# Energy Efficient Sensing of Non-cooperative Events in Wireless Sensor Networks

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*Abstract*— **In a wireless sensor network, energy efficiency is one of the primary concerns since typically the sensor nodes rely on small battery to operate. Non-Cooperative events refer to such events that they are not easily monitored as they come and go. As a result, they can be observed only if the sensors are constantly monitoring the environment. However, energy efficiency is a serious concern if the sensors are always ON. In this work, the tradeoff between energy efficiency and non-cooperative events coverage in a wireless sensor network is studied. We begin with fixed listen and sleep time schemes for a single sensor node and quantify the performance results in terms of event miss rate and normalized average power consumption. If the statistics of the event is unknown, an adaptive scheme based on a "*additive increase/multiplicative decrease*" rule is proposed to adapt the sleep schedule with the sensing data. Both fixed and adaptive schemes are extended to multiple nodes and the coverage of the entire area of a network is taken into consideration in addition to energy efficiency. Discrete-event simulations are carried out to demonstrate the effectiveness of the proposed scheme.**

## I. Introduction

In a wireless sensor network, energy saving is one of the primary concerns since typically the sensor nodes rely on small battery to operate. A sensor node is typically composed of two parts, one part for taking measurements (sensing) and the other part for wireless communications. For example, a XBOW sensor node includes a sensor board and a communication board [1]. While many energy saving schemes (for example, [4], [5], [3], [6]) have been proposed for the wireless communications part, very few have considered energy saving schemes for sensing. Recent measurement results show that the sensor nodes spend a lot of energy when taking measurements [2] and the energy expenditure of sensing is comparable to that of data communications (transmission and reception). As a result, it is necessary to study energy saving schemes for sensing, in other words, put the sensor board to sleep when no active sensing is in process.

Wireless sensor networks are usually deployed to monitor static or dynamic events. Static events (such as temperature, humidity), are easy to measure. On the contrary, dynamic events are typically non-cooperative and thus are not easy to catch. The movement of an enemy's vehicle in a battlefield, migration of whales in the ocean, are examples of non-cooperative events. They are not easily monitored as they come and go. As a result, they can be observed only if the sensors are constantly monitoring the environment. However, energy efficiency is a serious concern if the sensor boards are always ON. Hence, it is critical to study energy saving schemes for sensing of non-cooperative events.

Because sensor nodes in a wireless sensor network operate in a fully distributed manner, it is hard to organize the sensor nodes switching between sleeping mode and active mode without centralized control and global knowledge of the network. In order to minimize the event miss rate and at the same time minimize and balance the energy consumption of the sensor nodes, a distributed scheme is needed to put the sensor nodes to sleep and wake them up when needed. Performance analysis of various distributed alternate sensing schemes including both fixed and adaptive schemes and their implications on network coverage of the non-cooperative events will be the focus of this paper. Specifically, the tradeoff between energy efficiency and non-cooperative events coverage in a wireless sensor network is formulated as a joint optimization problem. We begin with fixed listen and sleep time schemes for a single sensor node and quantify the performance results in terms of event miss rate and normalized average power consumption. If the statistics of the event is unknown, an adaptive scheme for a single sensor node is proposed to adapt the sleep interval with the sensing/measurement data. Both fixed and adaptive schemes are extended to multiple nodes and the coverage of the entire area of the network is taken into account in addition to energy efficiency.

This paper is organized as follows: Section II discusses the alternate sensing schemes of a single sensor node, where both fixed and adaptive schemes are considered. Simulation results are provided for both schemes in Section III. Network-wide coverage is studied in Section IV. Related works are discussed in Section V. In Section VI we conclude the paper and provide suggestions for future research work in this area.

## II. Alternate sensing schemes

In this study, alternate sensing schemes are adopted in wireless sensor networks to save energy. One example of such schemes is shown in Fig. 1. During a listen interval, the sensor nodes turn their sensor boards on and take measurements. During a sleep interval, sensors are switched off to save energy. In spite of these schemes' popularity, how to design the listen and sleep intervals appropriately to monitor non-cooperative events is still an open problem.

