

Virtual MIMO-Based Cross-Layer Design for Wireless Sensor Networks

Yong Yuan, Zhihai He, *Member, IEEE*, and Min Chen

Abstract—In this paper, a novel multihop virtual multiple-input-multiple-output (MIMO) communication protocol is proposed by the cross-layer design to jointly improve the energy efficiency, reliability, and end-to-end (ETE) QoS provisioning in wireless sensor network (WSN). In the protocol, the traditional low-energy adaptive clustering hierarchy protocol is extended by incorporating the cooperative MIMO communication, multihop routing, and hop-by-hop recovery schemes. Based on the protocol, the overall energy consumption per packet transmission is modeled and the optimal set of transmission parameters is found. Then, the issues of ETE QoS provisioning of the protocol are considered. The ETE latency and throughput of the protocol are modeled in terms of the bit-error-rate (BER) performance of each link. Then, a nonlinear constrained programming model is developed to find the optimal BER performance of each link to meet the ETE QoS requirements with a minimum energy consumption. The particle swarm optimization (PSO) algorithm is employed to solve the problem. Simulation results show the effectiveness of the proposed protocol in energy saving and QoS provisioning.

Index Terms—Cross-layer design, energy efficiency, QoS provisioning, reliability, virtual multiple-input-multiple-output (MIMO), wireless sensor network (WSN).

I. INTRODUCTION

WIRELESS communication has been identified as the dominant power-consuming operation in wireless sensor network (WSN), which makes the energy efficiency a necessity for the wireless-communication scheme. In the harsh working environments, channel fading, interference, and radio irregularity further pose challenges on the design of such scheme. On the other hand, most applications of WSN, such as target tracking, habitat sensing, and fire detection, etc, have requirements on reliability and end-to-end (ETE) QoS in terms of latency and throughput. Energy efficiency, reliability, and QoS provisioning in WSN are multifaceted problems influenced by the physical, medium access control (MAC), network, and transport layers. The energy efficient wireless-communication schemes, routing schemes, power conservation schemes, and reliable transportation schemes should be jointly considered to maximize the performance.

Manuscript received July 17, 2005; revised November 29, 2005 and December 2, 2005. The review of this paper was coordinated by Prof. Y. Fang.

Y. Yuan is with Department of Electronics and Information, Huazhong University of Science and Technology, Wuhan City 430074, China (e-mail: yy_hust@hotmail.com).

Z. He is with Department of Electrical and Computer Engineering, University of Missouri, Columbia, MO 65211 USA (e-mail: HeZhi@missouri.edu).

M. Chen (corresponding author) is with Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, V6T1Z4, Canada (e-mail: minchen@ece.ubc.ca).

Digital Object Identifier 10.1109/TVT.2006.873837

As multiple-input-multiple-output (MIMO) technology has the potential to dramatically increase the channel capacity or reduce transmission energy consumption in fading channels, virtual MIMO schemes have been proposed for WSN to improve communication performance [1]–[8]. In those schemes, multiple individual single-antenna nodes cooperate on information transmission and/or reception for energy-efficient communications. In this paper, we propose a novel multihop virtual MIMO-communication protocol based on a cross-layer design to improve the energy efficiency, reliability, and provide the ETE QoS guarantee. In the protocol, radio irregularity of wireless communications, multihop routing, hop-by-hop recovery, and ETE QoS provisioning are jointly considered with the virtual MIMO scheme. During the transmission, the sensor nodes are organized into multiple clusters, and the cluster heads (CHs) form a multihop backbone. To improve the energy efficiency and reliability, the virtual MIMO scheme and hop-by-hop recovery scheme are incorporated into each single-hop transmission between each pair of CHs, and the CH can adaptively select the cooperative nodes (CNs) according to the channel qualities based on a novel strategy. The average energy consumption per successful packet transmission by the protocol is modeled, and an optimal set of transmission parameters, including the bit-error-rate (BER) performance, the number of CNs and the number of hops, is found to minimize the overall energy consumption. On the other hand, the queuing latency and throughput for packet transmission on each link will be dependent on the average transmission times per successful packet transmission, which is determined by the BER performance on the link in the hop-by-hop recovery scheme. Accordingly, the ETE latency and throughput will be determined by the set of BER performances of all links. Based on this observation, the ETE QoS performances of latency and throughput are modeled by the queuing theory in terms of the BER performances of all links. A nonlinear constrained optimization model is developed to seek the optimal BER performance for each link to meet the ETE QoS requirements with a minimum energy consumption. The particle swarm optimization (PSO) algorithm is employed to solve the problem. Note that the issue of ETE QoS provisioning by the cross-layer design of the virtual MIMO scheme is considered the first time in the paper.

The remainder of the paper is organized as follows. Section II presents the related work. In Section III, the system architecture and design of the virtual MIMO protocol are described. Then, the system analysis, including the energy consumption analysis and ETE QoS modeling, is described in Section IV. The simulation results are presented in Section VI. Finally, Section V concludes the paper.

II. RELATED WORK

Our work is closely related to the virtual MIMO scheme design and ETE QoS provisioning in WSN. We will give a brief review of the works in these aspects.

As for the work of virtual MIMO scheme design, Li proposed a virtual MIMO scheme based on the space-time block code (STBC) using two [1] or more [2] cooperative sensors to provide transmission diversity in WSN with neither antenna-array nor transmission synchronization. The author argued that in the scheme, the full diversity and full rate are achieved, which enhances power/bandwidth efficiency and reliability. In [3], Li also proposed a blind channel estimation and equalization scheme in such scheme. Azimi-Sadjadi and Mercado [4] proposed a method in code-division multiple access (CDMA) wireless multihop networks, which groups transmission nodes into cooperative clusters to reduce the total power expenditure of transmitting nodes. Cui *et al.* [5] analyzed a cooperative MIMO scheme with Alamouti code for the single-hop transmission in WSN. Jayaweera considered the training overheads of such scheme in [6], and found that the training overheads can be modeled as proportional to the number of cooperative nodes. Jayaweera also proposed a virtual MIMO-communication architecture based on the V-BLAST processing [7]. Laneman also did the research work on the system capacity analysis of the virtual MIMO scheme in [8]. Jagannathan *et al.* [9] investigated the effect of time synchronization errors on the performance of the cooperative MIMO systems, and concluded that the cooperative MIMO scheme has a good tolerance of up to 10% clock jitter. The above authors focus on the MIMO schemes design in WSN and the analysis of the system capacity and energy consumption. However, they did not consider the impacts of the specific issues of multihop networking, reliable transmission, and ETE QoS provisioning on the virtual MIMO scheme, which may result in suboptimal system performances. Our paper differs mainly with theirs in that the cross-layer design is considered, which integrates the virtual MIMO scheme with the multihop routing scheme, recovery scheme and ETE QoS provisioning.

