A survey on information processing technologies in wireless sensor networks

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Abstract: Recent advances of wireless sensor network have proposed many challenges on networking and information processing technologies. However, most research work in wireless sensor networks focused on networking protocols with only little work on information processing beyond what is referred to as 'aggregation'. This paper surveys the recent work on the information processing technologies in wireless sensor network for promoting novel technologies. The three main categories of the technologies explored in this paper are energy aware information processing algorithms design, space time signal processing algorithms and networked information processing algorithms.

Keywords: wireless sensor network; energy aware algorithms design; space time signal processing; networked information processing.

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1 Introduction

With the technological advances in MEMS, communication and computing, wireless sensor networks (WSN) have been attracting more and more attention (Warneke et al., 2001; Estrin et al., 1999; Gehrke and Seshadri, 2000; Noury et al., 2000; http://sensorwebs.jpl.nasa.gov/). In WSN, hundreds or thousands of small nodes with sensing, computation and wireless communications capabilities are deployed randomly in the field. The sensing circuitry of each node will measure ambient conditions related to the environment surrounding it and transform them into an electric signal. Through separately processing individual signal by each node and collaboratively processing multiple signals by a group of nodes, some interesting information will be extracted.

WSN has wide applications in many fields including military sensing, physical security, air traffic control, traffic surveillance, video surveillance, industrial and manufacturing, automation, distributed robotics, environment monitoring, building and structures monitoring, etc. MIT has identified it as one of the '10 Emerging Technologies That Will Change the World' (Terry, 2003) in 2003.

Networking and information processing are two vital operations for data gathering in WSN. Most of the attention in recent years has been given to networking technologies (Shih et al., 2001; Heinzelman et al., 2000; Manjeshwar and Agrawal, 2001; Demirkol et al., 2005; Sourabi et al., 2000) with only little work on information processing, beyond what is referred to as 'aggregation'. However, novel information processing technologies are also needed to process the spatially distributed multi modal information in networks and extract the useful information in an energy aware manner. Information processing technologies in WSN are very challenging due to several characteristics that distinguish them from traditional technologies.

- Since WSN is likely to contain a large number of nodes, cost is a significant problem. The main resources on each node are in short supply, including energy, CPU execution speed, memory and bandwidth. And the lifetime of the sensor nodes is dependent on battery life. Therefore, the information processing algorithms must be carried out in an energy aware manner.
- Since the density of nodes in WSN is high, nearby sensor nodes might generate significant redundant data in the space dimension. Therefore, appropriate space time signal processing algorithms must be considered to deal with such redundancy.
- Due to the of large scale characteristics, the information processing technologies in WSN should be designed in a distributed manner so as to improve the scalability.
- Since individual node has only a local view of information, the information processing technologies should rely on the collaboration among multiple nodes.
- Since the information flow in WSN is fundamentally governed by the activity in the information processing by the nodes, the coupling between information routing and information processing is more direct in WSN than traditional ad hoc networks. Therefore, the interplay with information routing should be considered in the design of information processing technologies in WSN.

To the authors' knowledge, there is no systematic survey about the information processing technologies in WSN, until now. Therefore, in this paper the authors will explore the novel information processing technologies for WSN developed in recent years. The technologies are classified into three main categories, including energy aware information processing algorithms design, space time signal processing algorithms and networked information processing algorithms. The representative work in each category will be discussed in this paper. The rest of the paper is organised as the following. The energy aware algorithm design is introduced in Section 2. The space time processing algorithms for WSN are discussed in Section 3. The networked information processing algorithms are introduced in Section 4. Finally, we will conclude the paper in Section 5.

2 Energy aware information processing

In wireless sensor network, sensor nodes are energy constrained and have a finite lifetime. It would be highly desirable to carry out the information processing algorithms in an energy aware manner. It is a unique feature of energy awareness for the information processing algorithms in WSN, compared to the traditional algorithms. Of late, there are two trends on energy aware design of information processing algorithms. The first is to find the tradeoff between computational accuracy and energy requirement of the algorithm on a single node. The purpose is to maximise the computational quality for a given energy constraint (Al-Karaki and Kamal, 2004; Sinha et al., 2000; Sinha and Chandrakasan, 2000; Ludwig et al., 1996). The second is to break down the algorithm into multiple tasks and distribute the tasks among a group of nodes, so that the energy consumption will be balanced among multiple nodes, and the overall lifetime will be prolonged (Raghunathan et al., 2002; Chiasserini and Rao, 2002).

