Chapter 10

Routing for Signal Processing

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10.1 Introduction

Signal processing (SP) is the process of information extraction or decision making by analyzing relevant observational or experimental data. SP such as estimation and detection is fundamental to numerous applications in wireless sensor networks (WSNs) such as environmental monitoring, industrial control, and military surveillance. WSNs designed for such applications normally consist of a large number of nodes densely scattered over an area of interest where multihop transmission is the only practical way to move data across the network [1]. Networking, therefore, is a vital process of multihop WSNs, and is carried out by routing protocols that are responsible for establishing routes between source and destination nodes.

One of the major constraints of WSNs is the limited energy supply. Since radio communication is often the most expensive operation a node performs in terms of energy usage, it is crucial for maximizing the lifetime of WSN that data packets are routed to the destination in an energy-efficient manner [2]. Indeed, intensive research has addressed energy-efficient routing for WSN (see Ref. [3] and the references therein). Common route metrics include the number of hops [4–6] and energy expenditure [7–11]. Hierarchical protocols [12,13] group nodes into clusters where cluster heads are responsible for intracluster data aggregation and intercluster communication in order to save energy. Location-based protocols utilize information on node locations to increase energy efficiency by relaying data only to certain desired regions [14]. These generic routing algorithms establish routes without considering the performance of signal processing (PoSP) that is achievable from the data being forwarded along the routes.

Protocols that incorporate application performance or data quality into routing are also available [15–17]. In particular, in data-centric routing, the node desiring certain types of information sends queries to certain regions and waits for data from the nodes located in the selected regions [15,16]. Alternatively, reference [17] introduces information-directed routing to minimize communication cost while maximizing information gain. Reference [18] proposes a link metric that considers packets delay as well as network lifetime.

SP in WSN has also been extensively studied. Traditionally, SP is carried out in a centralized manner where measurements from the nodes are collected and processed at a central location. In contrast, distributed methods [19–28] spread the computation across participating nodes to reduce communication cost and computational burden on any particular point of the system. For example, Ref. [26] proposes a hybrid energy-driven scheme where each sensor node sends out its 1 bit decision if that decision exceeds a predetermined detection accuracy threshold, and sends out all its observations otherwise. Two multihop fusion schemes are proposed in Ref. [27]. In the first scheme, each sensor transmits the histogram of the observations of its descendants and itself. In the second scheme, the normalized log-likelihood ratio (LLR) values for subsets of nodes are computed and propagated along the minimum spanning tree to the fusion center (FC) which decides the hypothesis based on the acquired LLR values. An energy-efficient distributed source localization algorithm is proposed in Ref. [28], where the intermediate estimates are progressively processed by nodes along the routes and the refined results are further relayed to the fusion centre.

Note that routing is not addressed in these distributed SP schemes and, therefore, a requirement for applying them is that routes between source and destination nodes are preestablished. One work related to joint optimization of routing and detection is Ref. [29]. It develops a serial fusion method for signal detection and proposes a routing scheme which is essentially a depth-first traversal technique enhanced with knowledge of locations of nodes. The intermediate detection decision is passed along the route which tries to traverse the network with as few hops as possible until a final detection decision can be made. However, the role of each node is considered identical; no quality of measurement of individual nodes is considered. Research on routing for signal processing (RfSP) protocols can be best represented by [30,31]. The protocols there facilitate joint optimization of PoSP and energy efficiency via metrics which directly connect PoSP with energy consumption associated with sensing and data transmission of each link along the routes. In particular, the problem of routing for the detection of a correlated random signal field is studied in Ref. [30]. A new link metric using the Chernoff information is proposed which characterizes detection performance based on the number and locations of nodes along the route. This novel metric captures the contribution of a given link to the decay rate of error probability of detection, and the route is determined using the shortest path framework though a centralized optimization algorithm. The problem of energy-efficient routing for detection subject to Neyman–Pearson

criterion is studied in Ref. [31]. There, routing metrics that connect the gain in signal-to-noise ratio and energy cost of each link are proposed, and combinatorial optimization programs are developed to solve for the best route in terms of a detection-probability-to-energy ratio.

Protocols in Refs. [30,31] are both centralized RfSP schemes, where the routes are computed centrally requiring complex optimization algorithms and global information such as locations and observation coefficients of all nodes in the network. Reference [32] proposes a distributed RfSP scheme for the same problem as in Ref. [31] where the routing decision is made at each node autonomously based on locally available information only. Clearly, for large-scale networks, or networks with dynamically changing topologies, distributed routing schemes which require neither global information nor centralized optimization would be more practical due to their superior flexibility and scalability.

In this chapter we address issues of building link metrics and the associated data aggregation schemes that realize RfSP, review RfSP protocols, and discuss the potential of and challenges facing RfSP. We also discuss in greater detail on how distributed RfSP schemes can be designed. Finally, we conduct numerical simulations to reveal the SP performance and energy efficiency of both centralized and distributed RfSP schemes as compared with generic routing protocols.

This chapter is organized as follows. Section 10.2 describes the problem concerning SP and RfSP in WSN. Section 10.3 reviews centralized RfSP schemes. Section 10.4 introduces distributed RfSP strategies. Section 10.5 provides the simulation results and Section 10.6 draws the conclusion.

10.2 Signal Processing and RfSP

In this section we give a general introduction to RfSP and discuss issues of building link metrics and the associated data aggregation schemes that one has to address in developing RfSP protocols.

10.2.1 Signal Processing Problem

Consider the scenario where sensor nodes are deployed over an area to collect measurements on a particular event or phenomenon. These measurements are then fed to a SP algorithm for the purpose of, for example, detecting the occurrence of the event or determining some information about the phenomenon. The data observed at node N_k can be described by

$$y_k = g_k s_k + w_k \quad (10.1)$$

where

s_k is the unknown signal sampled by N_k

w_k is the observation noise

g_k is the observation coefficient which is in general dependent on the characteristics of node N_k and its physical location

In a centralized SP scheme, all raw measurements $\{y_k\}$ are transmitted to a central location, that is, the FC, where the processing outcome D is achieved through a centralized computation:

$$D = F(\{y_k\}) \quad (10.2)$$

where $F(\cdot)$ denotes the fusion rule applied to the data.

