2007 International Conference on Sensor Technologies and Applications

Energy Driven Choice of Error Recovery Protocols in Embedded Sensor Network Systems

Rachit Agarwal[†‡], Emanuel Popovici[†], Oscar De Feo[†], Brendan O'Flynn[‡]
[†]Department of Microelectronic Engineering, University College Cork, Ireland
[‡]Microelectronics Application Integration Group, Tyndall National Institute, Cork, Ireland
Email: ragarwal@cs.ucc.ie, e.popovici@ucc.ie, oscar.defeo@ucc.ie, brendan.oflynn@tyndall.ie

Abstract

The transmission efficiency of Embedded Sensor Networks (ESN) is lower than that of conventional networks due to high Bit Error Rates and inconsistent channel conditions. Transmission efficiency as low as 47% has been experienced in deployments for various applications. Transmission errors in ESN can be recovered using three basic methods, Automatic Repeat Request, Error Control Coding or Hybrid ARQ. This paper presents insights into the choice of error recovery protocols guided by the energy constraints imposed by ESN. We classify the ESN applications into three major classes, which significantly simplifies the choice. Further, we develop an energy model to incorporate the three schemes and draw inferences on the choice based on expected channel conditions and ESN classification. We apply the energy driven choice to two case studies, demonstrating the simplified process of choosing error recovery protocols.

1. Introduction

The development of low cost, low-power, multi-functional sensor components that are small in size, perform sensing and data processing, and communicate untethered in short distances has stimulated a lot of interest in Embedded Sensor Network (ESN) systems. The two dominating sources of energy consumption in ESN are communications energy and information processing energy. Communications energy is the energy consumed in transmitting the information from the transmitter to the receiver, while the information processing energy is the energy consumed in processing that information.

We refer to the transmitting and receiving nodes as the source node and the sink node for the information and will use them interchangeably in the context of upstream and downstream data transfer.

In the context of data transfer, the following questions are of particular importance:

- *Given the amount of information to be transferred, what is the energy consumption in* CORRECTLY *communicating the data from the source to the sink node?*
- *In light of adverse channel conditions, which protocol ensures this correctness given energy constraints?*

In what follows, we refer to this *degree of correctness* in data transfer as the "transmission efficiency" of the network. The transmission efficiency of ESN varies with the deployment scenarios and applications. In general, the efficiency is lower than that of conventional networks due to frequent propagation errors. Hence, it becomes an important issue to choose an energy efficient error recovery protocol, specially for applications like medical, monitoring and surveillance, which require high reliability in data transfer.

Most of the deployment experiences reported in literature employ schemes for error recovery based on a *Hit-&-Trial* method. A study which guides the protocol choice given the expected behavior of the channel is important to reduce the design and experimentation time for such application deployments. In particular, we formulate a solution to the following problem:

> *We have to deploy our network in X scenario for application Y. Our network data will be similar to that of deployment reported in paper Z. We expect that our channel would be of type $\mathbb{C}$ and we want a significant degree of reliability. Which error recovery protocol should we choose, given that the batteries are a constant energy source?*

The objective of this paper is to provide a solution to the above question given the knowledge of X, Y, Z and $\mathbb{C}$. In the process, we approach the problem by developing an energy model for comparing the error recovery protocols and by categorizing ESN in three classes according to their combined energy-communication requirements.

0-7695-2988-7/07 $25.00 © 2007 IEEE
DOI 10.1109/SENSORCOMM.2007.14

2. Data Reliability in ESN

To study the choice of recovery protocols for ESN, we exploit the ESN deployment experiences reported in literature to extract and investigate the unique characteristics of the underlying communication network and applications in ESN. We then throw a quick glance on various protocols and present the energy model in this section.

Before going to the specifics of this contribution, it is worth mentioning that despite the adverse channel conditions repeatedly reported in literature, the problem of choosing the recovery protocol has not been addressed formally. The issues comprising of the relative costs and benefits of different error recovery strategies for transmission in ESN form an important part of system deployment. While the theoretical trade-offs involved are well-known and well-studied, there is comparatively little work that bridges these theoretical results with the practice of ESN.

Indeed, there are several factors which make the choice "apparently" difficult. In what follows, we quickly overview the reasons behind the difficulties faced in analyzing the practical applicability of these protocols:

2.1. ESN: Why is Analysis Difficult?

Channel Conditions: First, the channels in ESN are highly unreliable with high probability of introducing burst of errors at certain instants [2]. The behavior of the channel depends not only on the specific communication scheme employed in the applications [2] but also on deployment conditions [10][15][17]. Deployment experiences have shown that based on deployment conditions, the transmission efficiency can vary between 90% and 70% for the same system [17].