2.1 Energy aware algorithm design on a single node

The traditional information processing algorithms do not take energy awareness into consideration. It will be undesirable to carry out such algorithms in the energy constraint system, since the accuracy will be degraded severely if the energy is depleted unexpectedly. Sinha et al. have introduced the notion of energy scalable computation (Sinha et al., 2000). The basic idea is that it will be more energy scalable to transform the same algorithm by doing the most significant computations first. By doing this, the computational energy could be reduced without taking a significant hit in accuracy. Take an example from Sinha et al. (2000), considering the simple power series shown in equation (1), where $k_1, k_2, ..., k_N$ are similar.

$$y = f(x) = 1 + k_1 x + k_2 x^2 + ... + k_N x^N. \quad (1)$$

Figure 1, redrawn from Sinha et al. (2000), shows the standard and energy-quality scalable algorithms.

Figure 1 Power series computation

Standard algorithm	Energy-quality scalable algorithm

xpowi = 1.0; y = 1.0;
for(i = 1;i <= N;i ++){
xpowi *= x;
y += xpowi * k[i];
}
	if (x > 1.0){
	xpowi = pow(x, N);
	y = k[N] * xpowi + 1;
	for(i = N - 1;i > 0;i --){
	xpowi / = x;
	y+= xpowi * k[i];}
	}else{//standard algorithm}

Source: Sinha et al. (2000)

Let us assume that we have to compute *f*(2), the most significant terms would occur in the first few steps in the loop of the transformed energy quality scalable algorithm but not in the standard algorithm. Therefore, the energy quality scalable behaviour of the transformed algorithm will be much better, as a result of which the computational energy could be reduced without taking a significant hit in accuracy.

In Sinha et al. (2000), the authors also demonstrated that by using simple transformations on three distinct categories of commonly used signal processing algorithms including filtering, frequency domain transforms and classification, the Energy-Quality (E-Q) behaviour of the algorithms can be significantly improved.

Mcmilan and Westover (1992) also proposed an energy scalable implementation for Inverse Discrete Cosine Transform (IDCT) for image reconstruction, which is called Forward Mapping IDCT (FM-IDCT) algorithm. The standard IDCT algorithm and FM-IDCT algorithm are shown in equations (2) and (3) (Mcmilan and Westover, 1992).

$$o(x,y)=\sum_{v=0}^{N-1}\sum_{u=0}^{N-1}f(u)f(v)\times\cos\left(\frac{\pi(2x+1)u}{2N}\right)\cos\left(\frac{\pi(2y+1)v}{2N}\right) \quad (2)$$

$$\begin{bmatrix} o_{00} \\ o_{01} \\ \vdots \\ o_{LL} \end{bmatrix} = i_{00}\begin{bmatrix} c_0^{00} \\ c_1^{00} \\ \vdots \\ o_{00}M \end{bmatrix} + i_{01}\begin{bmatrix} c_0^{01} \\ c_1^{01} \\ \vdots \\ o_{01}M \end{bmatrix} + i_{LL}\begin{bmatrix} c_0^{LL} \\ c_1^{LL} \\ \vdots \\ o_{LL}M \end{bmatrix}. \quad (3)$$

In FM-IDCT, the algorithm incrementally accumulates the entire image, based on spectral contributions from the low to high frequencies, instead of reconstructing each pixel by summing up all its frequency contributions. The energy quality scalability of FM-IDCT can be improved due to the fact that most of the signal energy is concentrated in the DC coefficient (i_{00}) and in general, in the low frequency coefficients.

The idea of transforming the standard algorithms is to improve the energy efficiency from aspect of the algorithm's aspect. In Sinha et al. (2000), many algorithms are transformed into the energy quality scalable manner. But more efforts are needed to investigate the feasibility of such transformations on more algorithms. And the energy overhead attributed to such transformation should also be considered in the design.

2.2 *Energy aware algorithm design on multiple nodes*

Another idea to improve the energy efficiency is to break down the tasks of the algorithm and distribute the tasks among multiple nodes. There are several advantages to doing so.