One major issue of centralized SP schemes is the energy inefficiency associated with radio transmissions since no data compression is made when the packets are being relayed by intermediate nodes. As stated in Refs. [30,31], the energy consumption at each node N_k can be modeled by

$$e_{k,j} = \delta \Delta_{k,j}^\gamma + e_0, \quad (10.3)$$

where

e_0 accounts for energy consumption for sensing and processing

$\delta \Delta_{k,j}^\gamma$ is the energy of one data transmission over the link from N_k to its next-hop N_j , which depends on the distance $\Delta_{k,j}$ between N_k and N_j

Consider a route of M equally spaced nodes, $\Omega = \{N_1, N_2, \dots, N_M\}$, where the M -th node N_M is acting as the FC. Let Δ denote the node spacing, it can be easily verified that the total energy expenditure for the transmission along the route is. $(1 + 2 + \dots + (M - 1))(\delta \Delta^\gamma + e_0)$

10.2.2 Distributed Signal Processing

In a distributed SP scheme, nodes collectively achieve a global objective by each performing some processing based on locally available information and relaying the intermediate results. In particular, apart from the first node, the k -th node on the route receives the intermediate result u_{k-1} from the $(k - 1)$ -th node and combines it with its local observation y_k to generate its own intermediate result u_k , that is,

$$u_k = \begin{cases} F_k(u_{k-1}, y_k) & k = 1 \\ F_k(y_k) & k = 1 \end{cases} \quad (10.4)$$

which is relayed to the $(k + 1)$ -th node. Note that u_k may consist of multiple values. For example, it can include an estimate of a parameter and the associated confidence level. The last node on the route (i.e., the FC) generates the final result

$$D = u_M = F_M(u_{M-1}, y_M) \quad (10.5)$$

The strength of distributed SP is its potential of reducing energy consumption in transmission. Suppose u_k can be sent with one transmission, the total energy expenditure for the transmission along the route of M equally spaced nodes would be $(M - 1)(\delta \Delta^\gamma + e_0)$. In addition, in a distributed SP scheme, there is no special requirement on energy or computational power imposed on the FC. Here, any node can potentially act as a FC and the fusion (processing) process can stop at any node as soon as a preset performance measure (e.g., confidence level associated with the estimation) is achieved.

Despite all of its advantages, distributed SP algorithms are generally nontrivial to design. In other words, for a centralized fusion rule $F(\cdot)$ of (10.2), it is a challenging task to produce equivalent local fusion rules $\{F_k(\cdot)\}$ that collectively and incrementally achieve the objective and performance of $F(\cdot)$. This is a problem-specific practice and sometimes simplifying assumptions and approximations are necessary [18,24,28].

10.2.3 Routing for Signal Processing

RfSP protocols further exploit the potential of distributed SP schemes. In addition to energy-efficient data delivery via distributed processing, the issue of where to collect these data is addressed

in RfSP. The goal of RfSP is the joint optimization of PoSP and energy efficiency via routing metrics which directly connect SP performance and energy consumption. The advantages of RfSP over generic routing protocols are the ability to achieve optimum PoSP-to-energy-consumption ratio and the controlled trade-offs between PoSP and energy efficiency. The solutions to RfSP are highly dependent on the specific SP problems to solve, and usually involve the following three critical processes:

1. Design local fusion rules $\{F_k(\cdot)\}$ to be applied by nodes progressively and associated intermediate results to be forwarded further downstream along the route.
2. Develop a link metric $q_{k,j}$ that characterizes the contribution of a link to the performance of SP. It measures the gain of the link from node N_k to its next-hop N_j by means of a quantity directly related to PoSP, for example, estimation variance or detection probability, and therefore is in general dependent on the data quality (as measured by the observation coefficient) of N_j and the physical locations of both the local and next-hop nodes.
3. Build up a routing metric $\lambda(\cdot)$ that relates the total PoSP contribution ($Q(\Omega)$) and energy expenditure ($E(\Omega) = \sum_k e_{k,(k+1)}$) of a route Ω , and obtain the desired route Ω^* through the following constrained optimization:

$$\Omega^* = \arg \max_{\Omega \in \Pi} \lambda(Q(\Omega), E(\Omega)) \quad (10.6)$$

where Π is the set of routes which satisfy certain constraints. Typical constraints are

C1: $E(\Omega) \leq E_{\text{lim}}$ —route energy constraint

C2: $Q(\Omega) \geq Q_{\text{lim}}$ —guaranteed performance

For example, the routing metric $\lambda(\cdot) = Q(\Omega)/E(\Omega)$ under C1 leads to the route that has the best performance-to-energy ratio among all routes with energy expenditure up to E_{lim} . Note that the maximization in (10.6) could be replaced by minimization depending on how the metric $\lambda(\cdot)$ is formulated.

The task of developing RfSP protocols is, in general, challenging. First of all, as mentioned previously, the “splitting” of a central SP algorithm $F(\cdot)$ into local rules $\{F_k(\cdot)\}$ is nontrivial. Secondly, the development of the link metric which captures the gain in performance of individual links can be very complex. In addition, in order to facilitate solving the optimization in (10.6), it is important for a link metric to be (1) independent—contribution of a link is independent of past and future links; and (2) additive— $Q(\Omega) = \sum_k q_{k,(k+1)}$. As will be demonstrated in Section 10.3, depending on the specific SP problem, approximations are often required in deriving a link metric of desired forms.

Note that the optimization in the form of (10.6) is carried out centrally, demanding global information such as locations and observation coefficients of all nodes in the network. For such centralized RfSP schemes, although the SP is performed in a distributed fashion, the routes have to be precomputed and nodes programmed for each source-destination pair. Therefore, distributed RfSP (D-RfSP) schemes which require neither global information nor centralized optimization are more practical for large-scale networks, or networks with dynamically changing topologies. In a D-RfSP protocol, each node makes its routing decision autonomously based on locally available information only. However, since D-RfSP protocols only utilize local information, they will be suboptimum as compared to their centralized counterparts. Details on how to design D-RfSP protocols will be provided in Section 10.4.

10.3 Centralized RfSP Schemes

In this section we highlight the core development process of two innovative RfSP schemes [30,31] to illustrate how joint optimization of SP performance and energy efficiency can be achieved for specific SP problems.

10.3.1 Chernoff Routing

The detection of a correlated Gaussian signal field is considered in Ref. [30]. Let hypothesis H_1 denote the presence of the phenomenon within the sensor network and H_0 its absence, and assume all sensors have identical observation coefficients ($g_k = 1$), the observations at each node N_k along the route $\Omega = \{N_1, N_2, \dots, N_M\}$ under each hypothesis are given by

$$\begin{aligned} H_0: y_k &= w_k, \quad k = 1, \dots, M \\ H_1: y_k &= s_k + w_k, \quad k = 1, \dots, M \end{aligned}$$

where the s_k 's are correlated Gaussian samples of the signal with $s_k \sim N(0, \sigma_s^2)$ and a nondiagonal covariance matrix. The noise samples w_k are i.i.d. Gaussian with $w_k \sim N(0, \sigma_w^2)$. The centralized decision rule is to decide H_1 if

$$\ln \frac{p_1(y)}{p_0(y)} \geq \ln \frac{\pi_0}{\pi_1} \quad (10.7)$$

where

$$y = [y_1, \dots, y_M]$$

π_j and $p_j(y)$, $j = 0, 1$, are the prior probability of H_j and probability density function (PDF) of the joint Gaussian random variables under H_j , respectively

The development of the link metric for RfSP starts with using the Chernoff information as a tractable metric which captures the probability of detection error of a given route. Then, Schweppe's recursive representation of the likelihood function is used to express the Chernoff information in an additive form. Finally a link metric which is independent from link to link is created by assuming a Gauss–Markov signal correlation model.

