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Research Article

An Enhanced Distributed Scheme for WSNs

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This paper investigates data processing schemes that define the distribution of decision making that affects system accuracy and energy consumption. There exist two typical schemes, namely: centralized and distributed schemes. In a centralized scheme, nodes collect samples and send them to a "fusion center." This scheme provides optimal decision accuracy; however, it consumes considerable energy. In contrast, distributed schemes allow nodes to make local 1-bit decisions, which are sent to the fusion center to make the final decision. In a hybrid scheme, the network specifies the level of accuracy required for the whole system. This can be achieved by manipulating the scheme to work interchangeably as centralized or distributed. Most of the energy consumed is in the transmission process; therefore, this paper proposes an energy-saving hybrid scheme that focuses on optimizing transmission energy. In this proposed scheme, each node is able to alternate between centralized and decentralized scheme according to its location and path length. To validate the proposed approach, it is simulated and the results are compared with the hybrid scheme.

1. Introduction

The main goal of WSNs is to detect certain events in the environment. It is important to try to achieve maximum detection accuracy and to minimize false alarms. At the same time, availability of WSN resources and accessibility limitations should be considered. The solution is a trade-off between two factors: accuracy and energy efficiency. With sensor capabilities a tremendous societal benefit is achieved when sensors are integrated into available devices, machines, and environments. They can help to avoid infrastructure failure disasters, protect precious natural resources, enhance security, and enable new "smart" applications such as context-aware systems and home technologies. Wireless sensor networks are based on numerous advanced technologies such as very large scale integration (VLSI), microelectromechanical systems (MEMS), and wireless communications. The development of these technologies is contributing to a wider application of WSNs. For example, with the enhancement of MEMS technology, sensors are becoming smaller, and developments in semiconductor technologies are producing smaller microprocessors with higher processing capacities. The improvement of computing and sensing technologies is enabling the development of flexible WSNs, which can be widely applied [1, 2].

Monitoring environmental changes and detecting specified events is the main function of sensor networks. This function is achieved through four basic components of a sensor network [3]: distributed or localized sensors, an interconnecting network (most often wireless based), a central point of information clustering a set of computing resources at the central point or network core to handle data collecting, event trending, status querying, and data mining. WSNs use centralized fusion centers (sinks), which work as cluster gateways, and many distributed sensors (motes) [4]. These sensors sense and send observations to the centralized unit. The centralized unit decides if an event is initiated or not.

Most of the power consumed in a network is used in processing, transmitting, and sensing. Until now limited power resources for sensors has been the main constraint in WSNs. It is very important to reduce sensor power consumption while maintaining acceptable detection accuracy according to application requirements. Many researchers have focused on the above three processes [5], attempting to enhance the power consumption efficiency of the sensors for each of them. Some schemes enhance the operating system and reduce

Table 1: Wireless communication protocols.

Standards	IEEE 802.15.4 Low power wireless personal area network (LP-WPAN)				IEEE 802.51.1 (WPAN)	IEEE 802.11 (WLAN)	IEEE 802.16 (WWAN)
	ZigBee	6LoWPAN	WirelessHART	ISA 100.11a	Bluetooth	WiFI	WiMAX
Range in meters	100	50			100	100	15 Km
Data rate	250–500 Kpbs	250 Kbps	250 Kbps	250 Kbps	1–3 Kbps	250 Kbps	250 Kbps
Frequencies	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4 GHz	2.4, 3.7 and 5 GHz	2.3, 2.5 and 3.5 GHz
Network topology	Star, mesh, cluster tree	Star, mesh, cluster tree IPv6	Star, mesh, cluster tree	Star, mesh, cluster tree	Star	Star, tree, P2P	Star, tree, P2P
Applications	WSNs (monitoring and control)	WSNs, Internet, automation and entertainment	Wirelessly process monitoring and control application	Wireless systems of automation	WSNs (monitoring and control)	PC-based data acquisition mobile Internet	Mobile Internet

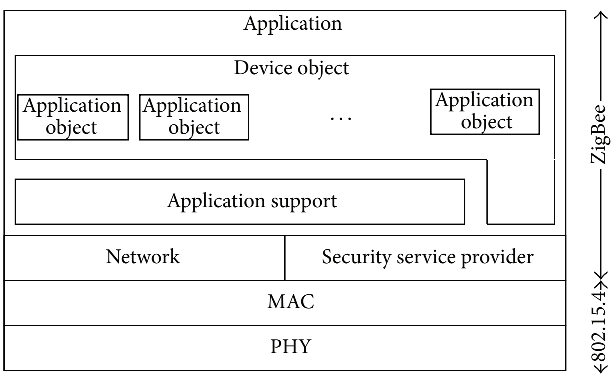

Figure 1: ZigBee protocol stack.

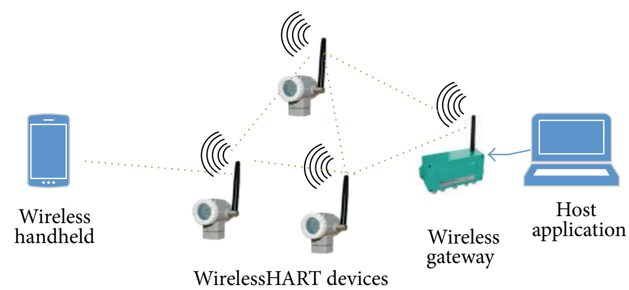

Figure 2: Elements of a typical WirelessHART installation.

the required processing cycles; other schemes optimize the RF part including collision space and noise filtering. This thesis focuses on schemes which study decision processing and transmitting where those schemes define how to collect observations (sampling rate), where to process them (locally or centralized), and the data to be sent from nodes to the fusion center, which will affect the degree of loss of data and accuracy [6]. The main goal of this paper is to produce an optimum controlling scheme that extends network/sensor lifetime by reducing power consumption and maximizing the network efficiency and accuracy. Our proposed scheme balances between the reduction of data transmission and processing by distributing these two activities among the nodes and the central unit (sink).

Existing wireless communication protocols are shown in Table 1, including IEEE 802.11 (WiFi), IEEE 802.15.1 (Bluetooth), IEEE 802.15.4 (ZigBee, 6LoWPAN, WirelessHART, and ISA-100.11a), and IEEE 802.16 (WiMAX).