- It can overcome the energy and computational limitations of individual nodes.
- The computation can be carried out in parallel, therefore it increases the allowable latency per computation, which enables the use of voltage scaling (Pering et al., 1998) or other energy-latency tradeoff techniques (Raghunathan et al., 2002) to save energy.
- It can balance the energy consumption among nodes to prolong the lifetime of WSN.

The feasibility of the idea is due to the fact that the density of nodes is high in WSN, and several neighbours always exist for each node.

The idea of the *Distributed Digital Signal Processor* (DDSP) is introduced in Chiasserini and Rao (2002), which makes nodes operate as a distributed DSP and generates the desired result by appropriate collaborative communication and computational schemes. The idea of the DDSP relies on the *divide-and-conquer* paradigm, which divides the problem into multiple sub problems of smaller size. Every processor solves each subproblem by using the same algorithm and the solution to the original problem is obtained by combining the outputs from the different processors. Take an example from (Chiasserini and Rao, 2002), considering a *N*-points Fast Fourier Transform (FFT) carried out by a two nodes DDSP. Denote s_1, s_2 and r as the two nodes and the vector containing the total N data samples over which we want to compute FFT. In the implementation of DDSP, s_1 and s_2 will operate with vectors of length equal to $N/2$ and then the results will be exchanged for the *butterfly* computation. Denote u, v and w_L as the vectors stored in s_1 and s_2 and the column vector of weights that are needed to compute the FFT. By taking u and v as input data, the output of the two nodes butterfly computation is given by: $u + w_L v$ and $u - w_L v$. The distributed computation of this butterfly operation requires communication between s_1 and s_2, which can be carried out as follows.

- s_1 sends a copy of u to s_2
- s_2 sends a copy of v to s_1
- s_1 computes $u + w_L v$
- s_2 computes $u - w_L v$.

The total number of samples sent over the radio channel is equal to N. Note that the scheme is load balanced since each node has roughly the same amount of computation and communication. On the other hand, since each node only operates with vectors of length equal to $N/2$, the computational complexity is significantly lower than in the case where all the N samples are handled by one single node.

Wang and Chandrakasan (2001) also investigate the energy efficiency by parallelising computation among nodes. The application of source localisation by Line of Bearing (LOB) estimation of acoustic sources is considered in Wang and Chandrakasan (2001). The authors found that energy reductions up to 60% can be achieved in the application by parallelising computation of FFT among nodes.

To distribute an algorithm's computations among nodes can reduce the computation complexity and reduce energy consumption on computation significantly. However, more data must be exchanged among nodes, which will result in energy consumption in communication. More research efforts are needed to investigate the scheme to jointly optimise the energy consumption on computation and communication.

3 Space time processing in WSN

The interesting event in the sensed region always generates a time varying, space-time signature field that may be sensed by multiple nodes. Individual nodes, however, only provide spatially local information. This necessitates collaboration between nodes to process the space-time signal to extract useful information such as the position of the moving object. On the other hand, due to the high density of nodes, there is always large *space redundancy* of data sensed by nearby nodes. It introduces the issue of removing such redundancy through the collaboration among nodes. Therefore, the information processing technologies in WSN must consider the issues in space dimension in addition to the issues in the time dimension focused by traditional technologies. Two research hot spots of this challenge will be introduced in this section, including the space time sampling in WSN and distributed source coding in WSN.

3.1 Space time sampling

The signal generated by an interesting event in WSN can be viewed as a time varying, space-time signature field $s(x, y, t)$. The information about the event is contained both in the spatial variation and time variation of $s(x, y, t)$. The nodes sample the signature field spatially and the density of nodes should be commensurate with the rate of spatial variation in the field. Similarly, the time series from each node should also be sampled at a rate commensurate with the rate of time variation in the field. Thus, an appropriate space-time sampling rate should be determined by the variation in $s(x, y, t)$.