ETE QoS provisioning in WSN has many applications, such as a real-time target tracking in battle environments, emergent event triggering in monitoring applications, etc. The applications often have the QoS requirements in terms of ETE latency and throughput. Sequential assignment routing (SAR) is the first routing protocol for WSN that includes a notion of QoS in its routing decisions [10]. SPEED [11] is an adaptive real-time routing protocol that aims to reduce the ETE deadline miss ratio in WSN. Chen proposed an energy-efficient differentiated directed diffusion protocol to support both best effort and real-time traffic at the same time [12]. The purpose is to meet the ETE delay constraint of the real-time traffic and maximize the throughput of the best effort traffic at the same time. Akkaya and Younis also used a weighted fair queuing (WFQ)-based packet scheduling to achieve the ETE delay bound in [13]. We also proposed an integrated energy and QoS aware wireless-transmission scheme for WSN [14], in which the QoS requirements in the application layer, the modulation and transmission schemes in the data link layer and physical layer are jointly

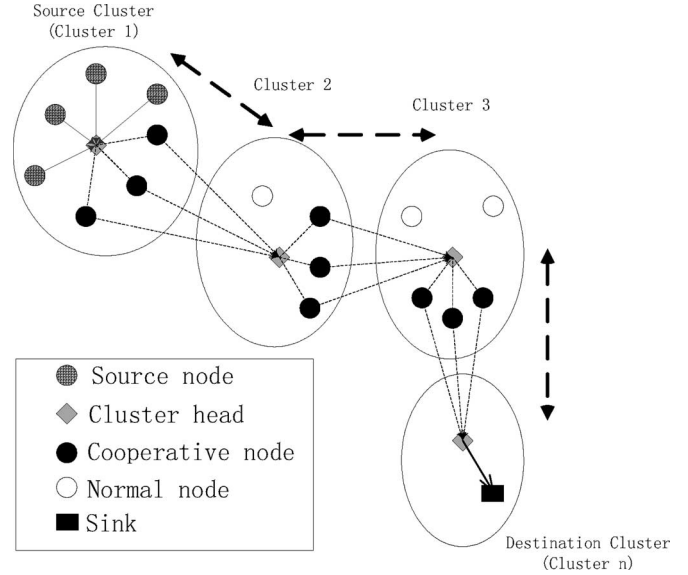


Fig. 1. Multihop virtual MIMO protocol.

optimized. In this paper, we consider the problem of energy aware QoS provisioning in another way, which is to model the ETE QoS performance and overall energy consumption in terms of the BER performance of each link based on the cross-layer design of the multihop virtual MIMO protocol. Then, the search for the optimal BER performance of each link is modeled as a nonlinear constrained optimization problem.

III. SYSTEM ARCHITECTURE AND PROTOCOL DESIGN

The reference system architecture of the proposed multihop virtual MIMO protocol is shown in Fig. 1, where the data bits collected by multiple source nodes will be transmitted to a remote sink by multiple hops. During the transmission, the sensor nodes will be organized into k_c clusters. The transmission in each hop can be divided into two main operations. First, the CH will broadcast the data bits to the CNs in local cluster. An additive white Gaussian noise (AWGN) channel with a squared power path loss is assumed in such transmission due to the short intracluster transmission range. Then, the CNs will encode and transmit the data bits to the CH in the next hop according to the orthogonal STBCs. We assume the frequency-nonselective slow Rayleigh fading channel with k^{th} power path loss in such transmission. The distance between the source cluster to the target cluster consisting the sink is denoted by d , the number of hops is denoted by H , and the number of CNs in each hop transmission is denoted by J . BPSK is used as the modulation scheme due to its efficiency in virtual MIMO design [7]. The bandwidth is denoted by B . Based on the system architecture shown in Fig. 1, we will present the strategy to find appropriate CNs in the single-hop communications in Section III-A and present the overall cluster based multihop virtual MIMO protocol in Section III-B.

A. Strategy to Choose Cooperative Nodes

To improve the energy saving performance of single-hop communications between CHs, appropriate strategy should be

designed to choose the CNs. Suppose J nodes will transmit data to a CH t by the cooperative MIMO scheme. Since the distance among the nodes is much larger than the carrier wavelength, we assume the transmission from each CN experiences independent fading. Denote the distance and path loss for CN j as d_j and k_j , respectively. The CNs will encode and transmit the transmission sequence according to the orthogonal STBCs to CH t . To analyze the energy consumption of the cooperative scheme, we refine the results presented in [5]. In [5], an equal transmit power allocation scheme is used since the channel state information (CSI) is not available at the transmitter. However, in our protocol, the average attenuation of the channel between each CN and t can be estimated during the formation of the clusters, so we can use an equal signal-to-noise (SNR) policy to allocate the transmit power due to its spectral efficiency and simplicity [16]. The average energy consumption per bit transmission by BPSK in such scheme can be approximated as

$$E_{bt} = (1 + \alpha) \frac{N_0}{P_b^{\frac{1}{J}}} \sum_{j=1}^J \frac{(4\pi)^2 d_j^{k_j}}{G_t G_r \lambda^2} M_1 N_f + \frac{(JP_{ct} + P_{cr})}{B} \quad (1)$$

where α is the efficiency of the power amplifier, N_0 is the single-sided noise power spectral density, M_1 is the link margin, N_f is the receiver noise figure, G_t and G_r are the transmitter and receiver antenna gains, respectively, λ is the wavelength, and P_{ct} and P_{cr} are the transmit and receive circuit power consumption.