The main WSN solutions such as ZigBee, WirelessHART, 6LoWPAN, and ISA-100 are based on this standard, which offers a complete networking solution by developing the remaining upper communication layers.

ZigBee. ZigBee [7–9] is a simple, low cost, low power wireless technology used in LR-PANs embedded applications. ZigBee provides the network layer and the framework for the application layer. The MAC sublayer and lower layers are based on the IEEE 802.15.4 standards (see Figure 1).

The ZigBee network layer supports star, tree, and mesh topologies. It is utilized in three types of devices: ZigBee coordinator, ZigBee routers, and end devices.

WirelessHART. Based on IEEE 802.15.4 standard highway addressable remote transducer (HART) foundation, WirelessHART [10–12] was developed for low-power 2.4 GHz operation. Similar to ZigBee, WirelessHART specifies four principal devices (Figure 2): network manager, gateways, field devices, and handhelds, as well as adapters, which allow existing HART field devices to be integrated into the network.

6LoWPAN. 6LoWPAN [13, 14] is the abbreviation of IPv6 over low power wireless personal area networks, in which standard IPv6 packets are enabled to communicate over an IEEE 802.15.4-based network. Using 6LoWPAN, low power devices have all the benefits of IP communication and management. It is targeted at wireless IP networking applications in home, office, and factory environments.

ISA100.11a. The core wireless technology employed by ISA100.11a [15] is IEEE 802.15.4, which sorts the 2.4 GHz unlicensed band into 16 channels.

As shown in Table 6, the network layer is based on IETF RFC4944 (6LoWPAN):

(i) IP connectivity through compressed IPv6 and UDP packets,

(ii) addressing scheme:

(a) EUI-64 (64 bits),
(b) IPv6 (128 bits),
(c) short address (16 bits IEEE 802.15.4).

The entire ISA100.11a stack is constructed employing widely accepted and proven industry standards.

2. Related Work

As mentioned earlier, each node has the responsibility of collecting, processing, transmitting, and receiving data. The common functions of every detection scheme are that (1) nodes collect observations, and (2) the fusion center (sink) takes the final decision.

There are two traditional detection schemes: the centralized detection scheme and the distributed detection scheme, the methodologies of which will be covered in details. In our approach, we use a tree topology where nodes are "independently and identically distributed" (i.i.d.). They are connected to the Fusion Center (FC) through a multihop route, where nodes also act as hops to receive data from child nodes and forward it to the FC with any processing, encryption or encoding. The focus here is only on accuracy and energy consumption, and it is assumed that lower layers are working perfectly and that there are no efficiency problems caused by RF or by packet collisions; that is, there is no data retransmission.

2.1. Bayesian Decision Theory

2.1.1. Binomial Distribution. A Bernoulli trial can result in a success with probability p and a failure with probability $q = 1 - p$. Equation (1) gives the probability distribution of the binomial random variable x. The number of successes in n independent trials is

$$f(x; n, p) = \Pr(x \mid p) = \binom{n}{x} p^x (1-p)^{n-x}. \tag{1}$$

The probability that two events, A and B, will both occur will be $P(A \cap B) = P(B \cap A) = P(B)P(A \mid B) = P(A)P(B \mid A)$. From this formula the main equations (2) of Bayes' rule can be derived:

$$P(A \mid B) = \frac{P(A)P(B \mid A)}{P(B)},$$
$$P(A) = \sum_{i=1}^{k} P(B_i \cap A) = \sum_{i=1}^{k} P(B_i) P(A \mid B_i). \tag{2}$$

From Figure 3 we find $P(E \cap A) = P(E)P(A \mid E) = (2/3)(3/50) = 0.04$.

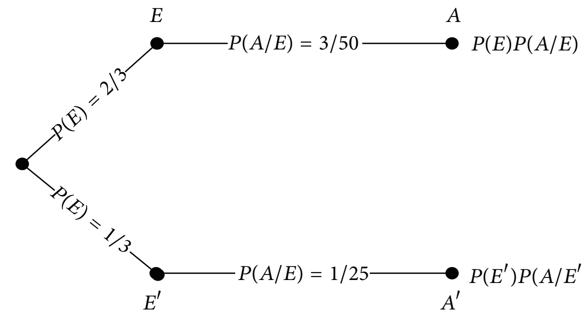

Figure 3: Conditional probability example.

The distribution of H, given D, which is called the posterior distribution, where $P(D)$ is the marginal distribution of D, is given by

$$P(H \mid D) = \frac{P(D \mid H) P(H)}{P(D)}. \tag{3}$$

Binary assumption is defined by H, which represents event occurrence: ($H = H_1$) if an event happens and ($H = H_0$) if not; $\widehat{H}$ is the actual event status: H' is the final decision; K is node counts; D is the collected samples, T is sample count at each node, and L is the node path length. For each sample S_{ij} where i is varied from 1 to K and J from 1 to T collected in a node i, $P(S_{ij} = 1 \mid \widehat{H} = H_1) = p_1$, $P(S_{ij} = 1 \mid \widehat{H} = H_0) = p_0$.

Bayes Decision. Choose event happened if $P(H_1 \mid D) \geq P(H_0 \mid D)$; otherwise choose not happened.

2.2. Centralized Detection Schemes. In centralized detection schemes a network will have K number of nodes. These nodes will collect T samples of observations from the environment every specific period, and they will send T samples together at the end of the period. At the fusion center $D = [T * K]$ samples will be received.

According to Bayes, a final decision can be calculated as shown in the following:

$$\widehat{H} = \begin{cases} 1, & P(H_1 \mid D) \geq P(H_0 \mid D) \\ 0, & \text{otherwise.} \end{cases} \tag{4}$$

The probability of error can be calculated using the following equation:

$$\begin{aligned} P_e &= \left(p * P_{\text{false positive}}\right) + \left((1-p) * P_{\text{false negative}}\right) \\ &\longrightarrow P_e = p * P\left[H' = H_1 \mid H_0\right] \\ &\qquad + (1-p) * P\left[H' = H_0 \mid H_1\right] \\ &\longrightarrow P_e = p * \left[1 - P(n \geq \gamma_{\text{FC}} \mid H_1)\right] \\ &\qquad + (1-p) * P(n \geq \gamma_{\text{FC}} \mid H_0). \end{aligned} \tag{5}$$

To calculate power consumption for the whole network in (6), the following equation can be used, where E = total energy, E_T = transmission energy, E_R = receiving energy, and E_P = processing energy:

$$E = E_T + E_R + E_P$$
$$\longrightarrow E = \sum_{i=1}^{K} (L_i * T * e_t) + \sum_{i=1}^{K} (L_i * T * e_r) \tag{6}$$
$$\longrightarrow E = \sum_{i=1}^{K} (L_i * T * (e_t + e_r)).$$

2.3. Distributed Detection Scheme. In this scheme nodes collect data and make local decisions according to these observations and conclude the event appearance as a 1-bit result. This result is sent to the fusion center to make a final decision according to the collected 1-bit results from all nodes. In this scheme data accuracy between nodes and the fusion center has been lost.