Dan et al. (2002) introduced the concept of space-time cells for space-time sampling in the object tracking application. A moving object in a region corresponds to a peak in the spatial signal field that moves with time. Tracking an object corresponds to tracking the location of the spatial peak over time. In such application, the entire space-time region must be divided into multiple space-time cells to facilitate local processing. The size of the space-time cell should approximately correspond to a region over which the space-time signature field remains nearly constant. Then, the space-time signal may be averaged over nodes in each cell to improve the signal to noise ratio. In Dan et al. (2002), the size of space-time cells may also be dynamically adjusted, as new space-time regions are created based on predicted locations of targets.

In determining the appropriate space-time sampling rate, Sayeed (2003) introduced a notion of spatial coherence regions (SCR's) that captures the salient second-order statistical characteristics of a wide variety of signals in space and time. The basic idea is that the spatial scales of variations in $s(x, y, t)$ are determined by the signal spatial bandwidth, B_x and B_y. The spatial bandwidth B_x induces a coherence distance $D_{cx} = 1/B_x$, over which the signal remains strongly correlated in the x dimension. Similarly, $D_{cy} = 1/B_{cy}$ denotes the coherence distance in the y dimension. So the query region R can be divided into disjoint SCRs of size $D_{cx} \times D_{cy}$. Each SCR needs only one node to measure the signal if it is noise free. Similarly the time sampling rate should be based on the coherence interval $T_c = 1/B$, where B is the temporal bandwidth.

The appropriate space-time sampling rate is the basis for the design of distributed signal processing and communication. It is varied with the variations of the signature field generated by different interesting event. Therefore, it is application specific.

3.2 Distributed source coding strategy

Gupta and Kumar (2002) have done a detailed research work on the capacity of wireless ad hoc networks. They proved that the capacity of a wireless ad hoc network consisting of N independent nodes is about $O(L\sqrt{N})$, where L is the capacity of a single link in the network. But the amount of data to transmit could be $O(N \log(N))$ in some extreme situations. So the network can hardly transmit all data when N is large, such as the case in WSN.

However, the high density of nodes induces a high level of network data redundancy, where spatially proximal sensor readings are highly correlated. If we can remove this spatial redundancy, the amount of data required to be transmitted will be reduced greatly. In 1973, Slepian and Wolf (1973) proved that if X, the discrete data of the sender and Y, the discrete data of the receiver are correlated according to the probability distribution $p(x, y)$, the sender can compress X by the conditional entropy $H(X|Y)$ even if Y can not be accessed by the sender. According to the information theory, $H(X|Y)$ can be seen as the uncertainty remaining in the random variable X, given the observation of Y (Cover and Tomas, 1991). So Y is called the side information of X in compressing X. In 1976, Wyner and Ziv (1976) extended this result to lossy distributed compression.

Based on this work, Sandeep et al. (2002) introduced the idea of distributed compression in WSN to remove the spatial redundancy. The problem considered in Sandeep et al. (2002) is to compress an information source in the presence of side information present only at the decoder in the form of another correlated source. The goal is for the decoder to reconstruct the original source using this side information as well as the bitstream sent by the encoder. Taking an example from Sandeep et al. (2002), suppose X and Y are 3 bit binary words correlated in the following sense: the Hamming distance between X and Y is no more than one. If Y is available only to the decoder but not the encoder, X can be described using only 2 bits of information according to the following solution. The solution consists in realising that since the decoder knows Y, it is wasteful for X to spend any bits in differentiating between the two words in the following four sets, $\{X = 000$ and $X = 111\}$, $\{X = 001$ and $X = 110\}$, $\{X = 010$ and $X = 101\}$ and $\{X = 011$ and $X = 100\}$, since the Hamming distance between the two words in each set is three, whereas *Y* is known to be within Hamming distance 1 of *X*. Thus, if the decoder knows the set which *X* belongs to, it can find the exact word by checking which word in the set is closer in Hamming distance to *Y* and declaring that as the value of *X*. Therefore, the encoder only needs to send the index of the set which *X* belongs to, which just cost 2 bits. Based on this observation, a constructive distributed source coding strategy for WSN is developed, which is called DISCUS (distributed source coding using syndromes). The authors concluded that the amount of data to transmit can be reduced greatly by using the side information in compression.

The rationale behind distributed compression in WSN is the high correlation of data from nearby nodes due to the high density. It can remove the redundancy efficiently at the encoder by the side information. However, the correlation structure of the data is varied with the dynamic environment. Therefore, the distributed compression scheme should have the ability of self learning the correlation structure so as to self adapt to the dynamic environment, which will be an interesting research topic in future.