Resource Constraints: Second, ESN are extremely resource-constrained networks. These constraints appear in terms of energy constraints, available memory constraints [10], and, in some scenarios, delay constraints [11][14]. Accordingly, we desire to reduce the energy overhead due to communications as much as possible, while keeping memory and delay requirements as low as possible.

Network Interference: Not only the channel conditions, the network services, application under consideration and number of nodes effect the data reliability in ESN. Such an experience has been reported in [2], where the system achieved 95% reliable communication service when tested with 9-16 nodes but its reliability fell to 50% when tested with 100 nodes due to significant increase in the background and application traffic levels. Almost 16% performance enhancement has been reported when the number of retransmission attempts were increased from 0 to 5 [12].

Application Types: Finally, but most importantly, in many applications, both the packet size and data transmission rate will be likely to be very small. For example, 32 bytes data in [14], up to 16 bits in [4], 36 bytes in [17], few of tens of bits in most medical applications etc. In terms of transmission rate, Mica2 (19.2 kbps) and MicaZ (250 kbps) are well-known examples. On one hand, the costly energy consumption of communications makes it desirable for sensors to minimize the size and frequency of data transmissions by doing as much local processing as possible. On the other hand, in most occasions, sensors only generate periodic messages consisting of only a few bits or bytes.

2.2. Error Recovery Schemes

Erroneous packets in ESN can be recovered by three basic methods, *Automatic Repeat Request (ARQ)*, *Error Control Coding (ECC)* or *Hybrid ARQ (HARQ)* (also known as Adaptive Error Control Coding (AECC)).

ARQ: The main advantage of ARQ is that it produces no overhead in a non-error situation: every packet correctly received is forwarded through the network and simultaneously acknowledges the fact that it was received correctly. Other advantages are the relative simplicity and the optimal throughput in non-error channel conditions.

The main disadvantage of ARQ are the retransmission costs in terms of huge delays and energy when an error does occur. Retransmissions (which effect both sensing and sink node) will result in reducing the node lifetime and hence ARQ is either applicable in no-error channel conditions or where certain amount of data loss is acceptable.

ECC: The advantages of ECC is that there are no time delays in the message flows (or a bounded small delay, considering the encoding and decoding operations). A disadvantage is that packets get lost when the coding scheme is not strong enough to correct the errors.

From the energy consumption perspective of ECC, specific features of ESN are particularly important. It is known that the computational complexity of most of the coding protocols is exponential in terms of data length. In the context of ESN, i.e., for short data lengths, the processing and hence the power consumption decreases exponentially.

HARQ: Hybrid ARQ combines ARQ and ECC [1][8]. The system incorporating HARQ can adapt to the channel conditions by changing the coding scheme and error correcting capability. HARQ is most energy consuming scheme and is employed only on demands of applications or in systems where delay is not an issue. Some schemes that can adapt in both directions (increasing and decreasing complexity) can result in further saving the overall energy consumption of the system [1][8].

2.3. Energy Model

The energy required by the transmitter E_{T_x} to cover a distance d can be expressed as:

$$E_{T_x} = E_{T_{x_0}} + \beta d^{\eta}$$

where η is the so-called propagation exponent and $E_{T_{x_0}}$ is a distance independent energy factor, while the receiver energy E_{R_x} can be modeled as

$$E_{R_x} = E_{R_{x_0}} + E_{ECC}$$

where, $E_{R_{x_0}}$ and E_{ECC} are communication and decoding costs respectively. More specifically, the energy consumed in transmitting a packet can be expressed as

$$E_{T_x}(N, R_c, P_{amp}) = P_{s-up}T_{s-up} + \frac{k}{R_c R}(\tilde{P}_{T_x} + P_{amp}) \tag{1}$$

where k is the number of information bits, R is the data rate, R_c is the code rate, T_{s-up} and P_{s-up} are the duration and power of the radio startup and $\tilde{P}_{T_x}$ is the fixed power in transmit mode. The power dissipated in the power amplifier for a transmission over a distance d (in meters) is

$$P_{amp}(d) = \alpha_{amp} + \beta_{amp} P_{1mAtt} d^{\eta} P_{rcvd}$$

where $\alpha_{amp}, \beta_{amp}$ are parameters of the power amplifier, P_{1mAtt} is the attenuation at one meter and P_{rcvd} is the amount of power that should be received to meet the performance objective.