We propose K number of nodes; these nodes will collect T samples of environmental observations with (n_i = number of 1s for node i) and will send a 1-bit local decision every specific period.

At the fusion center, $D = [1 * K]$ samples will be received.

According to Bayes, a local decision can be calculated as shown in the following:

$$\widehat{H}_i = \begin{cases} 1, & P(H_1 \mid n_i) \geq P(H_0 \mid n_i) \\ 0, & \text{otherwise.} \end{cases} \tag{7}$$

From (1) and (4), we can calculate local decision as shown in the following:

$$P(H_1 \mid n_i) \geq P(H_0 \mid n_i)$$
$$\longrightarrow \frac{P(n_i \mid H_1) P(H_1)}{P(n_i)} \geq \frac{P(n_i \mid H_0) P(H_0)}{P(n_i)}$$
$$\longrightarrow \frac{P(n_i \mid H_1)}{P(n_i \mid H_0)} \geq \frac{P(H_0)}{P(H_1)}$$
$$\frac{\binom{T}{n_i} p_1^{T} (1 - p_1)^{T-n_i}}{\binom{T}{n_i} p_0^{T} (1 - p_0)^{T-n_i}} \geq \frac{(1-p)}{p} \tag{8}$$
$$\longrightarrow n_i \geq \frac{\ln((1-p)/p) + T \ln((1-p_0)/(1-p_1))}{\ln(p_1(1-p_0)/p_0(1-p_1))}$$
$$= \gamma_{\text{local}}$$
$$\longrightarrow \widehat{H} = \begin{cases} 1, & n_i \geq \gamma_{\text{local}} \\ 0, & \text{otherwise.} \end{cases}$$

For final decision we collect b = total 1s if local decision

$$\widehat{H} = \begin{cases} 1, & P(H_1 \mid b) \geq P(H_0 \mid b) \\ 0, & \text{otherwise.} \end{cases} \tag{9}$$

From (1) and (4), we can calculate final decision as shown in the following:

$$P(H_1 \mid b) \geq P(H_0 \mid b)$$
$$\longrightarrow \frac{P(b \mid H_1) P(H_1)}{P(b)} \geq \frac{P(b \mid H_0) P(H_0)}{P(b)}$$
$$\longrightarrow \frac{P(b \mid H_1)}{P(b \mid H_0)} \geq \frac{P(H_0)}{P(H_1)},$$
$$P_D = \sum_{i=\gamma_{\text{local}}}^{T} \binom{T}{i} p_1^{T} (1-p_1)^{T-i},$$
$$P_F = \sum_{i=\gamma_{\text{local}}}^{T} \binom{T}{i} p_0^{T} (1-p_0)^{T-i},$$
$$\frac{\binom{K}{b} p_D^{K} (1-p_D)^{K-b}}{\binom{K}{b} p_F^{K} (1-p_F)^{K-b}} \geq \frac{(1-p)}{p}$$
$$\longrightarrow b \geq \frac{\ln((1-p)/p) + K \ln((1-p_F)/(1-p_D))}{\ln(p_D(1-p_F)/p_F(1-p_D))}$$
$$= \gamma_{FC}$$
$$\longrightarrow \widehat{H} = \begin{cases} 1, & b \geq \gamma_{\text{FC}} \\ 0, & \text{otherwise.} \end{cases} \tag{10}$$

The probability of error can be calculated using

$$P_e = (p * P_{\text{false positive}}) + ((1-p) * P_{\text{false negative}})$$
$$\longrightarrow P_e = p * [1 - P(b \geq \gamma_{\text{FC}} \mid H_1)] \tag{11}$$
$$+ (1-p) * P(b \geq \gamma_{\text{FC}} \mid H_0).$$

To calculate power consumption for the whole network (12) can be used, where E = total energy, E_T = transmission energy, E_R = receiving energy, and E_T = processing energy:

$$E = E_T + E_R + E_P$$
$$\longrightarrow E = \sum_{i=1}^{K} (L_i * 1 * e_t) + \sum_{i=1}^{K} (L_i * 1 * e_r)$$
$$+ \sum_{i=1}^{K} (T * e_p) \tag{12}$$
$$\longrightarrow E = \sum_{i=1}^{K} (L_i * (e_t + e_r)) + \sum_{i=1}^{K} (T * e_p).$$

2.4. Hybrid Detection Scheme. Neither the centralized nor the distributed detection scheme is flexible enough for designers to choose between detection accuracy and energy consumption. Yu et al. [16] proposed a hybrid scheme that balances detection accuracy and total energy consumption. According to a defined level of accuracy, the nodes will vary between sending all collected data and sending a 1-bit result. Thus, such schemes attempt to balance accuracy and energy consumption.