As stated in Ref. [33], the average error probability of the rule (10.7) is bounded by

$$P_\varepsilon \leq \pi_0^{1-s} \pi_1^s e^{\mu(s)}, \quad 0 \leq s \leq 1$$

where $\mu(s)$ is the cumulant generating function of the LLR under H_0 , that is,

$$\mu(s) = \ln E_0 \left\{ \exp \left(s \ln \frac{p_1(y)}{p_0(y)} \right) \right\}, \quad 0 \leq s \leq 1$$

with $E_j(\cdot)$, $j = 0, 1$, denoting the mathematical expectation under H_0 and H_1 , respectively. The Chernoff information [34] is defined as the $\mu(s)$ evaluated at the maximizing value of s , *that is*,

$$Q = \arg \max_{0 \leq s \leq 1} \{-\mu(s)\} \quad (10.8)$$

In order to reveal the contribution of each link to P_ε , Schweppe's recursive representation of the likelihood function [35] is utilized and it is shown that (10.8) can be approximated by $Q = \sum_{k=1}^M q_k$, with

$$q_k = \frac{1}{2} \ln \left(1 + \frac{P_{k/k-1}}{\sigma_w^2} \right) \quad (10.9)$$

where $P_{k/k-1} = E_1\{s_k - E_1\{s_k/y_1, \dots, y_{k-1}\}\}^2$ is interpreted as the power of the signal innovation. The proposed link metric (10.9) is monotonic in k . It indicates the amount of uncertainty resolved by collecting a sample from node N_k , and the optimal route as the one that provides the maximum reduction in uncertainty.

Since the link metric (10.9) is in general not independent from link to link, in order to make the optimization of finding the optimal route tractable, the signal field is assumed to be a Gauss–Markov process. For this special case, after some approximations, the link metric can be expressed as a function of the link length Δ_k ,

$$q_k = \frac{1}{2} \ln(\text{SNR} + 1 - (\text{SNR} - 1)e^{-2A\Delta_k}) \quad (10.10)$$

where A is a parameter in the signal model, and $\text{SNR} = \sigma_s^2/\sigma_w^2$. The Gauss–Markov model also allows the detection be carried out in a distributed fashion using the Kalman aggregation, where each node, based on data from previous-hop and local measurement, calculates and sends to its next-hop three quantities: the accumulated likelihood function, the variance of innovation, and the predicted measurement.

With this link metric which characterizes the additive and independent contribution of each link to detection performance, the Chernoff routing [30] finds the optimal route using the shortest path framework. In shortest path routing [36], each link in the network is assigned a link cost $\gamma_{k,j}$ which quantifies the consumed resources of the link N_k to N_j , and the “least cost” route, where the cost of a route is simply the sum of its link costs, is sought. A constant link cost, that is, $\gamma_{k,j} = \varepsilon$, leads to the minimum-hop routing. Alternatively, setting $\gamma_{k,j} = e_{k,j}$, where $e_{k,j}$ is the link energy consumption given by (10.3), results in the minimum-energy routing. The link cost of the Chernoff routing introduces a weighting factor $\alpha \geq 0$ to control trade-offs between detection performance and energy:

$$\gamma_{k,j} = (e_{k,j} - \alpha q_j)_\varepsilon^+$$

where

$$(x)_\varepsilon^+ = \begin{cases} x & x > 0 \\ \varepsilon & x \leq 0 \end{cases}$$

It is shown in Ref. [30] that with proper values of the design parameters α and ε , the Chernoff routing is able to achieve better detection performance for the same energy consumption than the minimum-hop and minimum-energy protocols.

10.3.2 Combinatorial Optimization Routing

The problem of target detection is considered in Ref. [31]. The measurement y_k at node N_k along the M -nodes route Ω depends on which of the two hypotheses, the noise-only hypothesis H_0 and

target-present hypothesis H_1 , is true. That is,

$$H_0 : y_k = w_k, \quad k = 1, 2, \dots, M \quad (10.11)$$

$$H_1 : y_k = Bg_k + w_k, \quad k = 1, 2, \dots, M \quad (10.12)$$

where g_k is the observation coefficient of N_k , $B > 0$ represents the reflection strength of the target in response to illuminating signals and is assumed unknown. The noise w_k is white Gaussian with zero mean and variance σ^2 . The PDFs under each hypothesis are, therefore, given by

$$p_0(y) = \frac{1}{(2\pi\sigma^2)^{M/2}} \exp\left(-\frac{1}{2\sigma^2} \sum_{k=1}^M y_k^2\right) \quad (10.13)$$

$$p_1(y) = \frac{1}{(2\pi\sigma^2)^{M/2}} \exp\left(-\frac{1}{2\sigma^2} \sum_{k=1}^M (y_k - Bg_k)^2\right) \quad (10.14)$$

According to the Neyman–Pearson criterion that maximizes the probability of detection P_D for a given probability of false alarm P_{FA} [37], H_1 is decided if the likelihood ratio $L(x) = p_1(y)/p_0(y)$ is greater than a threshold. By utilizing (10.13) and (10.14), this criterion can be realized by the test

$$T(y) = \sum_{k=1}^M g_k y_k > \gamma \quad (10.15)$$

where γ is determined via

$$P_{FA} = \int_{\{y: L(y) > \gamma\}} p_0(T(y)) dy \quad (10.16)$$

The test (10.15) immediately suggests a distributed processing scheme where each nondestination node N_I ($I < M$) computes the locally accumulated test statistic $\sum_{k=1}^I g_k y_k$ and forward it to the next-hop, and the detection decision is made at the destination node based on the accumulated $T(y)$.

The link metric for RfSP is derived by examining the performance of this detector as follows. Since the noise samples are uncorrelated and the test statistic $T(y)$ is Gaussian for both hypotheses, it can be shown that

$$p_0(T(y)) \sim N(0, \sigma^2 \varepsilon)$$

$$p_1(T(y)) \sim N(B\varepsilon, \sigma^2 \varepsilon)$$

where $\varepsilon = \sum_{k=1}^M g_k^2$.