The energy consumed in receiving a packet is given by

$$E_{R_x}(k, R_c, E_{DE}) = P_{s-up}T_{s-up} + \frac{k}{R_c R}\tilde{P}_{R_x} + \frac{k}{R_c}E_{DE/bit} \tag{2}$$

where $\tilde{P}_{R_x}$ is the fixed power in receive mode, while $E_{DE/bit}$ is the energy associated to the decoding of a single information bit, which depends on the code used as well as the implementation of the decoding algorithm and is equal to zero if no decoding is performed.

For an ARQ scheme, the components $\tilde{P}_{T_x}, \tilde{P}_{R_x}$ and P_{amp} from (1), (2) contribute to the consumed energy due to multiple transmissions. Here, we have ignored the situation when the transmitter is idle waiting for ACK/NACK. This assumption is acceptable for ESN where the idle (round-trip) time is negligible because of the close proximity of sensor nodes [13]. Hence, the total energy consumption for an ARQ implementation can be given by:

$$E_{ARQ} = (N_{TR} - 1)\{\frac{k}{R}(\tilde{P}_{T_x} + P_{amp} + \tilde{P}_{R_x}) + E_{R_x \leftrightarrow T_x}\} \tag{3}$$

where, N_{TR} is the average number of transmissions (including the initial transmission failure) required for receiving the correct data and $E_{R_x \leftrightarrow T_x}$ is the energy consumed in switching between transmission mode to receiving mode. Again, even though the power consumed during switching is almost average of P_{T_x} and P_{R_x}, the switching time is small enough that we can ignore $E_{R_x \leftrightarrow T_x}$. This is also acceptable since we are trying to find a bound on the performance rather than the actual performance.

For HARQ (Adaptive ECC) schemes, where ECC is combined with ARQ, energy consumption is given by:

$$E_{HARQ} = E_{T_x} + E_{R_x} + E_{ARQ} + (N_{TR} - 1)\,\frac{k}{R_c}E_{DE/bit} \tag{4}$$

Depending on the application, various performance metric can be defined to accept the applicability of a particular protocol. Our main aim is to simplify the whole mathematical computation and experimentation behind the choice of recovery protocol. In that context, researchers generally compute the overall energy consumption (in single-hop or multi-hop scenario) for the network and try to deduce the best protocol. We argue that by studying the energy consumption on a *per-hop basis* simplifies the whole computation, provided that a suitable performance metric can be defined.

Notice that if we try to find the relative performance of ARQ and ECC (ratio of energy consumption) on a per-hop basis, we can find an upper bound to the performance of a particular protocol for the network. This can be visualized in context of single-hop ESN being extended to multi-hop ESN on one-hop-addition basis. Based on the above discussion, we can define a performance metric (PM) as the ratio of energy consumption of ARQ and ECC protocols:

$$PM = \frac{(N_{TR} - 1)\dfrac{k}{R}(\tilde{P}_{T_x} + \tilde{P}_{R_x} + P_{amp})}{\dfrac{k}{R_c}E_{DE/bit}} \tag{5}$$

which can further be developed to:

$$PM = \frac{(N_{TR} - 1)R_c(\tilde{P}_{T_x} + \tilde{P}_{R_x} + P_{amp})}{RE_{DE/bit}} \tag{6}$$

This provides us with an analytical formula for comparing the performance of various schemes, including ECC, ARQ and HARQ. To simplify our further discussion, we modify this performance metric to exclude some experiment specific terms.

$$PM \simeq \frac{(N_{TR} - 1)R_c(\tilde{P}_{T_x} + \tilde{P}_{R_x})}{RE_{DE/bit}} \tag{7}$$

The simplification is based on the fact that $RE_{DE/bit} \gg (N_{TR} - 1)R_c P_{amp} > 0$ for the cases in which we are interested. Besides P_{amp} having significantly low value, N_{TR} would be low for ESN deployments of our interest (else we employ ECC) and R_c would be always less than 1.

Table 1. Scheme Selection for Various System Types for Various Channel Types

	Zero Errors			Low Error/Consistent			High Error/Varying		
	R-C	S-C	D-C	R-C	S-C	D-C	R-C	S-C	D-C
ARQ	√								
ECC		√	√	√	√	√	√		√
HARQ								√	√

This gives us an energy model to study the choice of error recovery protocols qualitatively (for known X, Y, Z and $\mathbb{C}$) and quantitatively for the variables in (7). A direct implication of the derived PM would be the choice of recovery protocol given the numerical values of the variables involved. If PM is higher than 1, ARQ consumes more energy than ECC (for one-hop and hence, far more for multi-hop) and hence ECC would be more energy efficient and vice-verse.