In this scheme, assume there are K number of nodes. These nodes will collect T samples of environmental observations with (n_i = number of 1s for node i). There will be upper and lower bounds N_0 and N_1, where $0 \le N_0 < N_1 \le T$. The node result will be 0 if the number of 1s is less than N_0. In other words, if the number of 0s collected is greater than or equal to $T - N_0$, 1 will be sent if the number of 1s is greater than or equal to N_1. Otherwise all the collected data will be sent, as shown in (17):

$$\text{Result}_i = \begin{cases} 1, & n_i \ge N_1 \\ n_i, & N_0 < n_i < N_1 \\ 0, & n_i \le N_0. \end{cases} \tag{13}$$

From (12), assume that out of K sensor nodes, t nodes send 1s, s nodes send 0s, and $K-s-t$ nodes send all their observations. The total data sent, Ω, will be

$$\Omega = \{1, \ldots, 1; n_1, \ldots, n_{K-s-t}; 0, \ldots, 0;\}. \tag{14}$$

From (12) we can derive the following probability:

$$\begin{aligned} P[b = 0 \mid H_\theta] &= \sum_{i=0}^{N_0} \binom{T}{i} {p_\theta}^T (1 - p_\theta)^{T-i}, \\ P[b = 1 \mid H_\theta] &= \sum_{i=N_1}^{T} \binom{T}{i} {p_\theta}^T (1 - p_\theta)^{T-i}, \end{aligned} \tag{15}$$

$$\begin{aligned} \text{PD} = {} & \binom{K}{s} \binom{K-s}{t} (P[b = 0 \mid H_1])^s (P[b = 1 \mid H_1])^t \\ & \cdot (P[n_i = 1 \mid H_1])^{k-s-t}, \end{aligned} \tag{16}$$

$$\begin{aligned} \text{PF} = {} & \binom{K}{s} \binom{K-s}{t} (P[b = 0 \mid H_0])^s (P[b = 1 \mid H_0])^t \\ & \cdot (P[n_i = 1 \mid H_0])^{k-s-t}. \end{aligned} \tag{17}$$

Following from (16) and (17), the final probability of error can be determined using

$$P_e = p * [1 - \text{PD}] + (1 - p) \times \text{PD}. \tag{18}$$

To calculate power consumption for the whole network (16) can be used, where E = total energy, E_T = transmission energy, E_R = receiving energy, and E_T = processing energy:

$$\begin{aligned} E &= E_T + E_R + E_P \\ \longrightarrow E &= \left[\sum_{i=1}^{s+t} (L_i * 1 * e_t) + \sum_{i=1}^{K-s-t} (L_i * T * e_t) \right] \\ &\quad + \left[\sum_{i=1}^{s+t} (L_i * 1 * e_r) + \sum_{i=1}^{K-s-t} (L_i * T * e_r) \right] \\ &\quad + \left[\sum_{i=1}^{K} (T * e_p) \right] \\ \longrightarrow E &= \sum_{i=1}^{s+t} (L_i * (e_t + e_r)) + \sum_{i=1}^{K-s-t} (L_i * T * (e_t + e_r)) \\ &\quad + \sum_{i=1}^{K} (T * e_p). \end{aligned} \tag{19}$$

Table 2: Telos typical operation conditions [24].

	Min	Nom	Max	Unit
Supply voltage	2.1		3.6	V
Supply voltage during flash memory programming	2.7		3.6	V
Operation free air temperature	−40		85	°C
Current consumption: MCU on, radio RX		21.8	23	mA
Current consumption: MCU on, radio TX		19.5	21	mA
Current consumption: MCU on, radio off		1800	2400	μA
Current consumption: MCU idle, radio off		54.5	1200	μA
Current consumption: MCU standby		5.1	21.0	μA

3. System Model (Telos)

In order to evaluate and develop our scheme, the behavior of WSN sensors should be understood, and a power consumption model should be defined [17]. For this purpose the typical operation conditions of TelosB (Figure 4) have been selected as a basis for our power model [18, 19].

I use the datasheet of Telos working at 250 kbps and 2.4 GHz (ultralow power IEEE 802.15.4 compliant wireless sensor module), which is one of the most widely known WSN nodes, and I use the power details from Table 2.

From the power consumption model in Figure 5, it can be concluded that transmission is responsible for a large amount of node power consumption.

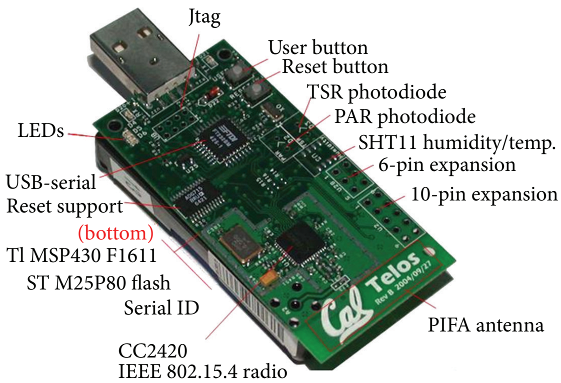

Figure 4: TelosB by the University of California.

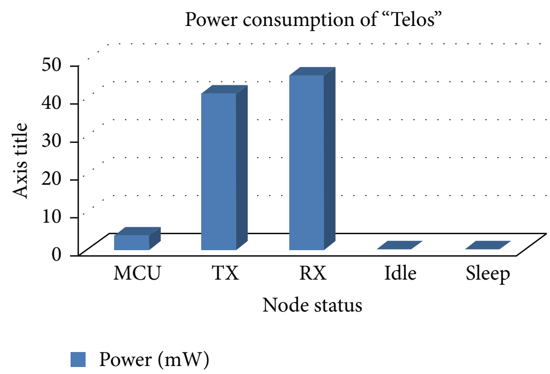

Figure 5: Power consumption of "TelosB."

So far, only the behavior of a single node has been discussed. Now the power consumption of all the nodes in the network should be addressed.

The formula for calculating the overall power consumed while sending a single bit from source (sensor node) to destination (fusion center) through N hop nodes equals the energy required to send and receive this bit between all of the N hops, where E = total energy, E_T = sending energy, and E_R = receiving energy:

$$\text{Energy consumed per node: } E = E_T + E_R \longrightarrow E = (N * e_t) + ([N-1] * e_r). \quad (20)$$

So, for the special case where a node is directly connected to the FC, energy used = $e_t + e_r$.

For instance, if hops count = 10, energy used will = $10e_t + 9e_r$.

Thus, the length of a route affects the overall power consumed in the network and the network life time as well.

3.1. Power Calculation. We use TelosB model to calculate power consumption [20, 21], with the following:

(i) MCU current consumption: 2.4 mA,

(ii) Rx current consumption: 23 mA,

(iii) Tx current consumption: 21 mA.

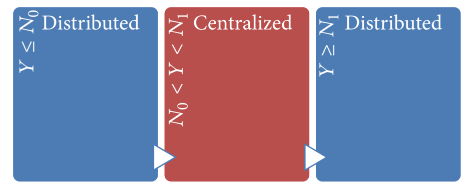

Figure 6: Node behaviour depends on N_0 and N_1.

