \frac{h_{ik}}{d_{ik}} \bar{X}_k e^{-jd_{ik}/c} + n_{i2}\right]$$

where h_{ik} is the Rayleigh fading coefficient between s_i and s_k, d_{ik} is the distance, c is the speed of light and n_{i1}, n_{i2} are additive white gaussian noise with variance $N_o/2$.

For a sensor $s_i \in U$ such that $X_i = 1$, it is sufficient to apply the detection only upon the signal received within channel 2 since the sensor itself has transmitted in channel 1. Therefore, the sensor need only to distinguish between the following two hypotheses:

$$\begin{array}{ll} H_1: & r_{i2} = n_{i2} \\ H_{e1}: & r_{i2} = \sum_{k\neq i: s_k\in U} \frac{h_{ik}}{d_{ik}} \bar{X}_k e^{-jd_{ik}/c} + n_{i2} \neq n_{i2}. \end{array} \quad (3)$$

Similarly, for sensor $s_i \in U$ such that $X_i = 0$, the two hypotheses are $H_{e0}: \exists X_j = 1$ for some $s_j \in U$ and $H_0: X_j = 0$ for all $s_i \in U$. However, for sensors that do not belong to the tested group, the detection must be imposed on both transmission channels, resulting in the four hypotheses: H_0, H_1, $H_e \equiv H_{e0} \cup H_{e1}$ and $H_{null} \equiv H_{e0}^c \cup H_{e1}^c$, where H_0, H_1 and H_e correspond to the 0, 1, e feedback shown in Fig. 2 while the event H_{null} occurs when the tested area, chosen from the location-based strategy, does not contain any sensor. In this case, an additional source of error may occur between H_0 and H_1 or between $\{H_0, H_1, H_e\}$ and H_{null} due to missed detection of signals. When an error resulting in the decision on H_{null} occurs, a random decision is taken between 0 or 1 for sensors within the tested group.

Consider a sensor field which is deterministic and unknown, and that the channel gains h_{ik} and distances d_{ik}, for all i, k, are fixed throughout the transmission of one observation sequence. We adopt the simple energy detector to detect the presence of the signal within channel 2. The energy detector [9] is optimal for the case of detecting deterministic and unknown signals in additive white gaussian noise. Therefore, the decision rule is defined as follows:

$$Z = \mathcal{D}(\mathbf{r}|s_i \in U, X_i = 1) = \begin{cases} e & \text{for } \|r_{i2}\|^2 > \tau \\ 1 & \text{otherwise.} \end{cases} \quad (4)$$

where Z is the feedback received and τ is the threshold chosen with respect to the desired false alarm probability. Similarly, one can utilize the same detection strategy on r_{i1} to solve the detection problem for tested sensors that observed $X_i = 0$.

Consider the case where $s_i \notin U$. In this case, the optimal decision rule for the hypothesis testing is $Z = \mathcal{D}(\mathbf{r}_i|s_i \notin U) = \max_{a=0,1,e,null} \Pr\{H_a|\mathbf{r}_i\}$. However, to simplify the receiver structure, we approximate the optimal decision rule by utilizing the same detection rule as shown in (4) for both transmission channels. The combined detection rule is

$$\mathcal{D}(\mathbf{r}|s_i \notin U) = \left(\mathbf{1}_{\{L(r_{i1})>\tau\}}, \mathbf{1}_{\{L(r_{i2})>\tau\}}\right),$$

where $\mathbf{1}_{\{.\}}$ is the indicator function. The outputs $(0,1)$, $(1,0)$ and $(1,1)$ correspond to the 0, 1, e feedback described in Section 2. $(0,0)$ indicates the case that no sensor resides in the tested area, *i.e.* the null case.