The threshold γ can then be determined according to (10.16) without knowing the value of B , and the probability of detection can be found to be

$$P_D = \int_{\gamma}^{\infty} p_1(y) dy = Q_f \left(Q_f^{-1}(P_{FA}) - \sqrt{\kappa^2} \right) \quad (10.17)$$

where

$$Q_f(x) = \int_x^\infty \frac{1}{\sqrt{2\pi}} \exp\left(-\frac{1}{2}t^2\right) dt$$

$$\kappa^2 = B^2 \varepsilon / \sigma^2$$

It can be seen from (10.17) that the detection performance is totally characterized by ε . Since $Q_f(x)$ is a monotonically decreasing function, P_D is monotonically increasing with increasing ε which is defined as the performance contribution of the route:

$$Q(\Omega) \triangleq \varepsilon = \sum_{k=1}^M g_k^2 \quad (10.18)$$

The corresponding link metric g_k^2 captures the performance contribution of each node on the route and, as demonstrated in (10.18), has the properties of additivity and independence. To facilitate joint optimization of detection performance and energy efficiency, the mean detection-probability-to-energy is introduced in Ref. [31]:

$$\lambda(\Omega) = \frac{Q(\Omega)}{E(\Omega)} \quad (10.19)$$

and the optimum route is obtained through the following optimization:

$$\Omega^* = \arg \max_{\Omega} \lambda(\Omega) \quad (10.20)$$

Two variants of (10.20) are also proposed in Ref. [31] where constraints on $Q(\Omega)$ and $E(\Omega)$ are introduced, respectively, to the optimization so that solutions with guaranteed performance or constrained energy can be sought. These routing metrics are shown in Ref. [31] to achieve superior detection performance and energy consumption trade-offs over the traditional minimum-hop and minimum-energy routing protocols.

10.4 Distributed RfSP Protocols

The centralized RfSP schemes demand global information such as locations and observation coefficients $\{g_k\}$ of all nodes in the network be available at a central location where Ω^* is computed in a static manner. As discussed in Section 10.1, in practice not only the network topology can change, $\{g_k\}$ can also change in situations such as target movements. Such dynamics would make recalculating and updating the centrally optimized routes unrealistic. In this section we present strategies for distributed RfSP (D-RfSP) where the next-hop is calculated on the fly using only locally available information. That is, each node selects the next-hop autonomously with the goal of maximizing the SP performance associated with unit energy expenditure. One protocol of such nature is proposed in Ref. [32] for a signal detection problem. In a D-RfSP scheme, a local node N_k evaluates the performance gain ($q_{k,j}$) each neighbor N_j can potentially provide and the associated energy cost ($e_{k,j}$), and selects the one which yields the largest performance-gain-to-energy ratio as the next-hop, that is,

$$N_j^* = \arg \max_{N_j \in \Theta} \frac{q_{k,j}}{e_{k,j}} \quad (10.21)$$

where Θ denotes the set of N_k 's neighbors which meet certain conditions. The neighbors of a node are the nodes that physically positioned within its radio range such that direct communications are possible. Apart from designing a distributed signal fusion scheme and the link metric $q_{k,j}$, two unique issues need to be addressed in developing a D-RfSP scheme. Firstly, energy constraining applied locally at each node is essential for the route to converge. Otherwise the route will attempt to traverse the whole network. Secondly, revisits should be avoided unless absolutely necessary since a revisited node does not provide any new contribution to the SP performance. The solutions to these matters are reflected in the design of the rules for Θ . In this section we first address these two matters and then present in detail a D-RfSP strategy that is based on logical relationships of nodes.

10.4.1 Meeting Energy Constraint

D-RfSP protocols rely on information of neighboring nodes. This information is readily available for most of WSN systems. In fact, in order to maintain connection to the network, a node needs to keep some information such as addresses of its neighbors. This is usually done through a local record termed as the neighbor table. The neighbor table is generally built up during a node's join process when it scans its neighborhood in order to discover its neighbors and find a potential parent node to join [38,39]. The ZigBee standard requires each node to keep the neighbor table up-to-date. This can be achieved, for example, by periodically scanning and/or monitoring the neighborhood.

If the locations of neighbors and the destination are available, to control energy expenditure a local node N_k can regard the neighbor N_j as a next-hop candidate (i.e., a member of Θ), only if it satisfies the following distance condition:

$$\delta\Delta_{k,j}^y + e_0 + \delta\Delta_{j,M}^y + e_0 < E_{k_lim} \quad (10.22)$$

where E_{k_lim} is the energy constraint of the route from N_k to the destination N_M . Since N_k does not know the hops beyond N_j , here the energy consumption from the neighbor N_j to N_M is only an approximation. Therefore (10.22) is a so-called soft constraint; it can be slightly dishonored if necessary. In Section 10.4, we will show that if the number of hops from N_j to the destination can be determined, the corresponding energy cost can be estimated by the average energy per hop.

10.4.2 Avoiding Unnecessary Revisits

When the next-hop is determined locally, visiting a node more than once by the same route can happen, although this would rarely occur for densely deployed sensor networks. Therefore, a mechanism should be built into a D-RfSP protocol to avoid unnecessary revisits while the route traverses to the destination. This can be accomplished by the visited node with observation coefficient $g_j > 0$ informing all of its neighbors that it will no longer contribute to the SP performance and should now be considered as having $g_j = 0$. One way to implement this messaging is through dedicated application messages with the associated additional cost in energy and bandwidth.

Another way to achieve this notification is to exploit the services of CSMA/CA-based MAC (medium access control). By using a reserved bit in the RTS (request-to-send) and CTS (clear-to-send) packets, the (re)visit status of a node can be probed and conveyed. This mechanism has been proposed in Ref. [40] for the purpose of informing neighbors of the type of packets to be transmitted.

The third way of carrying out this messaging is to take advantage of the broadcast nature of wireless transmission, where the radio transmission will be heard by all neighbors within the transmission range, not just the intended recipient. In the ZigBee protocol, the network layer is responsible for discarding overheard packets by checking the receiver address field in the received packets. Overhearing has been employed in WSN for network time synchronization [41,42], reducing redundant transmissions [43], and propagating the location of the mobile sink to the source node [44]. As proposed in the distributed RfSP protocol in Ref. [32], when a node with $g_j > 0$ is visited for the first time, it uses the energy which is enough to reach its farthest neighbor when transmitting to the next-hop. Upon hearing the transmission, both the intended recipient and overhearing nodes mark the transmitting node as *VISITED* and treat it as having $g_j = 0$ in subsequent routing. This mark is cleared at the end of current routing session through, say, a time-out at each node. The extra energy in transmission (to reach the farthest neighbor) is the cost one has to pay for lacking of centralized coordination and optimization.

10.4.3 Logical Topology and Tree Routing

This section discusses the logical structure expressed by nodes' addresses upon which the D-RfSP strategy in the next section will be built.

Sensor networks are normally constructed in a spanning tree manner by starting with a root node and growing as new nodes join the existing nodes as child nodes. Each node has one and only one parent while a parent can have multiple children. The resultant logical relationship (LR) is a simple tree structure although the network's physical topology can be quite complex. One parameter associated with each node is its network depth d . The root node has $d = 0$ and a nonroot node has a nonzero depth which equals its parent's $d + 1$. The depth indicates the minimum number of hops a transmitted frame must travel, using only parent-child links, to reach the root node. When a packet from a node N_j travels upward along the tree to the root, it will reach all its ancestors. Similarly, a node-to-root route from another node N_d will cover all ancestors of N_d . The node where the two node-to-root routes merge is termed as the joint node (JN) of the two starting nodes. Note that if the two nodes are the same, the JN is the node itself and, if one node is an ancestor of the other, their JN is the ancestor node.