3.2. Processing Energy. The MSP430 [22] is running at a clock rate of 8 MHz, Instruction Cycle Time = 200 ns, so in every cycle we can finish 40 Instructions/Cycle, $[(8 * 10^{-6})/(200 * 10^{-9})]$.

Let us assume that we need 2,000 instructions for the measurement, for data processing, and for preparing a packet for transmission over the network. This would result in $2000/(40 * 8 * 10^6) = 6.25 * 10^{-6}$ s; the amount of energy consumed per sample at a current of 2.4 mA would be

$$E_P = 2.4 * 6.25 * 10^{-6} = 15 * 10^{-6} \text{ mA/s}. \quad (21)$$

3.3. Transmission Energy. Using CC2420, sending data takes place at a speed of 250 kbps. If one node collects from a local sensor or from all the children 1 bit of data to be forwarded to the parent node, power consumption can be calculated as in the following equations:

$$\frac{1}{250 * 10^3} = 4 * 10^{-6} \text{ s}, \quad (22)$$

$$E_R = 23 * 4 * 10^{-6} = 92 * 10^{-6} \text{ mA/bit}, \quad (23)$$

$$E_T = 21 * 4 * 10^{-6} = 84 * 10^{-6} \text{ mA/bit}. \quad (24)$$

3.4. Simulation Network Design. In order to derive more realistic data from our simulation model, we will apply TelosB properties in our network, with maximum coverage = 100 m. A total of N sensors are randomly deployed in the region of interest (ROI) which is a square area of a^2. I have selected a to be equal to 300 m; hence the ROI = 0.09 km^2. The locations of sensors are unknown before deployment time. However, it is known that all sensors are i.i.d., and every sensor locations (x, y) will follow a uniform distribution in the ROI.

4. Enhanced Hybrid Detection Scheme

The hybrid scheme adjusts the behavior of the network to vary between centralized and distributed schemes and also establishes N_0 and N_1 parameters to define that behavior, and Y is the number of observations equal to 1. We propose to enhance the hybrid scheme by dynamically choosing the N_0, N_1 parameter instead of it being static.

In the hybrid scheme if Y is between N_0 and N_1 the node will act as centralized; otherwise it will act as distributed, as shown in Figure 6. For the special case $N_1 - N_0 \leq 1$ the node will always act as distributed, and the node will act more centralized if $N_1 - N_0$ becomes larger (until $N_0 = 0$ and N_1 = MAX).

However, N_0 and N_1 can be made dynamic, with a preference for a distributed orientation for nodes with longer route paths; for the remaining nodes it can remain more centralized, as in the original hybrid scheme, according to the requirements of the application.

For every sensor S varied from 1 to K we will assign specific $\{N_{0i}, N_{1i}\}$. These sensors will be classified according to the route path:

$$S_i = \begin{cases} 1, & n_i \geq N_{1i} \\ n_i, & N_{0i} < n_i < N_{1i} \\ 0, & n_i \leq N_{0i}. \end{cases} \tag{25}$$

Since $0 \leq N_0 < N_1 \leq T$, we will have a finite number of combinations for N_0 and N_1. These combinations—or groups of them should be mapped to all sensors, depending on sensor path weight.

The above mapping is a normal n-to-one mapping problem, which in our case can be solved experimentally by testing it in different deployed wireless sensor applications.

4.1. Network Deployment. Similar to most wireless sensor networks, the FC is deployed in an accessible location, while the sensor nodes are deployed randomly in the targeted area. This can be considered as a mesh network. After deploying the nodes, discovering the network is the first action to be taken. The FC broadcasts discover packets to all nodes in the covered area. These nodes then broadcast to further nodes until all the nodes are covered and routing paths; next hop and node configuration are defined.

To simplify the problem, nodes discover paths to the FC based on SPF (shortest path first) and select subsequent hops to forward received packets to. This information is crucial.

Since the nodes have already collected the broadcast packets, which include source, destination, and path, the nodes are able to select their routes based on the path length.

4.2. Nodes Configuration. For each node there are fixed configurations such as Tx/Rx power, frequencies, and calculation process. Some parameters need to be configured by the manufacturer or the user in order to optimize network efficiency. On the other hand, some parameters may be configured by the network itself.

In our scheme, every node has certain parameters that are defined during the manufacturing phase or by the developer during network deployment, that is, sampling rate (T), CP_{min}, and CP_{max}.

CP is the probability that the system works as centralized, which can be calculated from N_0 and N_1. In our scheme each node will select N_0 and N_1 depending on its path length. N_0 and N_1 should generate CP where $CP_{Min} \leq CP_{N_0,N_1} \leq CP_{Max}$.

From those inputs $\{T, p_0, p_1, \max(\text{path\_length}), CP_{min}, CP_{max}\}$ each node is able to calculate the N_0 and N_1 that satisfy application requirements.

From T we can find (N_0, N_1) combinations $= 2^T$, which is our ROT. Every node should be able to map the proper (N_0, N_1) from both (CP_{min}, CP_{max}) and max(path_length), as can be seen in Figure 7.

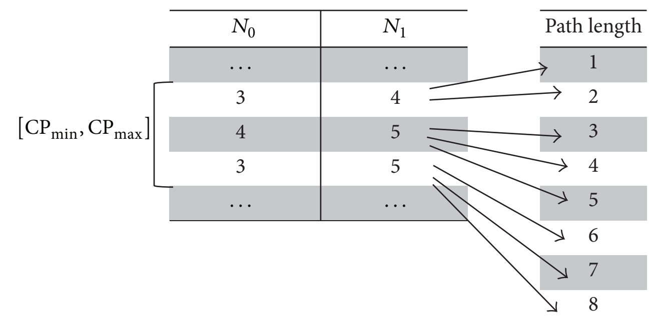

Figure 7: Mapping (N_0, N_1) combinations to available path length.

We can map these ranges by means of a simple 1-to-many mapping technique, where we index the initial range and assign the remaining ones equally to the next range, as applied in Algorithm 1.

4.3. N_0, N_1 Selection. To be able to select N_0 and N_1 at each node the problem is divided into simpler problems as follows:

(1) Define all combination of N_0 and N_1 and calculate the equivalent CP.

(2) Define valid N_0 and N_1 based on CP_{min} and CP_{max}.