3.2. Cooperative Transmission

In the non-cooperative transmission scheme, sensors broadcast their local response by transmitting a signal directly to all the other sensors through the wireless broadcast medium. At the receiver, an aggregate signal waveform is received with which the desired feedback information is obtained. In this case, the sensors must transmit with a sufficiently large power in order to achieve a reliable reception, which limits the application to sensors located in a small area. In fact, in the worst case scenario, one node may have to the detect the presence of a signal from the node farthest away in order to receive correctly the feedback, in which case the power necessary to reliably communicate the information is prohibitive. Hence, a cooperative form of information delivery would clearly provide an advantage over the non-cooperative scheme. Given that the feedback from each test is only a two-bit information, it is particularly important in this context to avoid the heavy duty networking and MAC protocols used in packet networks. Hence, we propose a cooperative transmission scheme based on what we called the Opportunisitc Large Array (OLA) [2], which is consistent with our architecture in Fig. 1.

Let U be the group of sensors tested in the present transmission period and let $U_0 \equiv \{s_i \in U : X_i = 0\} \subset U$. Similarly, let $U_1 \equiv \{s_i \in U : X_i = 1\}$. The transmission is initiated by having each sensor $s_i \in U$ transmit a signal as in (1). In this case, the group of sensors U_1 will serve as the leaders of the cooperative broadcast in channel CH1 while the group U_0 are leaders in channel CH2. Each cooperative broadcasting is operated independently in the two channels as described in the following. Let's consider, w.l.o.g., the aggregate signal received in CH2 after the transmission of the leaders U_0, *i.e.* for receiver $s_i \in \mathcal{S} - U_0$,

$$r_{i2}^{(1)} = \sum_{k:s_k\in U_0} \frac{h_{ik}}{d_{ik}} e^{-jd_{ik}/c} + n_{i2}. \quad (5)$$

This signal is equivalent to the received signal in the non-cooperative scheme. Based on the received signal, each receiver performs a Neyman-Pearson detection to determine the presence or absence of a transmitted pulse, *i.e.* the decision at sensor s_i is $\mathcal{D}(r_{i2}^{(1)}) = \mathbf{1}_{\{\|r_i(t)\|^2\geq\tau\}}$ where τ is the optimal decision threshold determined through the given false alarm probability. At this point, the performance of the system is equivalent to the non-cooperative scheme. However, instead of determining the feedback information based on the present decision, we let each sensor that detected the presence of a pulse to relay the information by retransmitting the same pulse. This set of sensors are defined as

$$L_1 \equiv \{s_i \in \mathcal{S} - U_0 : \mathcal{D}(r_i^{(1)}(t)) = 1\}.$$

The retransmission of the relaying nodes will then increase the energy of the received signal at the nodes that have not yet detected the pulse, *i.e.* for $s_i \in \mathcal{S} - U_0 - L_1$,

$$\begin{aligned} r_{i2}^{(2)} &= \sum_{k:s_k \in U_0} \frac{h_{ik}}{d_{ik}} e^{-jd_{ik}/c} + \sum_{m:s_m \in L_1} \frac{h_{im}}{d_{im}} e^{-j(d_{im}/c+\delta)} + n_{i2} \\ &\approx \sum_{m:s_m \in L_1} \frac{h_{im}}{d_{im}} e^{-j(d_{im}/c+\delta)} + n_{i2} \end{aligned} \quad (6)$$

where δ is the processing time of the first detection. In this case, the signal received from the source are negligible compared to the relaying signals and the newly informed sensors form a second layer of relay, *i.e.*

$$L_2 = \{s_i \in \mathcal{S} - U_0 - L_1 : \mathcal{D}(r_i^{(2)}(t)) = 1\}.$$

Continuing in this fashion, the retransmission of the relaying nodes will cause an avalanche of signalling that will spread the feedback throughout the entire network (given that the power of the transmission or the density of the sensors are sufficiently large [2]). The signal received by nodes in the l-th layer is approximately

$$r_{i2}^{(l)} \approx \sum_{k:s_k \in L_{l-1}} \frac{h_{ik}}{d_{ik}} e^{-j[d_{ik}/c+(l-1)\delta]} + n_{i2}.$$

However, if no pulse is detected by any of the receiving sensors, it is assumed that U_0 is an empty set and the test will proceed on a subsequently chosen group. The aggregate signal strength of both the sources and the relays provide the receiver with a reliable detection of the feedback information while maintaining the low latency of a symbol-based transmission system.