To make peer-to-peer communication possible, each node must have a unique identity that is typically in the form of its address. Due to the ad-hoc nature of the network topology, an address assignment scheme has to be in place to assign addresses to nodes when they join the network. We are particularly interested in those schemes where, instead of using randomly generated numbers, each parent node autonomously generates addresses for joining nodes according to specific rules. Various such structured address assignment schemes have been reported [38,45–52]. The most notable of them is the one specified in the ZigBee standard [38].

For such structured addresses it has been shown [38] that the LR of nodes *on the same branch* can be determined from their addresses. In particular, from the address of a node, the addresses of upstream nodes (i.e., its parent and all other ancestors) and downstream nodes (i.e., its children and all other descendants) can be determined. This vertical relationship has led to the so-called tree routing (TR) protocol. The TR is a distributed algorithm where the routing decision is made locally and the route is restricted to parent-child links only. In particular, when a packet is received by an intermediate node, it is forwarded either downward or upward along the logical tree. If it is determined that the destination is a descendant node, the data is sent down along the tree to either the destination node if it is a child or, otherwise, the ancestor of the destination node. Otherwise the parent node is chosen as the next-hop.

10.4.4 LR-Based RfSP Protocols

The TR protocol can be very inefficient because of the restrictions on next-hop candidates. In fact, relationship richer than that utilized in TR can be identified in networks with structured address assignment schemes and, therefore, more efficient LR-based routing is possible. It is shown in Ref. [53] that for such networks the logical distance between any two nodes, in terms of the number of hops via parent–child links, can be determined by their addresses. In particular, for any source–destination pair (N_d, N_j) , the hop-count from N_j to N_d via parent–child links is given by

$$H_j = d_j + d_d - 2d_{jd}, \quad (10.23)$$

where d_j , d_d , and d_{jd} are the depths of N_j , N_d , and the join-node of them, respectively. All these three depths can be readily determined from addresses of N_d and N_j . Note that this is a conservative prediction of the hop-count. That is, it is guaranteed that at most H_j hops are required for a packet to travel from N_j to N_d ; if a cross-branch jump happens at a downstream node along the route, the actual hops will be less.

This property can be used to evaluate all neighbors, not just parent and children, for finding the shortest possible route to the destination. As a result, the route cannot only traverse vertically along parent–child links, but also “jump” horizontally to other branches of the tree, generating more efficient routes. We now present a LR-based D-RfSP protocol which utilizes this routing potential. We assume that homogenous nodes are densely deployed and a structured address assignment scheme is in place to allow determination of (10.24). Each node is required to record locally the addresses and observation coefficients of its neighbors in its neighbor table. In addition, the distances to each neighbor are needed; their absolute locations are not required.

The routing starts at the source node N_1 which is assumed to be the only node with the knowledge of the route energy constraint E_{lim} . It transforms E_{lim} to the maximum number of hops of the route based on the average transmission energy to communicate with all of its neighbors:

$$H_{\text{max}} = \frac{E_{\text{lim}}}{\frac{1}{K} \sum_{j=1}^K (\delta \Delta_{1,j}^\nu + e_0)} \quad (10.24)$$

where K is the number of neighbors of N_1 . This conversion is valid due to the dense deployment and homogeneous nature of the network. Node N_1 then groups all neighbors which satisfy the following condition into the set Θ and selects the next-hop according to (10.21):

$$H_j + 1 \leq H_{\text{max}} \quad (10.25)$$

where H_j is the number of hops N_j takes to reach the destination. The value of H_{max} is transmitted along with locally derived intermediate SP results to the chosen next-hop, which uses $(H_{\text{max}} - 1)$ as the maximum number of hops in selecting its next-hop. It is assumed that the address of the destination node is known to all nodes. Otherwise, the destination address could be conveyed from the source node to subsequent nodes in the same way H_{max} is propagated. This process continues until the destination is reached.

In essence, the next-hop is the one with maximum performance-gain-to-energy ratio among the neighbors that have guaranteed number of hops to the destination. If all these neighbors have zero observation coefficients (i.e., $g_j = 0$ for all the nodes in Θ), then the minimum number of hops to the destination is obtained as follows:

$$H_{\text{min}} = \arg \min_{N_j \in \Theta} H_j \quad (10.26)$$

and the node with $H_{\min}$ and is physically closest to the local node N_k is chosen as the next-hop, that is,

$$N_j^* = \arg \min_{N_j \in \Theta} \Delta_{k,j} \quad \text{subject to } H_j = H_{\min} \quad (10.27)$$

This D-RfSP strategy is readily implementable in ZigBee networks, where a structured address assignment scheme is in place and the overhearing based revisit avoidance can be employed. In the next section, we evaluate the performance of this D-RfSP protocol as applied in a signal estimation problem.

10.5 Performance Evaluation

We conduct simulations to reveal the SP performance and energy efficiency of the LR-based D-RfSP scheme in comparison with that of its centralized counterpart (C-RfSP), the TR, minimum hop (min-hop), and minimum-energy (min-energy) protocols.

Consider the following data observation model at the k -th node of route $\Omega = \{N_1, N_2, \dots, N_M\}$:

$$y_k = g_k \theta + w_k \quad k = 1, 2, \dots, M \quad (10.28)$$

where

- $g_k \geq 0$ is the observation coefficient
- w_k is the white Gaussian noise with zero mean and variance σ^2
- θ is the unknown signal to be estimated

It is shown in Ref. [54] that the best linear unbiased estimate and its variance are given by

$$\hat{\theta} = \frac{\sum_{k=1}^M g_k y_k}{Q(\Omega)} \quad (10.29)$$

$$\text{var}(\hat{\theta}) = \frac{\sigma^2}{Q(\Omega)} \quad (10.30)$$

where $Q(\Omega) = \sum_{k=1}^M g_k^2$. The estimation (10.29) can be carried out in a distributed manner where each intermediate node N_I ($I < M$) sends locally computed results $\sum_{k=1}^I g_k y_k$ and $\sum_{k=1}^I g_k^2$ to the next-hop. It can be seen from (10.30) that $q_{k,j} = g_j^2$ captures the performance contribution of each neighbor N_j and is thus chosen as the link metric for RfSP schemes. Accordingly, the D-RfSP protocol implements the LR-based scheme introduced in Section 10.4 (may incur extra transmission energy as per overhearing based revisit avoidance), and the C-RfSP protocol obtains the optimum route through the following optimization:

$$\Omega^* = \arg \max_{\Omega} \lambda(\Omega) \quad \text{subject to } E(\Omega) \leq E_{\lim} \quad (10.31)$$

where $E(\Omega)$ is the route energy consumption and $\lambda(\Omega) = Q(\Omega)/E(\Omega)$ is the estimation-gain-to-energy ratio.