(3) Define max path length, and map valid (N_0, N_1) to every path zone.

4.3.1. All N_0, N_1 Combinations. A selection of N_0 and N_1 will define when the node will act as more centralized or more distributed. For T collected samples we will have $0 \leq N_0 < N_1 \leq T$. We can have C different combinations for those N_0 and N_1, where $C = T!/((T-2)!2!)$.

For each combination we can calculate its CP_{CENT}, and we will have the C list of CP, which should be sorted according to its values.

CP_{CENT} can be calculated as in the following:

$$CP_{CENT} = \text{binocdf}\left(N_1 - 1\right) - \text{binocdf}\left(N_0\right), \tag{26}$$

where cdf is the cumulative distribution function which can be calculated as in the following:

$$y = F\left(x \mid n, p\right) = \sum_{i=0}^{x} \binom{n}{i} p^i \left(1-p\right)^{(n-i)} I_{(0,1,\ldots,n)}\left(i\right). \tag{27}$$

For example, for $T = 5$, $P[S = 1] = 0.45$, we generate all possible combinations of (N_0, N_1) as shown in Table 3.

4.3.2. Valid N_0 and N_1 Combinations. For example, we can select initial $CP_{min} = 0.50$, $CP_{max} = 0.90$.

First of all we find the valid (N_0, N_1) combinations. The selection of $CP_{min} = 0.50$, $CP_{max} = 0.90$ gives us 4 valid combinations (Table 4).

```
Define {CP_min, CP_max}
for each {N_0, N_1}
        CP_i = binCDF(N_1i − 1, T, P[S = 1]) − binCDF(N_0i, T, P[S = 1]);
        if CP_min < CP_i < CP_max
                add CP_i to CP;
        end if
end for
seed = ⌈count(Path)/count(CP)⌉
for i = 1 → count(Path)
        cp_seed = min(ceil(i/seed), size(CP, 1))
        CP_i = CP(cp_seed);
end for
```

Algorithm 1: Local N_0 and N_1 selection.

Table 3: CP values for all (N_0, N_1) combinations.

N_0	N_1	CP
0	5	0.93
0	4	0.82
1	5	0.73
1	4	0.61
0	3	0.54
2	5	0.39
1	3	0.34
2	4	0.28
0	2	0.21
3	5	0.11
0	1	0.00
1	2	0.00
2	3	0.00
3	4	0.00
4	5	0.00

Table 4: (N_0, N_1) valid combination list.

CP	N_0	N_1
0.82	0	4
0.73	1	5
0.61	1	4
0.54	0	3

4.3.3. Map (N_0, N_1) Combinations to Available Zones. In our scheme, every node has certain parameters that are defined during the manufacturing phase or by the developer during network deployment, that is, sampling rate (T), $\mathrm{CP}_{\min}$, and $\mathrm{CP}_{\max}$. All nodes are classified according to path length to Z zones. We have here a random WSN where maximum path = 6, which means 6 different zones. Figure 8 shows an example of WSN nodes classified into zones.

We define minimum $\mathrm{CP}_{\min}$ and maximum $\mathrm{CP}_{\max}$, where $\mathrm{CP}_{\max}$ is the maximum CP combination that can be assigned for zone 1, and $\mathrm{CP}_{\min}$ is the minimum CP that can be assigned to the next zones (where all $\mathrm{CP} \le \mathrm{CP}_{\min}$).

For every zone z, we assign $\mathrm{CP}(z) = \mathrm{CP}_i$ from (23), which can be used to map between zones and (N_0, N_1) combinations (Table 5):

$$i = \left\lceil z \div \left\lceil \frac{\text{Count of all Zones}}{\text{Count of CPs between } \mathrm{CP}_{\min} \text{ and } \mathrm{CP}_{\max}} \right\rceil \right\rceil,$$
$$\mathrm{CP}_1 = \left\lceil \frac{1}{\lceil 6/4 \rceil} \right\rceil = \left\lceil \frac{1}{2} \right\rceil = 1,$$
$$\mathrm{CP}_2 = \left\lceil \frac{2}{\lceil 6/4 \rceil} \right\rceil = \left\lceil \frac{2}{2} \right\rceil = 1,$$
$$\mathrm{CP}_3 = \left\lceil \frac{3}{\lceil 6/4 \rceil} \right\rceil = \left\lceil \frac{3}{2} \right\rceil = 2, \quad (28)$$
$$\mathrm{CP}_4 = \left\lceil \frac{4}{\lceil 6/4 \rceil} \right\rceil = \left\lceil \frac{4}{2} \right\rceil = 2,$$
$$\mathrm{CP}_5 = \left\lceil \frac{5}{\lceil 6/4 \rceil} \right\rceil = \left\lceil \frac{5}{2} \right\rceil = 3,$$
$$\mathrm{CP}_6 = \left\lceil \frac{6}{\lceil 6/4 \rceil} \right\rceil = \left\lceil \frac{6}{2} \right\rceil = 3.$$

In this scheme we find that (N_0, N_1) are dynamically selected by the nodes, depending on the path length, and the entire procedure described above requires minimal extra processing at the node, since the whole process is part of the network discovery phase.

Out of K sensor nodes, t nodes send 1s, s nodes send 0s, and $k-s-t$ nodes send all their observation so total send data Ω will be $\Omega = \{1, \ldots, 1; n_1, \ldots, n_{k-s-t}; 0, \ldots, 0;\}$. Our final decision, based on Bayes' rule, is $H' = H_1$ if $P[H_1 \mid \Omega] \ge P[H_0 \mid \Omega]$. From the above rule we can derive the following relations:

$$\frac{P[\Omega \mid H_1]}{P[\Omega \mid H_0]} \ge \frac{1-p}{p}, \quad (29)$$

Table 5: All (N_0, N_1) combinations.

N_0	N_1	CP
0	1	0.00
1	2	0.00
2	3	0.00
3	4	0.00
4	5	0.00
3	5	0.11
0	2	0.21
2	4	0.28
1	3	0.34
2	5	0.39
0	3	0.54
1	4	0.61
1	5	0.73
0	4	0.82
0	5	0.93

Table 6: ISA100.11a stack (Internet source).