The average attenuation of the channel for node j can be estimated as follows. Assume the channel is symmetric, and t transmits a signal with transmit power P_{out} , then the power of the received signal at node j , P_{jt} can be described by

$$P_{jt} = P_{out} \frac{G_t G_r \lambda^2}{(4\pi)^2 d_j^{k_j} M_1 N_f} = \frac{P_{out}}{G(d_j, k_j)} \quad (2)$$

where $G(d_j, k_j) = P_{out}/P_{jt} = M_1 N_f (4\pi)^2 d_j^{k_j} / (G_t G_r \lambda^2)$. Therefore, (1) can be reformulated as

$$E_{bt} = (1 + \alpha) \frac{N_0}{P_b^{\frac{1}{J}}} \sum_{j=1}^J G(d_j, k_j) + \frac{(JP_{ct} + P_{cr})}{B}. \quad (3)$$

According to (3), the transmit power of node j to communicate with CH t can be described by

$$P_{outjt} = G(d_j, k_j) \frac{N_0 B}{P_b^{\frac{1}{J}}}. \quad (4)$$

From (3), E_{bt} can be minimized by choosing an appropriate set of CNs, whose $G(d_j, k_j)$ are minimal. In addition, in order to balance the energy consumption, we define $\beta_{jt} = E_j/G(d_j, k_j)$ as the selection criterion where E_j is the remaining energy. The rationale behind such criterion is that the node, which requires smaller energy to communicate with CH t and has larger E_j , should have a larger chance to be selected as the CN. Therefore, J nodes with maximum β_{jt} will be chosen as the CNs to communicate with CH t .

B. Protocol Design

In this section, we will design the overall cluster based multihop virtual MIMO protocol. In the design, the CHs form a multihop backbone, and the cooperative MIMO scheme is incorporated into each hop transmission. As assumed in low-energy adaptive clustering hierarchy (LEACH) [15] protocol, each node has a unique node's identity (ID). The transmit power of each node can be adjusted. Similarly, the operations of the proposed protocol are broken into rounds. Each round consists of three phases: cluster formation phase, during which the clusters are organized and CNs are selected; routing phase, during which routing table is constructed; and transmission phase, during which data are transferred from the nodes to the CH and forwarded to the sink.

1) *Cluster Formation Phase*: In the cluster formation phase, each node will elect itself to be a CH with a probability based on its remaining energy. After the CHs are elected, each CH will broadcast an advertisement message (ADV) by transmit power P_{out} using a nonpersistent carrier sense multiple access (CSMA) MAC protocol. The message contains the head's ID. If a CH receives the ADV from another head t and the received signal strength (RSS) exceeds a threshold th , it will take CH t as a neighbor CH and record t 's ID. If a non-CH node j receives an ADV from CH t and RSS exceeds th , it will calculate and save $G(d_j, k_j)$, β_{jt} and P_{outjt} by (2) and (4) for the selection of CNs for t . Then, node j will join the cluster, from the CH of which the maximum RSS is received, by sending a join-request (Join-REQ) message to the corresponding CH. This message includes the information of the node's ID, the CH's ID and the corresponding values of β_{jt} s. After a CH has received all Join-REQs, it will set up a time-division multiple access (TDMA) schedule and transmit it to the nodes in the cluster as done in LEACH protocol. If the sink receives the ADV, it will find the CH with maximum RSS, and send the sink-position (Sink-POS) message to the CH and mark the CH as the target cluster head (TCH).

After the clusters are formed, each CH will select corresponding optimal J CNs for cooperative MIMO communications with each of its neighbor CH. As stated in Section IV-A, the J nodes with maximum β_{jt} will be chosen to communicate with a neighbor CH t . If no such J nodes can be found for t , t will be removed from the neighbor list, since it will consume too much energy for communications with t . The reason maybe there is any obstacles between the CH and t . After the selections of the CNs, the total energy per bit transmission for communications with t , E_{bt} , can be derived by (1). Then, E_{bt} , the ID set of the CNs for each neighbor CH will be saved. At the end of this phase, the CH will broadcast a cooperate-request (COOPERATE-REQ) message to each CN, which contains the ID of the cluster, the ID of the neighbor CH t , the ID of the node, and the index of the node in the CNs set. Each CN that receives the COOPERATE-REQ message will save the ID of t , the index and the transmit power P_{outjt} and send back a cooperate-ACK (COOPERATE-ACK) message to the CH.

We assume the nodes are locally time synchronized in each cluster at the end of this phase. This could be achieved by having each CH transmit a reference carrier and all its

cluster members lock to this reference carrier using a phase locked loop. In fact, the clock jitter at the transmit nodes in transmission will cause an intersymbol interference (ISI). An accurate synchronization algorithm should be implemented to reduce the ISI, which will cost a significant energy consumption. However, as stated in [9], the clock jitter as large as 10% of the bit time do not have much effect on the BER performance for the cooperative MIMO scheme. Therefore, we do not implement the accurate synchronization algorithm to save energy.

2) *Routing Phase*: To construct the routing table, the basic ideas of distance-vector-based routing will be used. Each CH will maintain a routing table, in which each entry contains destination cluster ID, next hop cluster ID, IDs of CNs, and mean energy consumption per bit. Initially, only the records for the neighbor CHs exist in the routing table. Then, each CH will simply inform its neighbor CHs of its routing table. After receiving route advertisements from neighbor CHs, the CH will update its routing table according to route cost and notify its neighbor CHs the modified routes. After several rounds of route exchange and update, the routing table of each CH will be converged to the optimal one. Then, TCH will flood a target-announcement (TARGET-ANNOUNCEMENT) message containing its ID to each CH to enable the creation of the paths to it.