4 Networked information processing

From the view point of information processing, due to the limited communication and computational capability of each node, necessary data between nodes in the region must be exchanged for information processing. From the viewpoint of networking, the routing of data should minimise the communication cost so as to save energy. The coupling between networking and information processing is very close in WSN. Information routing and information processing should be both carefully controlled so as to extract accurate information and maximise the lifetime of WSN. Thus, the interplay between information processing and information routing becomes a key concern in designing WSN (Sayeed, 2003). The information processing in WSN should have the unique features introduced by networking. We call it *networked information processing*. Two representative research hot spots will be introduced in this section.

4.1 Maximise information utility and minimise communication cost

The task of information gathering in WSN is accomplished by the cooperation among nodes. When more nodes cooperate in the task, the accuracy of the gathered information will be incremented further. So the task of information gathering is carried out in a progressive manner in WSN. On the other hand, selecting different nodes to cooperate will improve the accuracy of information in different degrees and cost different amounts of energy at the same time.

Chu et al. (2001) introduced a scheme to select which node to cooperate and to dynamically guide data routing. The basic idea is to introduce the information utility measure to select which nodes to query and to dynamically guide data routing, so as to maximise information gain while minimising energy consumption at the same time. Information utility function $\psi : P(R^d) \to R$ is defined in Chu et al. (2001) to indicate the uncertainty of the probability distributions on R^d. Smaller values represent a more uncertain distribution while larger values represent a more certain distribution. Information utility functions can be defined in many forms, such as covariance, fisher information matrix, entropy of estimation uncertainty and volume of high probability region, etc., (Geman and Jedynak, 1996).

Assume that in the source localisation application, there are *N* nodes in the network. Let $U \subset \{1, ..., N\}$ be the set of nodes currently incorporated into the estimation of the source location, denoted as *x*. Let $\{z_i\}_{i\in U}$ be the measured values of these nodes. Then, the current belief is $p(x \mid \{z_i\}_{i\in U})$. The node selection task is to choose a node which has not been incorporated into the belief yet, which provides the most information. Incorporating a measurement z_j will further condition the belief with the new measurement. Hence, the new belief state is $p(x \mid \{z_i\}_{i\in U} \cup z_j)$, where $j \in \{1, ..., N\} - U$. From the view point of information processing, the best choice of *j* is the one that maximises $\psi(p(x \mid \{z_i\}_{i\in U} \cup z_j))$. Let $\phi(z_j)$ be the communication cost for incorporating node *j*. Then, from the view point of networking, the best choice of *j* is the one that minimises $\phi(z_j)$. Thus, an objective function is defined in equation (4) to trade off the accuracy of information processing and communication cost.

$$O(p(x \mid \{z_i\}_{i\in U} \cup z_j)) = \alpha\Phi(p(x \mid \{z_i\}_{i\in U} \cup z_j)) - (1-\alpha)\Psi(z_j^{(t)}). \tag{4}$$

Based on this idea, an algorithm called IDSQ (information driven sensor querying) was proposed in Chu et al. (2001) for the problem of sensor selection. The authors argued that IDSQ can gather information in an efficient manner and minimise communication cost to prolong the lifetime of network at the same time

4.2 Distributed compression and information routing

In WSN, the role of each node could be data source, data processor and data relay. Since multihop communication pattern is a feature of WSN, data must be relayed by multiple internal nodes. In each hop, the data of the sender and the receiver have different degrees of correlation. Based on this correlation, Scaglione and Servetto (2002) proposed a compression scheme according to the combination of classical source coding methods and routing algorithms.

The basic idea of the scheme is that, in multihop WSN, a message does visit multiple nodes before it reaches its destination. Therefore, the classical source coding strategy can be used to reencode the data as it hops around the network to remove correlations among samples.

For example, considering a communication scenario, each node wants to get the data of all other nodes. Two different routes can be used as shown in Figures 2 and 3, redrawn from Scaglione and Servetto (2002), where X_i is the data collected by node i, the label $(x)m\,|\,l, n$ on each arc means in the x step, the sender and the receiver both have the data of node l and node n and the sender will transmit the data of node m to the receiver. So it can compress the data of node m by using the conditional entropy $H(X_m\,|\,X_l, X_n)$ for transmission.