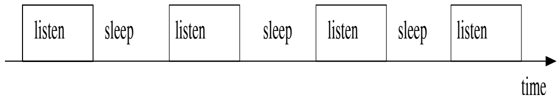


Fig. 1. An alternate sensing scheme

The following notations are used in this study

- $L$: Listen interval in seconds;
- $S$: Sleep interval in seconds;
- $\lambda$: Poisson rate of the non-cooperative events;
- $E_S$: Unit energy consumption for sensing one event;
- $P_S$: Average power consumption during sleep period;
- $P_L$: Average power consumption during listen period

The design of the alternate sensing schemes may be formulated as a joint optimization problem

$$\arg Min \;\; J \tag{1}$$

where

$$J = \{E[R_{miss}] + E[\bar{P}]\} \tag{2}$$

and the expected event miss-rate $E[R_{miss}]$ is given by

$$E[R_{miss}] = E\{\frac{\lambda S}{\lambda S + \lambda L}\} = \frac{E[S]}{E[S] + E[L]} \tag{3}$$

and the normalized average power consumption $E[\bar{P}]$ is given by

$$E[\bar{P}] = \frac{E[L] + \frac{P_S}{P_L}E[S]}{E[L] + E[S]} \tag{4}$$

The performance index $J$ addresses the fundamental tradeoff between event miss rate and energy consumption. A sequence of listen and sleep intervals need to be determined to minimize the sum of the expected event miss-rate and the normalized average power consumption. If the final state of the network is known, a dynamic programming approach may be applied to solve this optimization problem. However, this is not the case in practice and other sub-optimal design methods (heuristics) are needed.

Two types of alternate sensing schemes are considered here: Fixed Timer (FT) schemes and Adaptive Timer (AT) schemes. In a FT scheme, both sleep interval and listen interval are pre-determined and remain fixed once they have been set. In an AT scheme, each node tries to adjust its sleep schedule dynamically according to the (estimated) frequency of the events and some design parameters specified by users.

FT schemes may be useful when the statistics of the events are known or could be estimated in advance. AT schemes are more flexible than FT schemes and they have the capability of estimating the statistics of the events and adjusting the tradeoff between event miss rate and energy consumption on-the-fly, which are desirable in practice.

In this paper, we propose the following AT scheme where the duration of the sleep interval changes according to a "*additive increase/multiplicative decrease*" rule

$$S(k) = \begin{cases} S(k-1) + \delta S(k) & \text{if } I(L(k-1)) = 0 \\ \beta(k) S(k-1) & \text{if } I(L(k-1)) = 1 \end{cases}$$

where $\delta S(k) > 0$ is the incremental step size and $0 < \beta(k) < 1$ is the decreasing factor at time step $k$. Both of them are design parameters. $I(.)$ is an indicator function and defined by

$$I(t) = \begin{cases} 1 & \text{if event occurs during } t \\ 0 & \text{otherwise} \end{cases}$$

The essence of the proposed AT scheme is to probe the statistics of the events dynamically and tune the sleep interval accordingly. The two design parameters provide the capability of tradeoff between event miss rate and energy consumption. For example, large $\beta$ saves more energy but increases the miss rate.

Note that a lower bound exists for the performance index.

$$E[R_{miss}] + E[\bar{P}] = \frac{E[S] + E[L] + \frac{P_S}{P_L}E[S]}{E[S] + E[L]} > 1 \tag{5}$$

In other words, the sum of the expected miss-rate and the normalized average power consumption is lower bounded by 1, no matter FT or AT schemes are employed. However, the proposed AT scheme will perform closer to the lower bound than the FT schemes as observed later in Section III. The above observation also suggests that in order to minimize the expected miss-rate and the average power consumption jointly, $\frac{P_S}{P_L}$ should be close to zero. In other words, it is desirable to have $P_S << P_L$, which is true for most sensors.

## III. Performance analysis

In this section, discrete-event simulations are performed to evaluate both the FT scheme and the proposed AT scheme. OPNET is selected as the simulation tool.

### A. FT schemes

In this part of the simulation, the non-cooperative events are generated according to a Poisson process with Poisson rate $\lambda$. The parameters of the simulation cases for FT scheme are listed in Table I.

| Run | $\lambda$ | $L$ | $S$ |
|---|---|---|---|
| 1 | 1 | 0.1 | variable (0.1-10) |
| 2 | 1 | 1 | variable (0.1-10) |
| 3 | 1 | 2 | variable (0.1-10) |
| 4 | 1 | variable (0.1-10) | 0.1 |
| 5 | 1 | variable (0.1-10) | 1 |
| 6 | 1 | variable (0.1-10) | 2 |
| 7 | variable (0.1-10) | 1 | 0.1 |
| 8 | variable (0.1-10) | 1 | 1 |
| 9 | variable (0.1-10) | 1 | 2 |
| 10 | variable (0.1-10) | 0.1 | 1 |
| 11 | variable (0.1-10) | 1 | 1 |
| 12 | variable (0.1-10) | 2 | 1 |

TABLE I

Simulation parameters for FT scheme.