3) *Data Transmission*: In this phase, cluster members will transmit their data to the CH by multiple frames. In each frame, each cluster member will transmit its data during its allocated transmission slot specified by the TDMA schedule in cluster formation phase, and then sleep in other slots to save energy. The duration of a frame and the number of frames transmitted to the CH in a slot are the same for all clusters. Thus, the duration of each slot depends on the number of nodes in the cluster. After a CH receives data frames from its cluster members, it will perform data aggregation to remove the redundancy in the data. After aggregating received data frames, the CH will forward the data packets to the TCH by multiple-hops routing. In each single-hop communication, if there exist J CNs, the CH will add a packet header to the data packet, which includes the information of source cluster ID, next-hop cluster ID, and destination cluster ID.

In order to improve the reliability in data transmission, the CH will buffer and encode the data packet according to the linear block coding. Then, the encoded data packet broadcast. Once the corresponding CNs receive the data packet, they will encode the data packet by orthogonal STBC, and transmit to the CH in the next hop as an individual antenna with transmit power $P_{out,jt}$ in the MIMO antenna array. In the cooperative MIMO scheme, the transmission delay and channel estimation scheme proposed in [1] can be used in decoding. After receiving the packet, the CH in the next hop will decode it and correct the bit errors by the linear block coding. If a word error occurs after decoding, it will send an NACK message to the previous CH to retransmit, otherwise it will send an ACK message to the previous CH to remove the buffered packet. The stop-and-wait ARQ scheme is used in retransmission, since the propagation latency can be ignored in the small transmission distance in WSN.

IV. SYSTEM ANALYSIS

Based on the protocol design in Section III, we modeled the energy consumption and ETE QoS provisioning in terms of the transmission parameters in this section. Some considerations about the protocol are also discussed.

A. Energy Consumption Analysis of the Protocol

In the protocol, the hop-by-hop recovery scheme is used to improve the reliability. Therefore, the intermediate CH will decode the packet, correct the bit errors, encode, and broadcast it again. If a word error occurs after decoding, it will request the previous CH to send again. Therefore, the overall energy consumption per successful packet transmission by the protocol is jointly determined by the energy consumption per time transmission and the average transmission times for each hop.

1) *Energy Consumption per Packet Transmission in Each Hop*: As the design of the protocol, the energy consumption per packet transmission in each hop mainly comes from the encode/decode operations, the transmission in local cluster by broadcasting and the transmission between clusters by the virtual MIMO scheme. We assume the employed linear block code as (n, m, t) , in which m information bits will be encoded into a symbol word with n bits. In analysis, we denote the encoded symbol word as a packet, so the packet size is just n bits. Denote E_{code} as the energy consumption of the baseband signal processing to perform encoding algorithm, E_{enc} and decoding algorithm, E_{dec} . The E_{code} of different BCH codes can be found in [17]. Other energy consumption in baseband signal processing is ignored.

Under the assumption of AWGN channel with squared power path loss, the average energy consumption per packet transmission can be described by

$$E_0(d_0, J) = nr d_0^2 + \frac{n P_{ct}}{B} + \frac{n J P_{cr}}{B} \quad (5)$$

where d_0 is the transmission distance in the local cluster, r is a constant based on the circuit design.

In modeling the overall energy consumption for packet transmission between clusters by the virtual MIMO scheme, we need to consider the training overhead caused by channel estimation in addition to the model in (3). According to [6], the number of required training symbols is proportional to the number of CNs, we suppose that the block size of the STBC code is F symbols and in each block we include pJ training symbols. We also assume the differences among d_j, k_j of the CNs are neglectable in modeling since the intercluster distance is much larger than the intracluster distance. Then, the total energy consumption per packet transmission in the j th hop can be described by

$$E_1(P_b, d_{hj}, J) = \frac{nF}{F - pJ} \left(\frac{J N_0}{P_b^{\frac{1}{J}}} G(d_{hj}, k) + \frac{J P_{ct} + P_{cr}}{B} \right) \quad (6)$$

where d_{hj} is the intercluster distance of the j th hop and the definition of $G(d, k)$ can be found in Section III-A.

Based on the above analysis, the total energy consumption per packet transmission in the j th hop can be stated as

$$E_h(j) = E_{\text{code}} + E_0(d_0, J) + E_1(P_b, d_{hj}, J). \quad (7)$$

2) *Overall Energy Consumption per Packet Transmission:* Based on the above analysis, in order to model the overall energy consumption per packet transmission, we need further analyze the average transmission times per packet transmission in each hop. According to [18], the word error probability for the linear block code (n, m, t) can be computed as

$$P_w(P_b) = \sum_{i=t+1}^n \binom{n}{i} P_b^i (1 - P_b)^{(n-i)}. \quad (8)$$

Therefore, the average transmission times for each hop can be described as $1/[1 - P_w(P_b)]$. Then, the overall energy consumption per packet transmission can be described by

$$E_{\text{overall}} = \frac{1}{1 - P_w(P_b)} \times \left\{ H [E_{\text{code}} + E_0(d_0, J)] + \sum_{j=1}^H E_1(P_b, d_{hj}, J) \right\}. \quad (9)$$

As shown in (9), P_b has both impacts on the average transmission times and the energy consumption per time transmission, which should be traded off in minimizing the overall energy consumption. The transmission parameters, including P_b , H , and J , should also be jointly optimized to minimize the overall energy consumption according to (9). If we assume, the CHs are deployed uniformly. Then, the transmission distance of each hop, d_{hj} will be identical. The number of clusters, k_c can be estimated as H^2 in the square-sense region. Some realistic constraints can be introduced in seeking the parameters, such as $J \leq 5$, $k_c \leq (N/3)$, where N is the number of nodes in WSN. The first constraint comes from the fact that too many CNs will cause large circuit energy consumption while the performance does not increased much. Given the number of nodes in WSN fixed, the larger k_c is, the smaller size of the cluster is. Thus, the second constraint guarantees the size of the cluster is large enough to make an efficient aggregation. After determining P_b , k_c , and J , they will be programmed into the nodes before deployment, so that the energy efficient topology will be formed during the transmission by the protocol. On the other hand, P_b in each hop transmission has impact on the average transmission times and ETE latency and throughput in turn. The impacts will be modeled in next section.