Session	ISA native and legacy protocols (tunnelling)
Transport	UDP (IETF RFC 768)
Network	6LoWPAN (IETF RFC 4944)
Data link	Upper data link ISA100.11.a IEEE 802.15.4
Physical	IEEE 802.15.4

where we can calculate $P[\Omega \mid H_1]$ and $P[b_i = 0 \mid H_\alpha]$, $P[b_i = 1 \mid H_\alpha]$, and $P[b_i = 1 \mid H_\alpha]$ as follows:

$$P[\Omega \mid H_\alpha] = \binom{k}{s}\binom{k-s}{t} P[b=0 \mid H_\alpha]^s \cdot P[b=1 \mid H_\alpha]^t \times P[n_i \mid H_\alpha]^{k-s-t},$$

$$P[b_i = 0 \mid H_\alpha] = \sum_{n=T-N_{0i}}^{T} \binom{n}{T-N_{0i}-1} (1-p_\alpha)^{T-N_{0i}} p_\alpha^{i-(T-N_{0i})}, \quad (30)$$

$$P[b_i = 1 \mid H_\alpha] = \sum_{n=N_{1i}}^{T} \binom{n-1}{N_{1i}-1} (1-p_\alpha)^{n-N_{1i}} p_\alpha^{N_{1i}},$$

$$P[n_i \mid H_\alpha] = \binom{T}{n_i} (1-p_\alpha)^{1-n_i} p_\alpha^{n_i}.$$

5. Simulation Results

5.1. Enhanced Hybrid Detection Scheme

5.1.1. Power Consumption. By applying "Telos" power model and using (18), (19), and (21), power calculation is

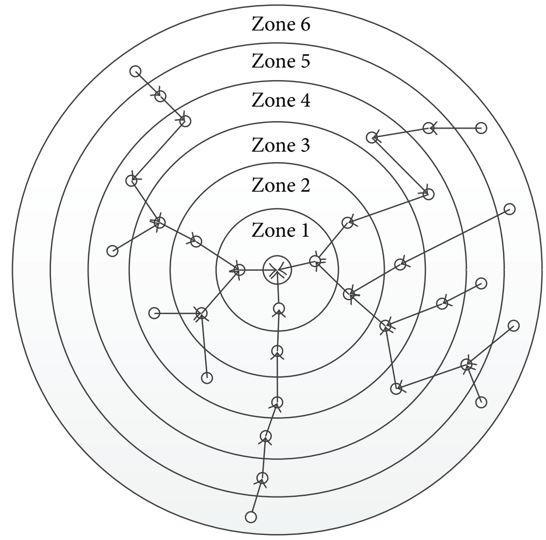

Figure 8: Network zones classification.

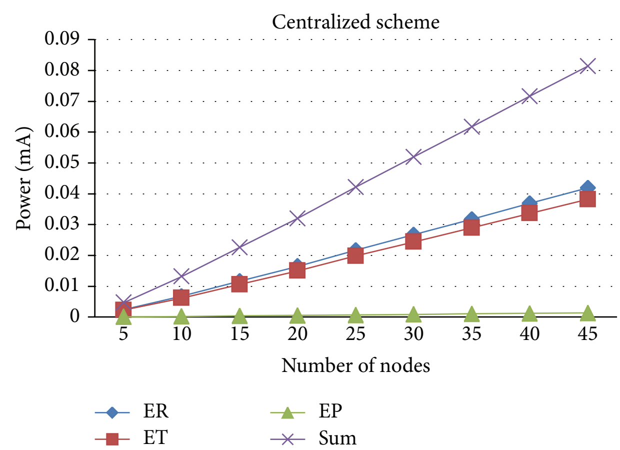

Figure 9: Centralized scheme power consumption.

processing power = $15 * 10^{-6}$ mA/sample, Rx power = $92 * 10^{-6}$ mA/bit, Tx power = $84 * 10^{-6}$ mA/bit, and $T = 5$.

Centralized. In centralized scheme, the RF transmission is the most power consuming process (Figure 9).

Distributed. Similar to the centralized scheme, in the RF scheme, the most power consuming process in is the transmission part, (Figure 10).

Hybrid ($N_0 = 1, N_1 = 4$). We assume the following: $p = 0.5$, $p_0 = 0.2$, $p_1 = 0.7$, and $T = 5$; K is varied from 10 to 30 (Figure 11).

Enhanced Hybrid. We define the probability of node behavior as centralized CP; we get CP values out of possible combination of N_0 and N_1.

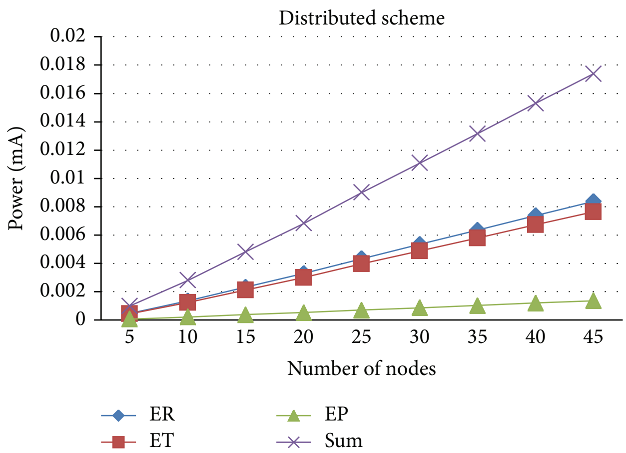

Figure 10: Distributed scheme power consumption.

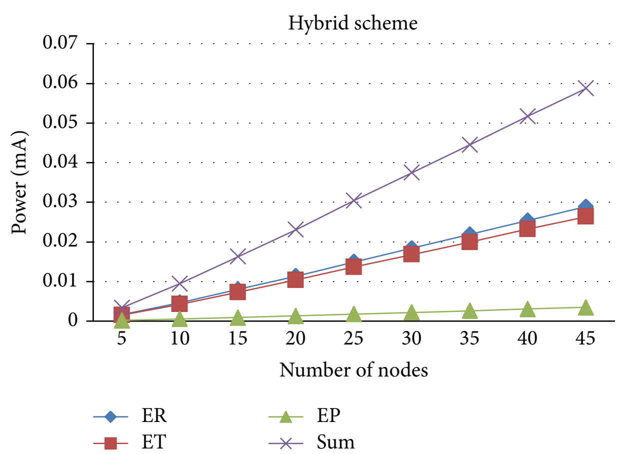

Figure 11: Hybrid scheme power consumption.