An event-driven simulator developed in MATLAB[®] is employed. In all the simulation scenarios, the ZigBee network parameter is set as $(C_M, R_M, L_M) = (5, 5, 6)$, where C_M, R_M , and

L_M denote the maximum number of children a parent can have, maximum number of router children a parent can have, and maximum network depth, respectively. Two types of nodes are specified in ZigBee networks, namely routers that can accommodate other nodes as children and end devices that cannot have children of their own. The network setup process including address assignment scheme of the ZigBee standard is followed. In particular, after the nodes are deployed with every node having acquired a physical location, the root node is powered on to start the network. All the other nodes then power on and search the neighborhood for a potential parent which is by definition a router already joined the network and having capacity to accommodate more children. The joining node and potential parent then exchange join request and response messages to complete the join process by which the joining node is assigned an address. The network is established after all nodes have joined the network. The target is then deployed and each node builds up its neighbor table which contains the observation coefficients of and distances to its neighbors.

For the C-RfSP optimization (10.31), all routes satisfying the energy constraint are sought [55] and the one with the largest estimation-gain-to-energy ratio is selected [31]. The routes by the min-hop and min-energy protocols are found using the algorithms in Ref. [55] as well. All these operations require centralized optimization based on the deployment information—nodes' locations and observation coefficients. The solutions of these schemes are, therefore, globally optimal in terms of the corresponding metrics. For the D-RfSP scheme, the routes are determined progressively at each node as the routes traverse to the destination. The TR protocol also determines the route locally but, as the min-hop and min-energy protocols, does so without considering the estimation performance. An event is defined as the transmission of a network layer packet from the source node to the destination node along the route determined by a routing protocol under study. The events happen sequentially, that is, an event starts after the previous one finishes. As a result, there is no packet collision or channel contention during packet transmission. This allows us to focus on the routing protocols under study by examining the performance of the routes generated.

We consider the scenarios where 100 nodes each with a transmission range of 200 m are randomly deployed in a square region with size 1000 m by 1000 m. The destination node is the root node which is located at the centre of the region (500 m, 500 m) and the signal source (i.e., the target) is located at (100 m, 100 m). The observation coefficient of a node within sensing range T_s is inversely proportional to its distance (Δ_k) to the target, that is,

$$g_k = \begin{cases} 1/\Delta_k & \text{if } \Delta_k \leq T_s \\ 0 & \text{otherwise} \end{cases} \quad (10.32)$$

For each simulation scenario, 200 instances of the sensor network are randomly generated. For each instance, a source node is randomly chosen among the nodes within 100 m away from the target and the routes to the destination node established by the routing protocols are studied, that is, their estimation variances and estimation-gain-to-energy ratios $\lambda(\Omega)$ are determined. The results over all the network instances are then averaged to produce the final measure. The following parameters of the data model (10.28) and energy consumption model (10.3) are chosen: $\theta = 1$, $\delta = 10^{-2}$, $\nu = 2$, $e_0 = 0.5 \mu\text{J}$ and the noise variance is chosen to be $\sigma^2 = 3.98 \times 10^{-5}$ which amounts to a 4-dB SNR at a node 100 m away from the target.

Figure 10.1 shows one instance of the network and the routes determined by the routing protocols when sensing range $T_s = 200$ m and energy constraint $E_{\text{lim}} = 5 \mu\text{J}$, where the star

Figure 10.1 One instance of the network and routes.

Table 10.1 Routes in Figure 10.1 and Their Performance Metrics

<i>Protocol</i>	Ω	$E(\Omega)$ in μJ	$Q(\Omega)$	$\lambda(\Omega)$ in $1/\mu J$	$var(\hat{\theta})$
Min-hop	$1 \rightarrow 8 \rightarrow 9 \rightarrow 6 \rightarrow 7$	3.4691	$0.9050e-3$	$0.2609e-6$	0.0440
Min-energy	$1 \rightarrow 4 \rightarrow 5 \rightarrow 12 \rightarrow 7$	3.2878	$0.9375e-3$	$0.2852e-6$	0.0425
TR	$1 \rightarrow 8 \rightarrow 10 \rightarrow 11 \rightarrow 6 \rightarrow 7$	4.0759	$0.9050e-3$	$0.2220e-6$	0.0440
C-RfSP	$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 12 \rightarrow 7$	4.3613	$1.8972e-3$	$0.4350e-6$	0.0210
D-RfSP	$1 \rightarrow 2 \rightarrow 3 \rightarrow 4 \rightarrow 5 \rightarrow 6 \rightarrow 7$	5.2261	$1.8972e-3$	$0.3630e-6$	0.0210

denotes the target and small circles denote sensor nodes. Table 10.1 lists the routes and associated performance metrics.

It can be seen from Table 10.1 that the min-energy route, as expected, has the least energy consumption. Since the min-hop route is not unique and the earliest identified one is chosen, it does not have the same performance metrics as the min-energy route even though they have the same number of hops in this particular case. The TR route has comparable performance both in estimation performance and energy efficiency as the other two generic protocols since in essence it is a hop-count-based scheme. Both the C-RfSP and D-RfSP routes traverse away from the destination initially in order to cover nodes with more information (i.e., the ones close to the target.)

Figure 10.2 Estimation variances with changing energy constraint.

The energy efficiency $\lambda(\Omega)$ of the D-RfSP route is less than that of the C-RfSP route which is the optimum solution in this regard. This inferior performance of the D-RfSP is due to the fact that a node only knows its neighbors and makes a routing decision based on local information only. Both RfSP routes are shown to have more accurate estimates and higher energy efficiency than that of the three generic routing routes.

Figures 10.2 and 10.3 show the $\text{var}(\hat{\theta})$ and $\lambda(\Omega)$, respectively, of the routes when $T_s = 200$ m and E_{lim} changes from 4 to 8 μJ . The estimation performance and energy efficiency of the TR, min-hop, and min-energy routes remain constant since they are independent of energy constraints. Both centralized and distributed RfSP protocols have increased estimation accuracy when the energy constraint is increased. For the D-RfSP protocol, it appears that when E_{lim} is tight ($< 5 \mu J$) there is not much room to maneuver, and when E_{lim} is loose ($> 7 \mu J$) the route traversals a larger number of nodes to increase the estimation gain $Q(\Omega)$, resulting in reduced energy efficiency in both cases. The two RfSP schemes are shown to yield better estimates and energy efficiency than the three generic routing protocols.