3 ESN Classification

ESN have recently been employed for a multitude of real-world applications. Most of the ESN deployment vary with the others in terms of channel conditions, system specifications, processing and communication scenarios and data dissemination schemes. ESN can be single-hop where sensing-sink node distance is very short, multi-hop for longer distances and diversified data types or clustered for diversified applications.

Such a diversity presents problems in classifying the ESN applications, which is an important step for simplifying the choice of system implementations. However, if we restrict our classification to the energy constraints aspects considered in our approach, and neglect the channels and communication scenarios for the time being, ESN can be broadly classified into three main categories given the application types:

Resource Constrained (R-C) Systems: These are systems in which both, the sensing node and the sink node, are battery-operated and are constrained by available memory for communications and information processing. It is important to ensure that the information processing and communications costs are minimized at both, the source and the sink node. Though most of the ESN have a base node which collects the data, most of them form a multi-hop communication protocol. The hops between the source node and the sink node are examples of such systems. Again, clustered ESN systems [6][9] become a part of this classification where each cluster can be considered as a R-C system.

Semi-Constrained (S-C) Systems: These are systems in which the sink node is not battery-operated (or can be operated using direct power supply) and hence, the energy constraints are not very harsh. The node lifetime, and hence the network lifetime, is determined by the energy consumption at the sending node. In most of the ECC schemes, encoding is assumed to be of zero cost compared to decoding and is much lower than the retransmission cost. The constraints are then imposed by the applications and expected channel behavior, whether or not the information processing is essential. Examples of such systems are given in [3][5].

Delay Constrained (D-C) Systems: Speed of information processing is the primary concern of such systems [11][16]. Wireless Multimedia Sensor Networks form an important part of this category, where delay in information processing overshoots that of data communication. The delay incorporated in retransmission may not be acceptable in such systems, though depending on the channel behavior, delay due to decoding process in presence of strong coding scheme may exceed that of retransmission cost.

It is worth mentioning again that the source and the sink nodes can be interchangeably used in upstream and downstream data transfer for system classification. While downstream data transfer may fall into one category, the same system can be a part of another category in upstream data transfer. This can be seen as the in-dependency of the source and the sink in terms of employing error recovery protocol.

4 Simplified Choice of Recovery Protocols

The classification of the ESN applications simplifies the choice of the protocols significantly. In this section, we discuss the answer to the question stated in the introduction. Notice that the knowledge of application Y and data type Z will help us to identify the class in which the proposed deployment network falls (R-C, S-C or D-C). The expected channel condition $\mathbb{C}$ then helps us to arrive at the following discussion.

R-C Systems: Energy consumption is the major concern of R-C systems. From our performance metric (7), we get a clue that N_{TR} would significantly increase the ratio and hence applicability of ECC, hence we would like the retransmissions to be as low as possible while making sure that ECC is not redundant.

Table 2. Specifications from the Deployment Reports for Case Studies

Deployment	Mote	Number	Month	Packets Rate	Data Rate	Successful Transmission	Transmit Power	Receive Power
SensorScope [12]	Mica2	14	November	9.0	2647.5	48%	82.5 mW	26.4 mW
Wisden Project [10]	Mica2	4, 7, 8 or 10	—	2.0	69	95%	82.5 mW	26.4 mW

In zero-error channel conditions, retransmissions will occur only once in a while, which makes N_{TR} low while ECC would be redundant. Hence, in such channel conditions, R-C systems would prefer ARQ. However, in consistent and varying channel conditions, retransmissions will occur every time a packet is lost due to errors, resulting in high N_{TR}. This makes ECC more applicable when compared to ARQ. HARQ would not be preferred in R-C systems because we would not like the energy to be consumed in both, retransmission and error control.

S-C Systems: The condition for S-C systems is a bit different. The energy constraints are not as harsh as in S-C systems, which makes ECC the first choice of this class. Keeping the "correctness" of data in mind, we would then have a choice between ECC and HARQ.

In zero-error channel conditions, ECC would be operating on the infinite energy decoding end (definition of S-C systems). In such cases, performance metric will be evaluated for the source node resulting in very high value of PM and hence no retransmission requirements from the source node. The sink node has infinite energy and strong decoding scheme can be employed to ensure required performance. Similar would be the case for consistent channels.