For an appropriately chosen false alarm probability and a sufficiently dense network, we can assume that the detection probability will be approximately equal to 1. Even when a false alarm occurs during the channel for which a source was in fact transmitting, the false alarm will not alter the received feedback information. However, when a false alarm occurred when no sensors were originally transmitting, the false detection will propagate throughout the network, causing an error in determining the subsequent group tests. In order to detect this error and the error that exists in the non-cooperative case, we introduce, in the following section, a simple error detection to increase the reliability of the resolved sequence of observations.

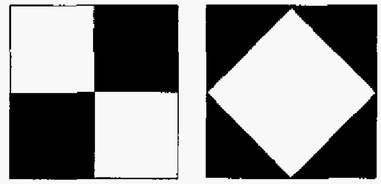
Remark 1 *In general, group testing protocols often determine their subsequent group tests based on the previously received feedbacks. In this case, the detection performance can be further improved by considering the correlation of the observations through the knowledge of previous feedbacks, i.e.* $Z_l = \mathcal{D}(r_i(t)|Z_0, \cdots, Z_{l-1})$. *However, the tree splitting protocol is a special case of the group testing protocols where the sequence of tests do not depend on the stochastic knowledge of the sensors field, therefore, we do not consider the feedback information in the decision rules shown in this section.*

4. ERROR DETECTION WITH GROUP TESTING

In designing the data collection protocol as done in [3–5] and Section 2, we utilized the concept of group testing to define the control and feedback information required to effectively schedule the collective transmission of sensor observations. However, it is clear from our physical layer model that feedback errors may occur in practice. These errors will cause erroneous state transitions within the group testing process, thus, propagating the error over the selection of subsequent tests. To overcome this effect, we impose an error detection bit after every m feedback transmissions and reiterate the corresponding sequence of group tests whenever an error is detected. Although a more complicated forward error correction strategy can be imposed, the simplicity of the following scheme allows us to illustrate the effectiveness of our physical layer transmission strategy.

Considering the 0, 1, e feedback system and the transmission protocol shown in Section 3, it is easy to see that the dominant errors occur between the symbols 1 and e, or between 0 and e. Therefore, after a sequence of m feedback transmissions, we let each sensor calculate the even parity of their erasure feedbacks within the block of m symbols, *i.e.* each sensor transmits a 0 if there is an even number of e's, otherwise, it transmits 1. Similarly, the parity transmission results in the 0, 1, e reception where the e outcome indicates the existence of an erroneous sensor. The block size m can be chosen to adapt to the error probability of the physical transmission strategy. More specifically, m is small for the non-cooperative case, where the error probability is higher compared to the cooperative case.

In general, higher dimensional error correction codes can be appended to every block of feedbacks to implement forward error correction capabilities. For example, by allowing the appended symbols to correct the earliest error within the block, one can recover from the erroneous state transitions if the subsequent symbols were received correctly. Even when an ambiguity occurs in the subsequent sequence of feedbacks, a maximum likelihood decoder can be implemented to obtain the optimal reconstruction, much like the well-known Viterbi decoder. A more complete discussion on the error correction coding for GTMA is beyond the scope of this paper and will be the focus of our future work.



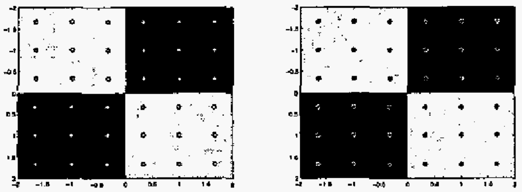
(a) (b)

Fig. 5. The illustration of the deterministic binary field.