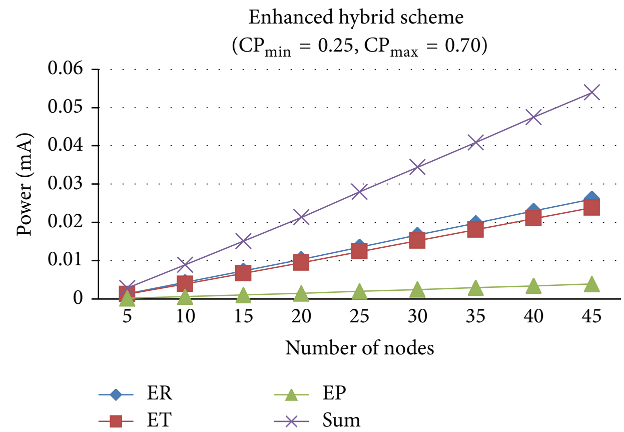

Figure 12: Enhanced hybrid scheme power consumption.

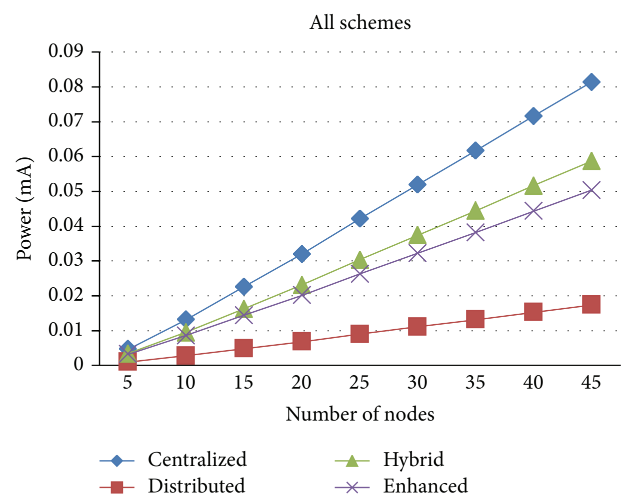

Figure 13: Power consumption of all schemes.

Figure 12 shows the power consumption of enhanced hybrid scheme, where we assign $CP_{min} = 0.25$ and $CP_{max} = 0.70$.

All Energy Schemes. The performance of the four schemes is shown in Figure 13, as we can see that enhanced scheme outperforms other schemes.

Accuracy Behavior. In our simulation we are able to get the same result which is given in [16], where we used hybrid $(N_0, N_1) = (1, 3), (1, 4)$, and $(0, 4)$ as shown in Figure 14.

The performance of the four schemes is shown in Figure 15, as we can see that enhanced scheme outperforms other schemes. In comparison to hybrid scheme our scheme gives a very close level of accuracy, as illustrated in Figure 15.

6. Conclusions

The main purpose of this paper is to enhance the event collection and detection capability of current WSN schemes. Two of the available schemes—centralized and distributed schemes—are basic and have no flexibility. The third scheme—the hybrid scheme—uses the two previous schemes to balance accuracy and energy; nevertheless all the nodes remain with fixed configuration and limited flexibility. On the contrary, the proposed scheme is designed to be more flexible in order to balance the power consumption and the detection accuracy at the node level. Every node is flexible in deciding how to behave, that is, whether to be more centralized or distributed.

To be able to compare the tradeoff between accuracy and power consumption in these schemes the model used should be realistic. This is one of the most significant weaknesses of the previous research, in which all power consumption calculations have been based solely on an assumed model. In the proposed scheme this weakness has been overcome by using a real WSN model, which produces realistic results.

As can be seen from the simulation results, our scheme saves a substantial amount of energy compared to the hybrid scheme, while retaining accuracy to almost the same degree. In addition, our scheme deals more efficiently with larger network area and denser node-number.

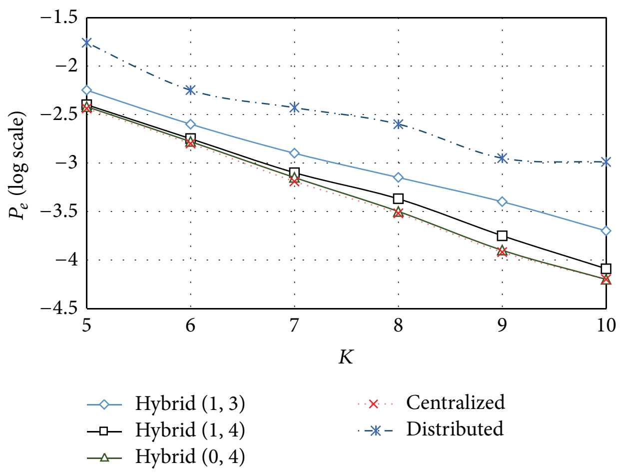

Figure 14: Comparison of three schemes in detection accuracy.

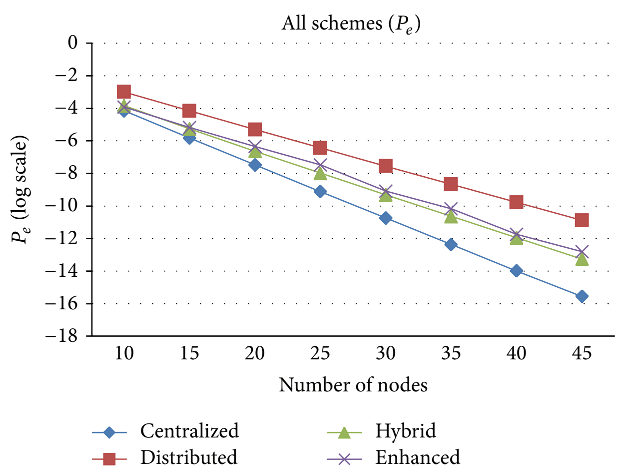

Figure 15: Probability of error for all schemes.

Although the focus of this paper has been on reducing overall power consumption, other future enhancements are also possible, for example, enhancing overall network lifetime by improving (N_0, N_1) selection techniques where the following factors can be considered:

(i) individual node power level,

(ii) event occurrence probability at each node,

(iii) next-hop distance and real Tx, Rx power.

Conflict of Interests

The author declares that there is no conflict of interests regarding the publication of this paper.

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