The average power consumption during sleep period and listen period are $P_S = 0.01$ mW and $P_L = 1$mW, respectively.

In the first 4 figures, the miss rate and the normalized (by power in listening interval) power consumption, both in percentage (%), are shown for various FT parameter settings given in Table 1. The miss rate from the discrete event

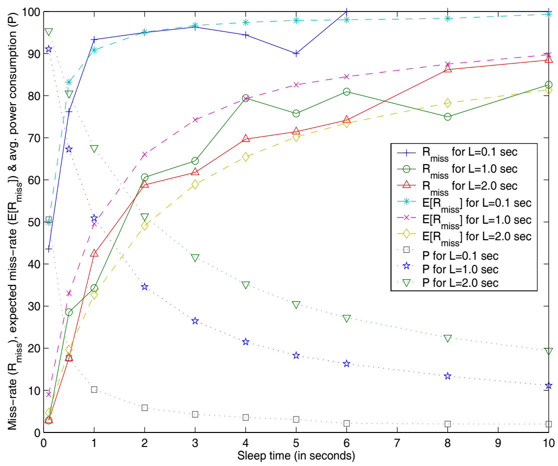


Fig. 2. event miss rate and normalized average energy consumption vs. sleep time when the Poisson rate of events and listen intervals are fixed.

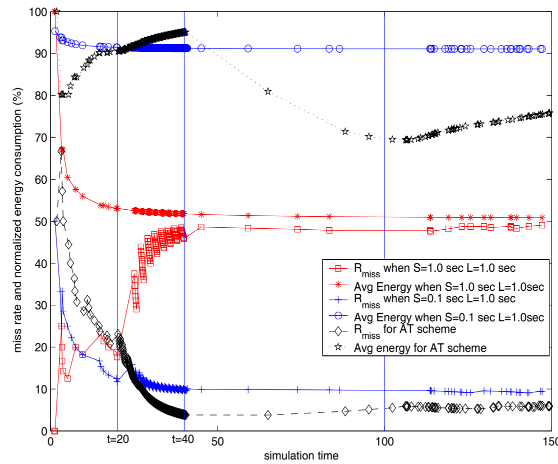


Fig. 4. event miss rate and normalized average energy consumption using 2 FT schemes and the proposed AT scheme (with $\delta S = 0.1$ and $\beta = 0.5$).

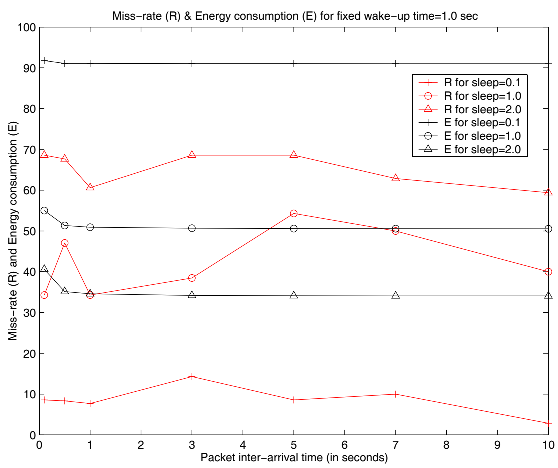


Fig. 3. event miss rate and normalized average energy consumption vs. Poisson rate of events and the sleep time when listen intervals are fixed.

simulation is also compared with the expected miss-rate given in equation 3.

Fig. 2 shows the behavior of the miss-rate and average power consumption for various sleep time of a node when Poisson rate $\lambda$ equal to one. The figure presents the tradeoffs between event miss-rate and energy consumed with the amount of time a node is inactive. A higher sleep interval time can achieve better energy consumption, but it will increase the event miss-rate. The figure also shows that miss-rate and energy consumption are not affected much by the higher sleep interval time. So the appropriate choice of the sleep interval depends on the type of the sensor network that can tolerate tradeoffs between the amount of miss-rate and energy consumption. Fig. 3 shows that miss-rate and energy consumption are not affected by the event frequency on average, as expected.

In summary, event-miss rate and energy consumption depend on the sleep and listen intervals of a node using FT scheme. Hence, in order to minimize the energy consumption and miss-rate, network designer can choose an appropriate operating point for the sensor network on the miss-rate and energy trade offs curve that best suits the needs of the application.