Another point should be mentioned is that we also compared the hop-by-hop recovery scheme to the ETE recovery scheme similar to [18] in the protocol design, and found that the hop-by-hop recovery scheme is more energy efficient. Due to the limited space, we will not discuss it here.

B. ETE QoS Model of the Protocol

As the protocol design in Section III, during transmission each CH will find the minimum energy consumption-relaying

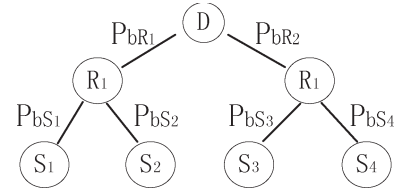


Fig. 2. SPT of the cluster heads.

route among other CHs to the sink. The multihop data transmission topology among CHs can be treated as a shortest path tree (SPT), which is shown in Fig. 2. The BER performance, P_b , on each link will determine the packet throughput, which can be treated as the packet service rate μ for the sender of the link. Therefore, the queuing latency and throughput of the node can be modeled by P_b according to the queuing theory. Based on the result, the ETE latency and throughput can also be modeled in terms of the P_b s of all links.

1) *QoS Performance Along Each Path:* According to the assumptions in Section IV-A, the mean time to transmit a packet can be described as $t_f = nF/B(F - pJ)$. Since the stop-and-wait ARQ scheme is used, the throughput can be described as (10) when the propagation latency, the processing latency and the ACK packet transmission latency are ignored [21].

$$G = \frac{1 - P_w(P_b)}{t_f}. \quad (10)$$

From the view point of the network layer, the throughput can be viewed as the packet service rate, which can be described as $\mu = (1 - P_w(P_b))/t_f$ packets/s. Suppose the packets arrive according to the Poisson process and the packet arrival rate is denoted by λ . Let $P_0(\mu, \lambda)$, $P_N(\mu, \lambda)$, and $W(\mu, \lambda)$ denote the probabilities of the queue being empty, being full, and the mean sojourn time for a packet including queuing and servicing. The existing solutions by the queuing theory can be used directly to compute P_0 , P_N , and W [14].

2) *Model of ETE QoS Performance:* Now, we are ready to model the ETE QoS performance in terms of the BER performance of each link in SPT. The SPT can be represented by $T = \langle V, E_T \rangle$, where node set V is the set of all CHs in the SPT, and edge set E_T denotes the set of directed communication links between each pair of CHs in the SPT. V can be grouped into two subsets, the set of leaf CHs (denoted by V_s) and the set of internal CHs (denoted by V_r). As for the leaf CH, such as S_1 in Fig. 2, it only receives the packets from its members. However, the internal CH, such as R_1 in Fig. 2, not only receives the packets from its members but also the packets from its children CHs in SPT. Then, the packet arrival rate can be described by

$$\lambda_i = \begin{cases} \lambda_c, & (i \in V_s) \\ \sum_{j \in N_{si}} \mu_j(P_{bj}) (1 - P_0(\mu_j(P_{bj}), \lambda_j)) + \lambda_c, & (i \in V_r) \end{cases} \quad (11)$$

where N_{si} is the set of children CHs in SPT, λ_c is the intra-cluster packet arrival rate and $\mu_j(P_{bj}) = (1 - P_w(P_{bj}))/t_f$. To simplify the analysis, we assume λ_c s are the same for all clusters. However, the extension to the scenario with different λ_c is simple. Therefore, the probabilities of the queue being empty, being full and the mean sojourn time of a packet

TABLE I
OPTIMIZATION MODEL

Objective: $\min E_a(\{P_{bj}\})$. Refer to Eqn.(14) for the expression of $E_a(P_{bj})$.
Subject to:

- The requirement on mean ETE latency, $La(\{P_{bj}\}) \leq \tau_{app}$.
- The requirement on mean ETE packet loss ratio, $Th(\{P_{bj}\}) \leq th_{app}$.
- $P_{bmin} \leq P_{bj} \leq P_{bmax}$.

Expected solution: Find the optimal $\{P_{bj}\}$.

transmission for CH j can be described as $P_0(\mu_j(P_{bj}), \lambda_j)$, $P_N(\mu_j(P_{bj}), \lambda_j)$, and $W(\mu_j(P_{bj}), \lambda_j)$. Denote L_j as the path from CH j to the sink in SPT, the ETE latency and throughput for j can be described by

$$\begin{aligned} La_j &= \sum_{i \in L_j} W(\mu_i(P_{bi}), \lambda_i) \\ Th_j &= \prod_{i \in L_j} (1 - P_N(\mu_i(P_{bi}), \lambda_i)). \end{aligned} \quad (12)$$

And the mean ETE latency and throughput for the whole network can be described by

$$\begin{aligned} La(\{P_{bj}\}) &= \frac{\sum_{j \in V_s \cup V_r} \lambda_j La_j}{\sum_{j \in V_s \cup V_r} \lambda_j} \\ Th(\{P_{bj}\}) &= \frac{\sum_{j \in V_s \cup V_r} \lambda_j Th_j}{\sum_{j \in V_s \cup V_r} \lambda_j}. \end{aligned} \quad (13)$$

Strictly speaking, we only considered the QoS performance of the intercluster communication in (13). We have considered the QoS performance of the intracluster communication in [14], which will not be discussed here due to the limited space. On the other hand, based on the analysis in Section IV-A, the overall energy consumption of all CHs is

$$\begin{aligned} E_a(\{P_{bj}\}) &= \sum_{j \in V_s \cup V_r} \frac{1}{1 - P_w(P_{bj})} \\ &\times [E_{code} + E_0(d_0, J) + E_1(P_{bj}, d_j, J)]. \end{aligned} \quad (14)$$

3) *Optimization Model:* Based on the above analysis, we developed a model to find the optimal $\{P_{bj}\}$ to minimize the overall energy consumption under the application's ETE QoS requirements, which is shown in Table I.