However for varying channel conditions, employed ECC might not be strong enough for the worst channel conditions and hence HARQ would be more applicable. This is a direct consequence of the fact that retransmissions will be required only when the channel conditions are really bad. This can be seen as a case when burst errors may be expected, where system faces burst errors only once or twice over the overall deployment cycle.

D-C Systems: D-C systems would prefer ECC for reduced delay due to retransmissions. This is particularly acceptable for large-scale networks and multi-hop networks, where retransmission will occur through multiple hops and delay would be higher. While for zero-error and consistent channel conditions, ECC would be directly favourable, in varying channel conditions the analysis is very much dependent on the degree of "correctness" required for the application.

This is due to the fact that delay incorporated in decoding very strong codes might overshoot the delay in ARQ. We leave this option to the discretion of the application.

This discussion is summarized in Table 1.

5 Case Study: SensorScope, EPFL

SensorScope is an indoor environmental monitoring network implemented and deployed by the Ecole Polytechnique Federal de Lausanne (EPFL) [12]. A multi-hop hybrid ARQ (MHARQ) layer between the network and the link layers has been implemented in the system for packet reliability. [12] reports that due to the inverse relation between distance and channel quality, the sensing nodes transferred 96%, 54% and 48% and $\leq\ 35\%$ packet transfers only. We will choose the third mote as our discussion point (Table 2). We first follow the conventional technique for protocol selection and then demonstrate the simplifications based on the energy consumption model developed.

ARQ Implementation: Assuming that an ARQ implementation for such a transfer scheme would require only 1 retransmission on an average, the overall transmitted data would be [(Success Rate)*(Data Rate) + N_{TR}*(Failure Rate)*(Data Rate)] $\equiv$ [(48% (2647.5)) + 2 $\times$ (52% (2647.5))] = 152% (2647.5) bytes = 4024.2 bytes. Assuming a consistent data transfer rate, the overall time for transmitting the packets for ARQ scheme will be given by: $\frac{4024.5}{2647.5}$ = 1.52 min = 91.21 seconds. Hence, the overall energy consumption would be: $91.21 \times (82.5 + 26.4)$ = 9.931 J.

ECC Implementation: For ECC implementations, we pick the data provided in [7]. We consider a (255,239) Reed-Solomon digital decoder that transmits 255 bytes for every 233 bytes out of 2647.5 bytes and is shown to be one of the most energy consuming scheme (0.1193 nJ/bit). The overall energy consumption due to employing ECC will hence be given by: [(Data Length)*(Code Rate R_c)*(Decoding Energy per bit)] $\equiv 2647.5 \times 8 \times (255/239) \times (0.1193 * 10^{-9})$ = 2695.93 nJ $\simeq$ 3 μJ. The transmission time in this case will be given by [(Data Length)*(Code Rate)/(Data Rate)] $\equiv \frac{2647.5*(255/239)}{2647.5}$ minutes = 64 seconds and hence the energy consumption $64 \times (82.5 + 26.4)$ = 6.971 J.

Simplified Choice & Comparison: As can be seen, given the poor channel condition for this mote, ECC results in an energy saving of $\simeq 9.931 - 6.971$ = 2.96 J. Using the model developed, this inference requires the following computations. Plugging the values from Table 1 in (7), $PM \simeq \frac{(2-1)(233/259)(82.5+26.4)}{(2647.5/60)*0.1193} \gg 1$. Hence, ECC will be the preferred protocol.

6 Case Study: Wisden, UCLA

The next case study we choose is that of the deployment experiences from WISDEN system for Structural Health Monitoring (SHM) [10]. This deployment experience reports the performance of a multi-hop wireless data acquisition system called WISDEN on a large seismic test structure used by civil engineers. Wisden implements a NACK-based hybrid hop-by-hop and end-to-end reliability scheme.

It has been reported that nodes 4, 7, 8 and 10 were within single-hop from the sink transmitted 95% of the packets without need of retransmission. We will take either of these nodes as our discussion point.

ARQ Implementation: Assuming that an ARQ implementation for such a transfer scheme would require 1 retransmission on an average, the overall transmitted bytes would be [(95% (2*69)) + ($2 \times 5\%$ (2*69))] = 105% (2*69) bytes = 144.9 bytes. Assuming a consistent data transfer rate, the overall transmit power for ARQ scheme will be given by: $\frac{144.9}{138}$ = 1.05 sec. Hence, the overall transmit energy would be: 1.05 *(82.5 + 26.4) = 114.345 mJ.