### *B. AT schemes*

In this part of the simulation study, the Poisson rate $\lambda$ varies along time. $\lambda = 1$ during the first 20 seconds, then increases to 10 from 20 to 40 seconds, then it drops to 0.1 from 40 to 100 seconds, then returns to 1 thereafter. The purpose of the changing event rate is to create a realistic (dynamic) environment and compare FT scheme with the proposed AT scheme.

The event miss rate and normalized average energy consumption using 2 FT schemes (with $S = 1, L = 1$; and $S = 0.1, L = 1$, respectively) and the proposed AT scheme are shown in Fig. 4. It is observed that FT scheme with inappropriate setting (with $S = 1, L = 1$) has unacceptable performance. FT scheme with better setting (with $S = 0.1, L = 1$) can achieve good performance. However, the proposed AT scheme outperforms the FT scheme in *both* event miss rate and normalized average energy consumption. Furthermore, no knowledge of the event process is needed for the proposed AT scheme.

The event miss rate and normalized average energy consumption using the proposed AT scheme with different parameter settings are shown in Fig. 5. It is observed that the proposed AT scheme performs well under a wide range of parameter settings. It is also demonstrated the flexibility of the proposed AT scheme.

## IV. Network-wide Coverage

In the previous sections, both FT scheme and AT scheme have been studied for a single node to monitor non-cooperative events. However, in practical applications, it is often necessary to monitor the entire area of a wireless sensor network.

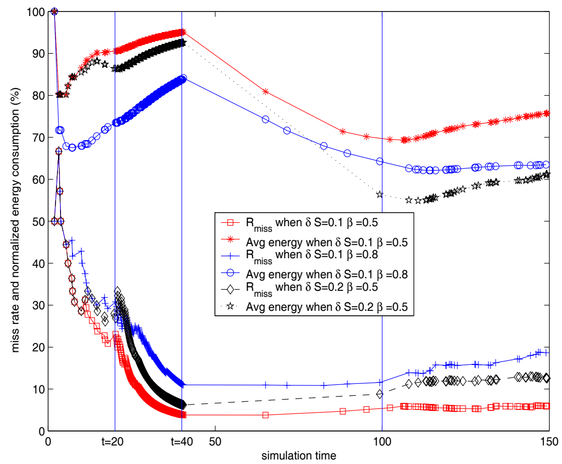


Fig. 5. event miss rate and normalized average energy consumption using the proposed AT scheme with different parameter settings.

For example, a wireless sensor network may be deployed to monitor a battlefield for possible enemy movements. Hence, it is interesting to study how the FT scheme and AT scheme will perform network-wide together with various network coverage schemes.

A major goal in sensor network is to preserve the coverage of the sensing network for the maximum possible time. Network coverage problem determines how well a sensor network is monitored by the sensors. In the past years, a number of researches have been done in the area of coverage for sensor network. Meguerdichian et al. [8] defines a sensor coverage metric called surveillance that can be used as a measurement of quality of service provided by a particular sensor network. An optimal polynomial time algorithm that uses graph theoretic and computational geometry constructs was proposed for solving for best and worst case coverage. However, their algorithms rely heavily on specific geometrical structures such as the Delaunay triangulation and the Voronoi diagram which cannot be constructed locally or even efficiently in a distributed manner. So [11] provides more efficient distributed algorithms by correcting method proposed in [8]. In [9], coverage preserving node scheduling scheme is presented which deals with energy-coverage problem in sensor networks. They use probabilistic probing schemes to determine when a node can be turned off and when it should be rescheduled to become active again. The schemes guarantee that the original sensing coverage is maintained after turning off redundant nodes. [10] investigated coverage problem that alternate between active and sleep states to conserve energy. The authors consider two types of mechanism in the context of coverage: the random sleep type where each sensor keeps an active-sleep schedule independent of another, and the coordinated sleep type where sensors coordinate with each other in reaching an active-sleep schedule. It is shown with either type of sleep schedule the benefit of added redundancy saturates at some point in that the reduction in duty cycles starts to diminish beyond a certain threshold in deployment redundancy. It is also shown that at the expense of extra control overhead, a coordinated sleep schedule is more robust and can achieve higher duty cycle reduction with the same amount of redundancy compared to a random sleep schedule.

In general, it is very difficult to coordinate sensor nodes without centralized control. And a big overhead penalty will be introduced for distributed control. Thus, sensor nodes will adopt an asynchronous scheme in this work, where each sensor will independently determine its sleep schedule according to the proposed AT scheme discussed in Section II.