Figures 10.4 and 10.5 show the $\text{var}(\hat{\theta})$ and $\lambda(\Omega)$, respectively, of the routes when $E_{lim} = 5 \mu J$ and T_s changes from 100 to 500 m. When T_s increases, all the five routes are shown to produce better estimates since more nodes are included in the sensing range. These additional nodes, however, have relatively small observation coefficients g_k because they are further away from the target (see (10.32)). This leads to reduced energy efficiency of D-RfSP routes since they try to capture more estimation again by visiting increased number of nodes. A possible modification to the D-RfSP protocol is to incorporate a threshold τ and treat all neighbors with $g_j < \tau$ as having $g_j = 0$. Once again, the two RfSP protocols outperform the three generic protocols in both estimation performance and energy efficiency.

Figure 10.3 Energy efficiency with changing energy constraint.

Figure 10.4 Estimation variances with changing sensing range.

Figure 10.5 Energy efficiency with changing sensing range.

10.6 Concluding Remarks

Routing protocols that jointly optimize SP performance and energy efficiency have great potential in achieving energy-efficient routing. Although being inferior to the global optimum solution in terms of energy efficiency, distributed RfSP protocols do not require centralized optimization and, therefore, are viable alternatives to centralized schemes for large-scale networks due to their flexibility and scalability. Simulation results have shown that both centralized and distributed RfSP protocols are able to achieve significant improvement in both SP performance and energy efficiency over generic routing schemes.

Developing RfSP schemes is challenging and problem specific. Future work in this area could involve extending link metrics for Gauss–Markov signals to more general models and dealing with colored or non-Gaussian noise. Another interesting work is to develop RfSP schemes for other WSN SP algorithms such as beam-forming [56], channel identification [57], and principal component analysis [58].

References

1. F. Zhao and L. Guibas, *Wireless Sensor Networks: An Information Processing Approach*, Boston, MA: Elsevier-Morgan Kaufmann, 2004.
2. C. Chong and S.P. Kumar, Sensor networks: Evolution, opportunities, and challenges, *Proceedings of the IEEE*, 91, 1247–1256, 2003.
3. K. Akkaya and M. Younis, A survey on routing protocols for wireless sensor networks, *Ad Hoc Networks*, 3, 325–349, 2005.

4. C. Perkins and P. Bhagwat, Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers, in *Proceedings of the ACM SIGCOMM*, London, UK, pp. 1–11, 1994.
5. D.B. Johnson and D.A. Maltz, Dynamic source routing in ad hoc wireless networks, in *Mobile Computing*, (eds.) Tomasz Imielinski and Henry F. Korth, pp. 153–181, Boston, MA: Kluwer Academic Publishers, March 1996.
6. C.E. Perkins and E.M. Royer, Ad hoc on-demand distance vector routing, in *Proceedings of Second IEEE Workshop Mobile Computing Systems and Applications*, New Orleans, Louisiana, USA, pp. 90–100, 1999.
7. J.H. Chang and L. Tassiulas, Maximum lifetime routing in wireless sensor networks, *IEEE/ACM Transactions on Networking*, 12, 609–619, August 2004.
8. M. Zimmerling, W. Dargie, and J.M. Reason, Energy-efficient routing in linear wireless sensor networks, in *IEEE International Conference on Mobile Ad hoc and Sensor Systems*, Pisa, Italy, pp. 1–3, 2007.
9. F. Shao, X. Shen, and L. Cai, Energy efficient reliable routing in wireless sensor networks, in *First International Conference Communications and Networking*, Beijing, China, pp. 1–5, 2006.
10. H. Chang and L. Tassiulas, Energy conserving routing in wireless ad hoc networks, in *Proceedings of IEEE INFOCOM 2000*, Tel-Aviv, Israel, pp. 22–31, March 2000.
11. S. Singh, M. Woo, and C. Raghavendra, Power-aware routing in mobile ad hoc networks, in *Proceedings 4th ACM/IEEE Conference on Mobile Computing and Networking (MobiCom)*, Seattle, Washington, USA, pp. 181–190, October 1998.
12. W. Heinzelman, A. Chandrakasan, and H. Balakrishnan, Energy-efficient communication protocol for wireless sensor networks, in *Proceeding of the Hawaii International Conference System Sciences*, Honolulu, HI, Vol. 8, pp. 1–10, 2000.
13. S. Lindsey and C.S. Raghavendra, PEGASIS: Power efficient gathering in sensor information systems, in *Proceedings of the IEEE Aerospace Conference*, Big Sky, MT, Vol. 3, pp. 1125–1130, 2002.
14. K. Sohrabi et al., Protocols for self-organization of a wireless sensor network, *IEEE Personal Communications*, 7(5), 16–27, 2000.
15. C. Intanagonwiwat, R. Govindan, and D. Estrin, Directed diffusion: A scalable and robust communication paradigm for sensor networks, in *Proceedings of the 6th Annual International Conference on Mobile Computing and Networks (MobiCom 2000)*, ACM Press, Boston, MA, pp. 56–67, 2000.
16. D. Braginsky and D. Estrin, Rumor routing algorithm for sensor networks, in *Proceedings of the 1st ACM International Workshop on Wireless Sensor Networks and Applications*, Atlanta, GA, pp. 22–31, 2002.
17. J. Liu, F. Zhao, and D. Petrovic, Information-directed routing in ad hoc sensor networks, *IEEE Journal on Selected Areas Communications*, 23, 851–861, April 2005.
18. T. Girici and A. Ephremides, Joint routing and scheduling metrics for ad hoc wireless networks, in *Proceedings of the 36th Asilomar Conference on Signals, Systems and Computers*, College Park, MD, pp. 1155–1159, November 2002.
19. R. Viswanathan and P.K. Varshney, Distributed detection with multiple sensors: Part I—Fundamentals, *Proceedings of the IEEE*, 85, 54–63, January 1997.
20. R.S. Blum, S.A. Kassam, and H.V. Poor, Distributed detection with multiple sensors: Part II—Advanced topics, *Proceedings of the IEEE*, 85, 64–79, January 1997.
21. J.-F. Chamberland and V.V. Veeravalli, Decentralized detection in sensor networks, *IEEE Transactions on Signal Processing*, 51(2), 407–416, February 2003.
22. B. Chen, L. Tong, and P.K. Varshney, Channel aware distributed detection in wireless sensor networks, *IEEE Signal Processing Magazine*, 23, 16–26, July 2006.
23. Y. Huang and Y. Hua, Multi-hop progressive decentralized estimation of deterministic vector in wireless sensor networks, in *Proceedings of Forty-First Asilomar Conference on Signals, Systems and Computers*, Pacific Grove, CA, USA, pp. 2145–2149, 2007.