ECC Implementation: We consider the same code as used in SensorScope study. The overall energy consumption due to employing ECC will hence be given by: $(2 * 69) * (255/239) * 8 * 0.1193 * 10^{-9}$ = 140.52 nJ $\simeq$ 1.4 μJ. The transmit and receive power in this case will be given for (2*69) * (255/239) bytes: 1.07 *(82.5 + 26.4) = 116.19 mJ.

Simplified Choice & Comparison: As can be seen, in this case, ARQ turns out to be more energy efficient than employing ECC. It can be simply shown that plugging the values in (7) would result in $PM < 1$ for a single hop case, thereby decreasing the ratio significantly with increasing number of hops.

7 Discussions

We have presented a study to direct the choice of error recovery protocol in energy-constrained ESN. ESN have been broadly classified in three major categories and choice of recovery protocol has been studied via an energy model and performance metric. Two case studies have been performed to demonstrate the simplified process based on energy model and ESN classification, rather than extensive computations and numerous experiments.

8. Acknowledgement

This work was funded by the Irish Marine Institute Body (Smartcoast Project), and the support of the Informatics Commercialisation initiative of Enterprise Ireland is gratefully acknowledged for its funding of the D-Systems project (ATRP-02/227A).

References

[1] R. Agarwal, E. M. Popovici, and B. O'Flynn. Adaptive wireless sensor networks: A system design perspective to adaptive reliability. In *Intl. Conf. Wireless Communications and Sensor Networks*, pages 216–225, 2006.

[2] A. Arora, P. Dutta, S. Bapat, and et. al. A line in the sand: A wireless sensor network for target detection, classification and tracking. *Computer Networks, Elsevier*, 46(5):605–634, December 2004.

[3] A. Bakshi and V. K. Prasanna. Structured communication in single hop sensor networks. In *European Wireless Sensor Networks Conf.*, pages 138–153, 2004.

[4] D. Chen, G. Cao, and L. Zuo. A multihop data relay scheme for wireless networked sensors. In *IEEE* 62^{nd} *Vehicular Technology Conference*, pages 1814–1818, 2005.

[5] S. Chessa and P. Maestrini. Fault recovery in single-hop sensor networks. *Elsevier, Computer Communications*.

[6] M. N. Halgamuge, S. M. Guru, and A. Jennings. Energy efficient cluster formation in wireless sensor networks. In *IEEE Intl. Conf. Telecommunications*, pages 1571–1576, 2003.

[7] S. L. Howard, C. Schlegel, and K. Iniewski. Error control coding in low power wireless sensor networks: When is ecc energy-efficient? *Eurasip Jourl. on Wireless Communications and Networking*.

[8] J. V. D. Meer, M. Nijdam, and M. Bijl. Adaptive error control in a wireless sensor network using packet importance valuation. In *Draft*.

[9] S. Misra and G. Xue. Efficient anonymity schemes for clustered wireless sensor networks. *Intl. Jour. Sensor Networks*.

[10] J. Paek, K. Chintalapudi, R. Govindan, and et. al. A wireless sensor network for structural health monitoring: Performance and experience. In *IEEE EmNets*, pages 1–10, 2005.

[11] P. K. Pothuri, V. Sarangan, and J. P. Thomas. Delay-constrained, energy-efficient routing in wireless sensor networks through topology control. In *IEEE Intl. Conf. on Networking, Sensing and Control*, pages 35–41, 2006.

[12] T. Schmid, H. Duboid-Ferrirre, and M. Vetterli. Sensorscope: Experiences with a wireless building monitoring sensor network. In *Workshop on Real-World Wireless Sensor Networks*.

[13] W. Su and I. A. Akyildiz. Time-diffusion synchronization protocol for wireless sensor networks. *IEEE/ACM Trans. Networking*, 13(2):384–397, April 2005.

[14] G. Werner-Allen, J. Johnson, M. Ruiz, and et. al. Monitoring volcanic eruptions with a wireless sensor network. In *EWSN*, pages 108–120, 2005.

[15] N. Xu, S. Rangwala, K. K. Chintalapudi, and et. al. A wireless sensor network for structural monitoring. In *ACM SenSys*, pages 13–24, 2004.

[16] R. Yu, G. Wang, and S. Mei. Designing energy-efficient routing scheme with delay constraint for wireless sensor networks. In 3^{rd} *IEEE Consumer Communications and Networking Conf.*, pages 437–441, 2006.

[17] J. Zhao and R. Govindan. Understanding packet delivery performance in dense wireless sensor networks. In *ACM SenSys*, pages 1–13, 2003.