### A. Theoretical Results

The following notations are used in our analysis

- $(X, Y)$: The 2-dimensional coordinates (location) of a sensor node;
- $N$: Number of sensor nodes in the network;
- $r$: Sensing range of a sensor node;
- $A$: The area of the network.

It is assumed that random non-cooperative events happen according to a Poisson process with Poisson rate $\lambda$. The location of the event is randomly chosen and is assumed to be uniformly distributed across the network.

*Theorem 1:* Assuming that there are $N$ sensor nodes uniformly distributed in a wireless sensor network of area $A$, and each sensor node has sensing range $r$, the miss-rate (the probability that a random event will be missed) is given by

$$R_{miss} = e^{-\frac{E[L]}{E[S]+E[L]}\frac{N}{A}\pi r^2} \tag{6}$$

*Proof:* The probability that a random event has $N_0$ sensor nodes in range is

$$P_0 = \frac{(\pi r^2 N/A)^{N_0}}{N_0} e^{-\pi r^2 N/A} \tag{7}$$

The expected number of sensor nodes that are in range of a random event is

$$E[N_0] = \frac{N}{A}\pi r^2 \tag{8}$$

The expected number of sensor nodes that are in range of a random event and in listen mode is

$$E[N_0^L] = \frac{E[L]}{E[S]+E[L]}\frac{N}{A}\pi r^2 \tag{9}$$

Then the probability that a random event will be sensed by some senor node is $1 - e^{-\frac{E[L]}{E[S]+E[L]}\frac{N}{A}\pi r^2}$. The theorem follows. ■

This theorem states that the event miss rate is a function of average number of nodes per unit area and the sleep schedule. Discrete-event simulations are performed to evaluate the performance using FT and AT schemes under different average number of nodes per unit area.

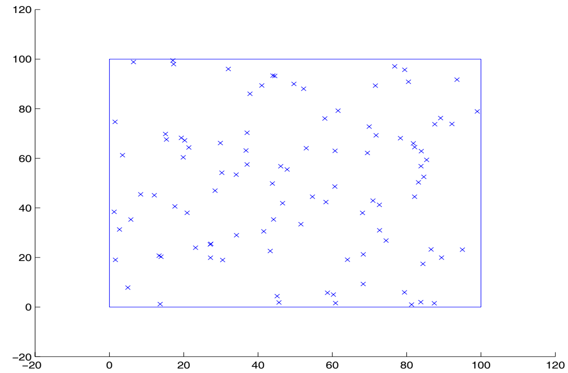

Fig. 6. A sample wireless sensor network: node locations

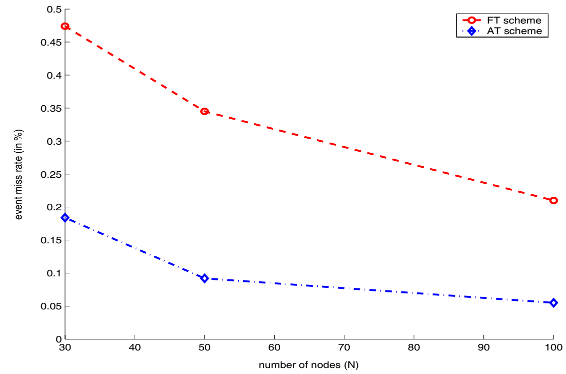


Fig. 7. event miss rate vs. number of sensor nodes in the network (r is fixed, r=15m)

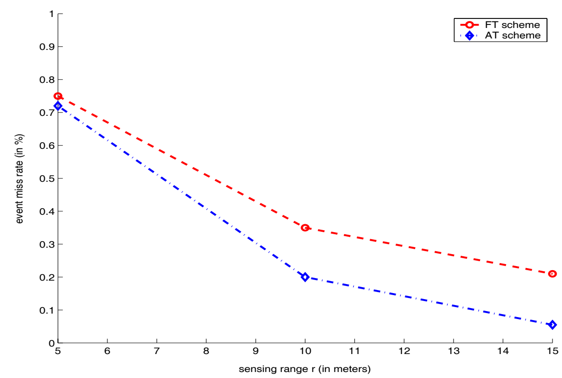


Fig. 8. event miss rate vs. sensing range (N is fixed, N=100)

### B. Simulation Results

There are $N$ sensor nodes in the wireless sensor network and they are uniformly distributed in the network coverage area. Each node has a binary event detector with sensing range $r$. It is assumed that the network covers a $100m \times 100m$ area. A sample sensor location map ($N = 100$) is given in Fig. 6. Note that the nodes' locations are not optimized for coverage here because of practical constraints. For example, sensors are deployed by unmanned aircraft.