Figure 2 The route of low communication load

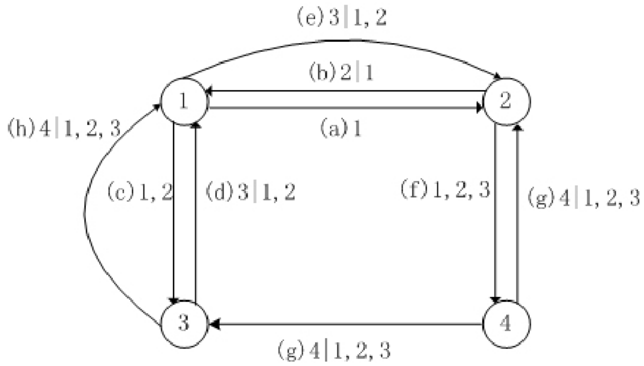
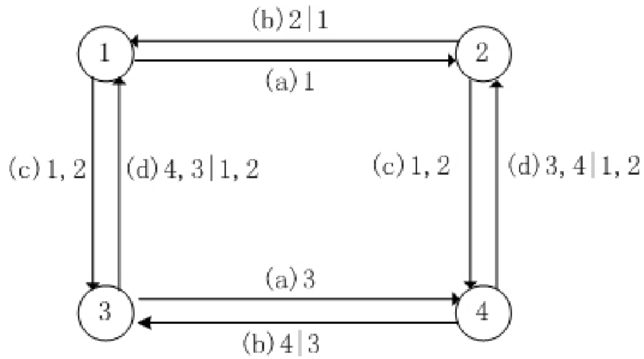


Figure 3 The route of low latency



In Figure 1, the total communication load is

$$\begin{aligned} &H(X_1)+H(X_2\,|\,X_1)+H(X_1,X_2)+H(X_3\,|\,X_1,X_2) \\ &+H(X_3\,|\,X_1,X_2)+H(X_1,X_2,X_3) \\ &+H(X_4\,|\,X_1,X_2,X_3)+H(X_4\,|\,X_1,X_2,X_3) \\ &+H(X_4\,|\,X_1,X_2,X_3)=3H(X_1,X_2,X_3,X_4)\text{ bits.} \end{aligned}$$

It spends eight steps transmitting all data.

In Figure 2, the total communication load is

$$\begin{aligned} &H(X_1)+H(X_2\,|\,X_1)+H(X_3)+H(X_4\,|\,X_3) \\ &+H(X_1,X_2)+H(X_1,X_2)+H(X_3X_4\,|\,X_1,X_2) \\ &+H(X_3,X_4\,|\,X_1,X_2)=2H(X_1,X_2,X_3,X_4) \\ &+H(X_1,X_2)+H(X_3,X_4)\text{ bits.} \end{aligned}$$

It spends four steps transmitting all data.

Since $H(X_1, X_2, X_3, X_4)$ is less than $H(X_1, X_2) + H(X_3, X_4)$, the communication load of Figure 2 is larger than the load of Figure 1. But the latency caused by the Figure 2 is less than the load of Figure 1 (Scaglione and Servetto, 2002). Thus, there is an inherent tradeoff between bandwidth use and decoding delay, and these two quantities are linked together by the routing strategy employed (Scaglione and Servetto, 2002). Based on this idea, the authors (Scaglione and Servetto, 2002) explicitly formulated the tight coupling between routing and source coding in a simple and analytically tractable model.

The two research hot spots in this section reflect the fact that the coupling between information routing and information processing is very close in WSN. To extract the timely and reliable information and maximise the lifetime, the information routing and information processing should be jointly optimised. Thus, more efforts should be paid to find the key principles governing the interplay between information processing and information routing in WSN, which is a central question at the heart of integrated design of WSN (Sayeed, 2003).

5 Conclusion

WSN is a new information gathering technology, where information processing is a vital operation for accurate, timely information gathering. Due to the unique features of WSN, the information processing technologies on it are different from the traditional technologies. The authors present a survey of the different technologies in this paper. The technologies are classified into three main categories, including energy aware design, space time processing and networked information processing. The representative work in each category is discussed in the paper.

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