By solving the optimization model, we can obtain the optimal $\{P_{bj}\}$ to meet the ETE QoS requirements with minimum energy cost. However, the problem shown in Table I is a nonlinear constrained optimization problems, which is difficult to solve especially when the number of clusters is large. Due to its efficiency in solving such optimization problems, we use the PSO algorithm to find the optimal solution. PSO algorithm is an evolutionary programming technique where a "swarm" of test solutions, analogous to a natural swarm of bees, ants, or termites, is allowed to interact and cooperate to find the best solution to the given problem [20]. In using the PSO algorithm to solve our problem, we define the particle as the vector containing the $\{P_{bj}\}$. A population with N_p particles are generated. The PSO algorithm is iterated for N_{iter} times to find the optimal solution. Also, since our problem is a constrained

optimization problem, we convert it to an unconstrained one by the punished function.

During the transmission, the sink node will gather the information about the topology of the SPT and $G(d_{hj}, k)$ of each link to find the optimal P_{bj} for each link by Table I. As the protocol design, in the cluster formation phase, each CH will calculate and record $G(d_{hj}, k)$ of each neighbor CH. In the routing phase, each CH can find the optimal next hop CH to TCH. Then, each CH will transmit a packet including the ID of the next hop CH to TCH and the related $G(d_{hj}, k)$ to the sink. Based on these packets, the sink can get the necessary information. Then, the sink will carry out the PSO algorithm to find the optimal P_{bj} of each link by Table I. Since the sink is more powerful than the sensor node, it can find the optimal P_{bj} s efficiently by using PSO algorithm. After determining the optimal P_{bj} for each link in the SPT, the sink will transmit it to the related CHs via the control packet. After receiving the control packet, the CH will broadcast in its cluster a transmit power adjustment packet including P_{bj} and the ID of its parent CH in the SPT. After receiving the adjustment packet, the CNs corresponding to the parent CH will adjust the transmit power by the P_{bj} according to (4).

C. Discussion

Energy consumption, reliability, and QoS provisioning are conflicting objectives in WSN. In the protocol design, they are traded off by adjusting P_b of each link. The low P_b will decrease the average transmission times per successful packet transmission, which will result in low ETE latency and high ETE throughput. However, the lower P_b will cost more energy in the packet transmission. In current design, the hop-by-hop reliability is accomplished by the recovery scheme, which will cost different amount of energy for a successful packet transmission based on P_b of the link. The ETE throughput can also be treated as a measure of the event-based reliability [19], which should also be traded off with the overall energy consumption by the P_b s of all links.

On the other hand, the whole task of finding the optimal P_{bj} s is carried out in the sink. In order to improve the scalability, we can also design a distributed scheme to adjust P_{bj} of each link online based on the idea similar to the feedback control method in [14]. In the distributed scheme, we can make the sink to estimate the actual ETE latency, throughput, and disseminate the difference to the required ETE QoS performance to the children CHs in the SPT. Each CH will adjust the P_b of the link to its parent CH based on the feedback and the QoS performance introduced by its subtree. Since the task of calculation and information exchange is distributed to each CH, the scalability can be improved greatly. Such distributed scheme is just the simplified approximation scheme, which can reduce the complexity of the design to improve the efficiency of the protocol. Due to the page limitation, we will present the work in the future. The interested readers are referred to [14].

Another point should be mentioned is as follows. To incorporate the virtual MIMO scheme into the data transmission, the design of cluster formation and routing schemes becomes more complex. However, in the harsh working environments

TABLE II
SYSTEM PARAMETERS

$r = 10pJ/bit/m^2$	$P_{ct} = 98.2mw$	$P_{cr} = 112.6mw$
$d_0 = 10m$	$C_2 = 4.0605e - 12$	$F = 200$
$E_{code} = (445 + 752) \times 39nJ$ [17]	$p = 2$	

TABLE III
INVESTIGATED SCENARIOS AND OPTIMAL PARAMETERS

Scenarios	P_b S3	J S3	k_c S3	k_c S2	k_c S1
$N = 400$ $200m \times 200m$	0.03	3	13	41	25
$N = 400$ $150m \times 150m$	0.03	3	18	27	9
$N = 300$ $150m \times 150m$	0.03	3	16	28	9

with channel fading and radio irregularity, the advantages of virtual MIMO scheme can overcome the overhead caused by the complex design, which is shown in Section V.

V. SIMULATION AND NUMERICAL RESULTS

In this section, we evaluate the energy saving performance and QoS provisioning of the proposed protocol. The investigated system parameters are shown in Table II.

Our experiments are organized as follows. First, to demonstrate the energy saving performance of the proposed protocol in the phenomena of fading and radio irregularity. Second, to find the optimal $\{P_{b,j}\}$ s to meet the ETE QoS requirements with the minimum energy consumption by solving the problem in Table I using PSO algorithm. In the experiments, the related system parameters are the same, as shown in Table II.

A. Energy Saving Performance of the Proposed Protocol

The energy saving performance of the proposed protocol, denoted by $S3$, is compared with the original LEACH protocol, denoted by $S1$ and the multihop LEACH protocol, denoted by $S2$, which is a refined version of the proposed protocol with no cooperative MIMO communications implemented. The hop-by-hop recovery scheme is also incorporated into $S2$ and $S3$. During the simulation, three application scenarios are considered, as shown in Table III. To simulate the phenomena of radio irregularity, the path loss of the communication between each pair of nodes is distributed randomly from 3 to 5. The optimal k_c , P_b , and J for the proposed protocol are determined by minimizing (9), where $k_c = H^2$. The optimal k_c for $S1$ is determined by the model in [15]. We also developed a model to find the optimal k_c for $S2$, which will not be discussed here due to the limited space. Table III gives the optimal transmission parameters for the three protocols in the investigated scenarios.