It is assumed that random non-cooperative events happen according to a Poisson process described in Section III-B. The location of the event is randomly chosen and is assumed to be uniformly distributed across the network. In other words, both coordinates of a random event, $X$ and $Y$, are uniformly distributed in $[0, 100]$.

In order to evaluate the network coverage of the FT scheme, all nodes are assumed to have the same energy budget and event miss rate is used as performance criterion. A missed event means an event happens in place where no sensor node is in range or all sensors in range are in sleep mode.

The parameters for the FT scheme are $S = 0.1$ and $L = 1$, and the parameters for the proposed AT scheme are $\delta S = 0.1$ and $\beta = 0.5$, respectively. FT scheme is compared with the proposed AT scheme in networks with different number of nodes and different sensing ranges. The results are summarized in Fig. 7 (for different $N$) and Fig. 8 (for different $r$). It is observed that the proposed AT scheme has significant less event miss rate than that of the FT scheme in all tests. Fig. 7 also shows that when $N$ increases the difference between the FT scheme and the proposed AT scheme starts to decrease due to the increase of node density. When the sensing range $r$ is very small, the geometric coverage dominate the event miss rate. Thus, there is a small difference between the FT scheme and the proposed AT scheme. As the sensing range $r$ increases, the sensing schemes start to play an important role in event coverage and the difference between the FT scheme and the proposed AT scheme becomes larger.

## V. Related Work

Energy saving is a hotly pursued topic of research in wireless sensor networks. A number of energy efficient protocols have been proposed for medium access control (MAC) in wireless sensor networks, for example, [4], [5], [3], [6]. S-MAC [4] is a contention based MAC protocol for energy saving in wireless sensor networks. It uses a simple scheduling scheme to allow neighbors to sleep for long periods and synchronize wakeup. During the wakeup period state, nodes use CSMA/CA for communication. It reduces energy waste of idle listening significantly, but it increases latency because the data arrived during sleep is queued until the next active cycle. T-MAC [5] tries to improve the S-MAC by introducing the adaptive duty cycle by dynamically ending the active part of it. This also reduces the amount of energy wasted in idle listening. STEM [3] protocol provides a way to establish communications when the nodes are sleeping. The protocol uses two-radio architecture, data radio and wakeup radio. The sender sends data to the target nodes by using the data radio. The wakeup radio uses ultra low power radio to wakeup the target nodes. If a node wants to establish communication, it starts sending beacons polling a specific user. Within a bounded time, the polled node will wakeup and start communication. An alternative approach is adopted where target nodes are waken up by busy tone instead of using beacons. Span [6] reduces energy consumption of a multi-hop ad hoc wireless network by selecting a connected set of nodes as a coordinator and turning the rest of the nodes off. Span coordinators stay awake and perform multi-hop packet routing.

There are also a few works on monitoring static events, such as ELECTION [7]. In ELECTION [7], sensor nodes sense the environment periodically and turn sensors off during sleep. It also adjusts sleep cycles according to the measurements. To measure time critical data, nodes switch to radio mode only when the measurement exceeds a threshold value and report to the base station.

Although the above papers give effort to minimize energy consumption at MAC and data collection level, none of them has emphasized on sensing mechanism for non-cooperative events.

## VI. Conclusions and Future Work

In this paper, the tradeoff between energy efficiency and fault-tolerant event monitoring is considered through flexible and dynamic scheduling of sensing. Detailed simulation studies provide guidance for practical deployment. Network coverage results are also presented.

Readers may notice that the proposed AT scheme uses the same principle as the TCP congestion control. Indeed, the essence of the TCP congestion control is to measure the path throughput (congestion level) and tune the transmissions accordingly. Similarly, the essence of the proposed AT scheme is to estimate the event occurrence and adapt the sleep schedule accordingly.

Note that the proposed schemes may be generalized to tracking specific target. It would be interesting to compare our proposal with other approaches such as [12], and it is one of our future efforts.


## Acknowledgment

The authors would like to thank OPNET Technologies, Inc. for providing the OPNET software to perform the simulations in this study. This research work is supported in part by the National Science Foundation (NSF) under award HRD-0531507 and by the U.S. Army Research Laboratory under Cooperative Agreement No. W911NF-04-2-0054. Contents are solely the responsibility of the authors and do not necessarily represent the official views of the National Science Foundation (NSF), the Army Research Laboratory or the U. S. Government.


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