5. PERFORMANCE EVALUATION

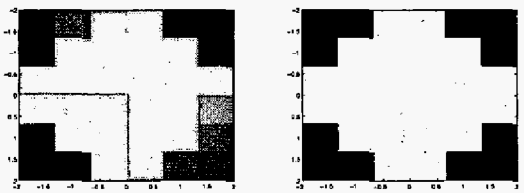
Consider the case where N sensors are distributed in a regular grid within a $d \times d$ square area. In our experiments, we consider two examples of the binary field as shown in Fig. 5, where each sensor observes the local binary information according to the illustrated figures. The field described in Fig. 5(a) is ideal for the location-based splitting as defined in Fig. 4 since the partitioning of the area is consistent with the realization of the sensor field. In this case, the number of tests necessary to resolve the field is equal to 7. However, the field illustrated in Fig. 5(b) requires a much higher number tests which depends on the distribution of the sensors.

In the first experiment, we look at a network of $N = 36$ sensors where the sensors are distributed in a 6-by-6 regular grid as shown in Fig. 6. Let each sensor observe its local information ac-



(a) Non-Cooperative (b) Cooperative

Fig. 6. The reconstruction of the field using no error detection when detecting the field shown in Fig. 5(a).

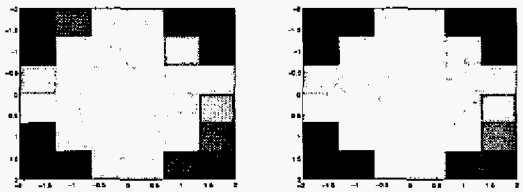


(a) Non-Cooperative (b) Cooperative

Fig. 7. The reconstruction of the field using no error detection when detecting the field shown in Fig. 5(b).

cording to the image shown in Fig. 5(a). In Fig. 6, we show the performance of the non-cooperative and cooperative transmission schemes using the receiver model specified in Section 3. The channel coefficients, h_{ij} for all i and j, are assumed to be independent Rayleigh coefficients with variance 1, which are randomly determined for each trial but fixed over different experiments. In this simulation, we set the noise variance $N_o = 0.002$ and the detection threshold $\tau = 0.01$. Through the sequence of feedbacks, each sensor will have a local reconstruction of the sensor field degraded by the channel errors. In Fig. 6, the reconstruction, with no error detection, is illustrated in a gray scale image with each block representing the average reconstruction over all sensors and over 10 different sets of channel coefficients. We can see that both schemes perform relatively well, however, the cooperative case is slightly better than the non-cooperative case. The average number of tests required for the cooperative scheme is 9 while 11 is required for the non-cooperative scheme, indicating a higher error probability in the latter case. However, if a larger number of tests are required for the detected image, as it is for Fig. 5(b), a significant difference may be observed between the two schemes due to the error propagation that results from the sequential selection of group tests. This effect is shown in Fig. 7 for $N_o = 0.001$, which shows that the cooperative scheme provides us with a much more reliable transmission channel than the non-cooperative scheme without sacrificing the latency necessary in packet networks.

In order to overcome the error effect, we impose an even parity bit for the *erasure* feedback after every block of $m = 4$ symbols. For the example shown in Fig. 7, we show, in Fig. 8, the performance of the error detection scheme for the limited number of retransmissions ReTX= 10 and 1000, and for $N_o = 0.001$. We assume that the parity bit is received without error[2]. We see that a simple error detection strategy combined with retransmissions



(a) ECC, ReTX= 10 (b) ECC, ReTX= 10^3

Fig. 8. The reconstruction of the sensor field is shown for $N = 36$ and parity bit every $m = 4$ symbols.

can significantly improve the average reconstruction performance as shown in Fig. 8. However, the number of channel accesses also increases significantly, *e.g.* an average of 293.1 and 9317.9 transmissions are required for the cases ReTX= 10 and 1000, as opposed to 45 for the noiseless case. We note that the improvement between the cases ReTX=10 and 1000 are limited while the total number of retransmissions are significantly increased. In this case, it is desirable to adopt a small number of retransmissions that achieves sufficient resolution for applying standard denoising techniques at each local site. Although the retransmission scheme shown in this paper is simple and sufficient for illustrating the physical layer protocol that we propose, a more complicated error correction code can be derived as mentioned in Section 4.

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