In comparison, the overall network energy efficiency is defined as the percentage of alive nodes versus operation rounds. Some typical results are presented in Fig. 3, in which the initial energy for each node is 200 J. The percentages of alive nodes of the three protocols in the investigated scenarios are plotted versus operation rounds. From the experimental results including those shown in Fig. 3, we can see that even with the overhead introduced by the protocol, the energy efficiency is still improved greatly by the proposed protocol based on virtual MIMO scheme. If define the network lifetime of WSN

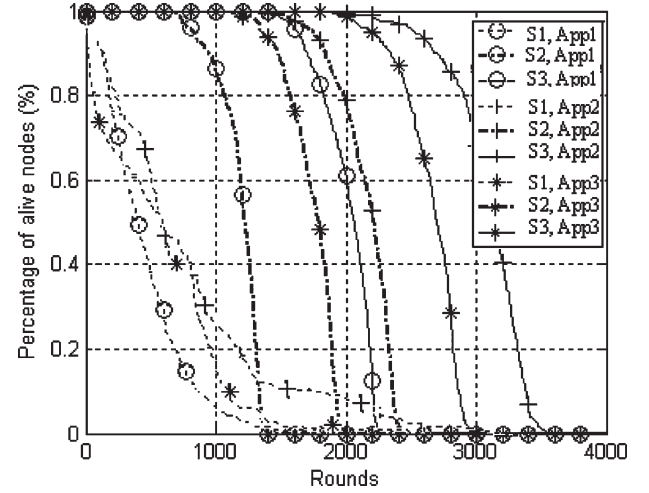


Fig. 3. Compare energy efficiency of three protocols in three scenarios.

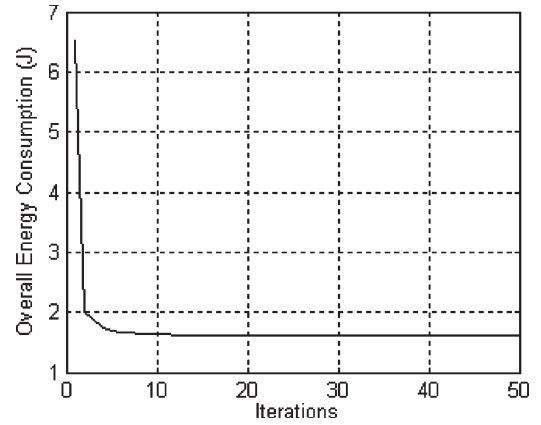


Fig. 4. Minimum energy consumption versus iterations.

as the duration of more than 60% of network nodes are alive, then we can observe that the network lifetime of WSN with $S1$, $S2$, and $S3$ are about (287, 1215, 2000) rounds for scenario 1, (427, 2000, 3045) rounds for scenario 2, and (417, 1757, 2607) rounds for scenario 3, respectively. The improvement on network lifetime obtained by the proposed protocol is about 6 times and 1.5 times over $S1$ and $S2$.

B. ETE QoS Provisioning by the Protocol

In order to investigate the ETE QoS provisioning ability of the protocol, we vary the ETE QoS requirements and seek the optimal P_b of each link by the model in Table I using the PSO algorithm. In the investigated scenario, 400 sensor nodes are deployed randomly in a $200m \times 200m$ sensed region and the nodes are clustered into 22 clusters. λ_c for all CHs are set to be 60 pps. In the PSO algorithm, N_p is set to be 10 000 and N_{iter} is set to be 100 in the simulation.

Figs. 4 and 5 show the convergence of the minimum overall energy consumption, ETE latency during the search process of the PSO algorithm. The desired ETE latency and throughput are fixed as 0.01375s and 0.94, respectively. From Figs. 4 and 5, we can find the algorithm can converge quickly in about

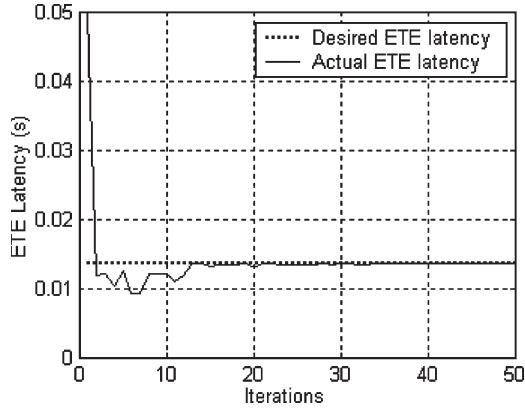


Fig. 5. Acquired ETE latency versus iterations.

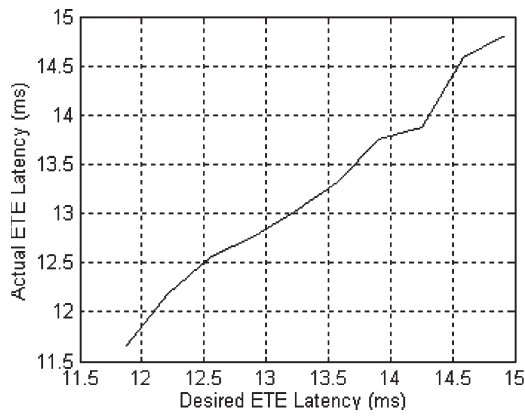


Fig. 6. Actual ETE latency versus desired ETE latency.

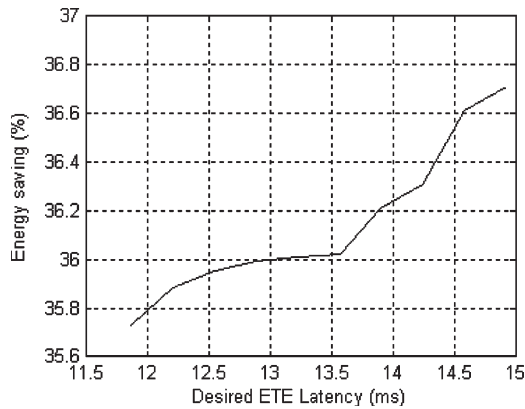


Fig. 7. Energy saving performance versus desired ETE latency.

20 iterations. Therefore, the PSO algorithm is very efficient to solve the problem.