24. M.G. Rabbat and R.D. Nowak, Decentralized source localization and tracking, in *ICASSP'04*, Montreal, Quebec, Canada, Vol. 3, pp. 17–21, May 2004.
25. A. Bertrand and M. Moonen, Distributed adaptive estimation of node-specific signals in wireless sensor networks with a tree topology, *IEEE Transactions on Signal Processing*, 59(5), 2196–2210, 2011.
26. L. Yu, L. Yuan, G. Qu, and A. Ephremides, Energy-driven detection scheme with guaranteed accuracy, in *Proceedings of the 5th International Conference Information Processing Sensor Networks (IPSN)*, New York, pp. 284–291, April 2006.
27. W. Li and H. Dai, Energy efficient distributed detection via multi-hop transmission in sensor networks, in *Proceedings of the Military Communications Conference (MILCOM)*, Washington, DC, pp. 1–7, October 2006.
28. W. Qiu and E. Skafidas, Distributed source localization based on TOA measurements in wireless sensor networks, *Journal of Electrical and Computer Engineering*, Vol. 8, pp. 1–5, January 2009.
29. S. Patil, S.R. Das, and A. Nasipuri, Serial data fusion using space filling curves in wireless sensor networks, in *Proceedings of the IEEE Communications Society Conference on Sensor Ad Hoc Communications and Networks (SECON)*, Santa Clara, CA, pp. 182–190, October 2004.
30. Y. Sung, S. Misra, L. Tong, and A. Ephremides, Cooperative routing for distributed detection in large sensor networks, *IEEE Journal on Selected Areas in Communications*, 25, 471–483, February 2007.
31. Y. Yang, R.S. Blum, and B.M. Sadler, Energy-efficient routing for signal detection in wireless sensor networks, *IEEE Transactions on Signal Processing*, 57(6), 2050–2063, June 2009.
32. W. Qiu and E. Skafidas, Distributed routing for signal detection in wireless sensor networks, July 2011, submitted.
33. H.V. Poor, *An Introduction to Signal Detection and Estimation*, New York: Springer-Verlag, 1994.
34. A. Dembo and O. Zeitouni, *Large Deviations Techniques and Applications*. New York: Springer, 1998.
35. F.C. Schwegpe, Evaluation of likelihood functions for Gaussian signals, *IEEE Transactions on Information Theory*, IT-1, 61–70, 1965.
36. D. Bertsekas and R. Gallager, *Data Networks*, 2nd edn., New York: Springer, 1991.
37. S.M. Kay, *Fundamentals of Statistical Signal Processing: Detection Theory*, Englewood Cliffs, NJ: PTR Prentice-Hall, 1998.
38. ZigBee Specification Version 1.0, ZigBee Alliance. 2005.
39. Institute of Electrical and Electronics Engineers, Inc., IEEE Std. 802.15.4–2003, IEEE Standard for Information Technology—Telecommunications and Information Exchange between Systems—Local and Metropolitan Area Networks—Specific Requirements—Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (WPANs), New York: IEEE Press, 2003.
40. C.M. Vuran and I.F. Akyildiz, Spatial correlation-based collaborative medium access control in wireless sensor networks, *IEEE/ACM Transactions on Networking*, 14(2), 316–329, April 2006.
41. K. Cheng, K. Lui, Y. Wu, and V. Tam, A distributed multihop time synchronization protocol for wireless sensor networks using pairwise broadcast synchronization, *IEEE Transactions on Wireless Communications*, 8(4), 1764–1772, 2009.
42. K. Nohk, E. Serpendine, and K. Qaraqe, A new approach for time synchronization in wireless sensor networks: Pairwise broadcast synchronization, *IEEE Transactions on Wireless Communications*, 7(9), 3318–3322, 2008.
43. H. Le, H. Guyennet, and V. Felea, OBMAC: An overhearing based MAC protocol for wireless sensor networks, in *Proceedings of the International Conference on Sensor Technologies and Applications*, Washington, DC, pp. 547–553, 2007.
44. F. Yu, S. Park, E. Lee, and S.H. Kim, Elastic routing: A novel geographic routing for mobile sinks in wireless sensor networks, *IET Communications*, 4(6), 716–727, 2010.

45. M. Mohsin and R. Prakash, IP address assignment in a mobile ad hoc network, *Proceedings of Milicom* 2002, 2, 856–861, 2002.
46. G. Bhatti and G. Yue, A structured addressing scheme for wireless multi-hop networks, Technical Report TR2005–149, Mitsubishi Electronic Research Laboratories, June 2006, <http://www.merl.com/reports/docs/TR2005–149.pdf>
47. H.J. Ju, D. Ko, and S. An, Enhanced distributed address assignment scheme for ZigBee-based wireless sensor networks, in *Proceedings of 2009 International Conference on Intelligent Networking and Collaborative Systems*, Washington, DC, pp. 237–240, 2009.
48. M.S. Pan, H.W. Fang, Y.C. Liu, and Y.C. Tseng, Address assignment and routing schemes for ZigBee-based long-thin wireless sensor networks, in *IEEE Vehicular Technology Conference*, Marina Bay, Singapore, VTC Spring 2008, pp. 173–177, 2008.
49. Y. Li, H. Shi, and B. Tang, Address assignment and routing protocol for large-scale uneven wireless sensor networks, in *International Symposium on Computer Network and Multimedia Technology, CNMT2009*, Wuhan, China, pp. 1–4, 2009.
50. J. Jobin, S.V. Krishnamurthy, and S.K. Tripathi, A scheme for the assignment of unique addresses to support self-organization in wireless sensor networks, in *IEEE 60th Vehicular Technology Conference, VTC2004-Fall*, Los Angeles, CA, USA, Vol. 6, pp. 4578–4582, 2004.
51. M.S. Pan, C.H. Tsai, and Y.C. Tseng, The orphan problem in ZigBee wireless networks, *IEEE Transactions on Mobile Computing*, 8(11), 1573–1584, 2009.
52. L.H. Yen and W.T. Tsai, Flexible address configurations for tree-based ZigBee/IEEE 802.15.4 wireless networks, in *22nd International Conference on Advanced Information Networking and Applications*, Okinawa, Japan, pp. 395–402, 2008.
53. W. Qiu, E. Skafidas, and P. Hao, Enhanced tree routing for wireless sensor networks, *Ad Hoc Networks*, 7, 638–650, 2009.
54. S.M. Kay, *Fundamentals of Statistical Signal Processing: Estimation Theory*, Englewood Cliffs, NJ: PTR Prentice-Hall, 1993.
55. V.M. Jiménez and A. Marzal, Computing the K shortest paths: A new algorithm and an experimental comparison, in *Lecture Notes in Computer Science*, Berlin, Germany: Springer-Verlag, Vol. 1668, pp. 15–29, 1999.
56. M.F.A. Ahmed and S.A. Vorobyov, Collaborative beam forming for wireless sensor networks with Gaussian distributed sensor nodes, *IEEE Transactions on Wireless Communications*, 8(2), 638–643, 2009.
57. X. Li, Blind channel estimation and equalization in wireless sensor networks based on correlations among sensors, *IEEE Transactions on Signal Processing*, 53(4), 1511–1519, 2005.
58. S. Yang and J.N. Daigle, APCA-based vehicle classification system in wireless sensor networks, in *Proceedings of IEEE Wireless Communications and Networking Conference*, Las Vegas, NV, USA, 2006, pp. 2193–2198.