Then, we vary the desired ETE latency from 11.8 to 14.8 ms with ETE throughput requirement fixed as 0.78. The optimal P_b s and the minimum overall energy consumption are found by the PSO algorithm. The energy saving performance by employing the optimal P_b s is defined as $\eta_E = ((E_{\text{ref}} - E_{\text{opt}})/E_{\text{ref}}) \times 100\%$, where E_{ref} and E_{opt} are the overall energy consumptions by a random setting (meeting the ETE QoS requirements) and optimal setting of P_b s. Figs. 6 and 7 show the actual ETE latency and energy saving performance varied with the desired ETE latency.

From the experimental results including those shown in Figs. 6 and 7, it can be observed that the time-varying ETE QoS requirements can be met efficiently by varying the P_b s of all links. The significant energy saving performance can be observed by selecting the optimal P_b s.

VI. CONCLUSION

In this paper, the cross-layer design of the virtual MIMO scheme is considered to jointly improve energy efficiency, reliability, and provide the ETE QoS guarantee. In the scheme, radio irregularity of wireless communications, multihop routing, hop-by-hop recovery and ETE QoS provisioning are jointly considered with the virtual MIMO scheme. At first, a distributed multihop virtual MIMO-communication protocol is proposed by the cross-layer design. In the protocol, the original LEACH protocol is extended by incorporating the cooperative MIMO-communication, multihop routing and hop-by-hop recovery schemes. Based on the protocol, the overall energy consumption per packet transmission is modeled and the optimal transmission parameters are found. Then, the ETE latency and throughput of the protocol are modeled in terms of the BER performance of each link by the cross-layer design. Then, a nonlinear constrained programming model is developed to find the optimal BER performances for all links. The PSO algorithm is employed to solve the programming problem. Simulation results show the effectiveness of the proposed protocol to achieve the goals of minimizing energy consumption and ETE QoS provisioning.

In the future work, we are interested in incorporating the network layer retransmission schemes into the protocol. A distributed scheme will be developed to adjust the BER performance of each link in the SPT.

REFERENCES

- [1] X. Li, "Energy efficient wireless sensor networks with transmission diversity," *Electron. Lett.*, vol. 39, no. 24, pp. 1753–1755, Nov. 2003.
- [2] X. Li, M. Chen, and W. Liu, "Application of STBC-encoded cooperative transmissions in wireless sensor networks," *IEEE Signal Process. Lett.*, vol. 12, no. 2, pp. 134–137, Feb. 2005.
- [3] X. Li, "Blind channel estimation and equalization in wireless sensor networks based on correlations among sensors," *IEEE Trans. Signal Process.*, vol. 53, no. 4, pp. 1511–1519, Apr. 2005.
- [4] B. Azimi-Sadjadi and A. Mercado, "Diversity gain for cooperating nodes in multi-hop wireless networks," in *Proc. IEEE VTC—Fall*, Sep. 2004, vol. 2, pp. 1483–1487.
- [5] S. Cui, A. J. Goldsmith, and A. Bahai, "Energy-efficiency of MIMO and cooperative MIMO techniques in sensor networks," *IEEE J. Sel. Areas Commun.*, vol. 22, no. 6, pp. 1089–1098, Aug. 2004.
- [6] S. K. Jayaweera, "Energy analysis of MIMO techniques in wireless sensor networks," in *Proc. Annu. CISS*, Princeton, NJ, Mar. 2004.
- [7] —, "An energy-efficient virtual MIMO architecture based on V-BLAST processing for distributed wireless sensor networks," in *Proc. 1st Annu. IEEE Commun. Soc. Conf. Sensor Ad Hoc Commun. Netw.*, Oct. 2004, pp. 299–308.
- [8] J. N. Laneman and G. W. Wornell, "Distributed space-time-coded protocols for exploiting cooperative diversity in wireless networks," *IEEE Trans. Inf. Theory*, vol. 49, no. 10, pp. 2415–2425, Oct. 2003.
- [9] S. Jagannathan, H. Aghajan, and A. Goldsmith, "The effect of time synchronization errors on the performance of cooperative MISO systems," in *Proc. IEEE Global Telecommun. Conf. Workshops*, Dec. 2004, pp. 102–107.
- [10] K. Sohrabi, J. Gao, V. Ailawadhi, and G. J. Pottie, "Protocols for self-organization of a wireless sensor network," *IEEE Pers. Commun.*, vol. 7, no. 5, pp. 16–27, Oct. 2000.

- [11] T. He, J. A. Stankovic, L. Chenyang, and T. Abdelzaher, "SPEED: A stateless protocol for real-time communication in sensor networks," in *Proc. IEEE ICDCS*, May 2003, pp. 46–55.
- [12] M. Chen, T. Kwon, and Y. Choi, "Energy-efficient differentiated directed diffusion (EDDD) for real-time traffic in wireless sensor networks," *Elsevier Comput. Commun.—Special Issue on Dependable Sensor Networks*, vol. 29, no. 2, pp. 231–245, Jan. 2006.
- [13] K. Akkaya and M. Younis, "Energy and QoS aware routing in wireless sensor networks," *J. Cluster Comput.—Special Issue on Ad Hoc Networks*, vol. 8, no. 2/3, pp. 179–188, Jul. 2005.
- [14] Y. Yuan, Z. K. Yang, Z. H. He, and J. H. He, "An integrated energy aware wireless transmission system for QoS provisioning in wireless sensor network," *Elsevier Comput. Commun.—Special Issue on Dependable Sensor Networks*, vol. 29, no. 2, pp. 162–172, Jan. 2006.
- [15] W. R. Heinzelman, A. Chandrakasan, and H. Balarishman, "An application-specific protocol architecture for wireless microsensor networks," *IEEE Trans. Wireless Commun.*, vol. 1, no. 4, pp. 660–670, Oct. 2002.
- [16] C. S. Park and K. B. Lee, "Transmit power allocation for BER performance improvement in multicarrier systems," *IEEE Trans. Commun.*, vol. 52, no. 10, pp. 1658–1663, Oct. 2004.
- [17] R. Min, M. Bhardwaj, S. H. Cho *et al.*, "Low-power wireless sensor networks," in *VLSI Symp. Tech. Dig.*, Jan. 2001, pp. 205–210.
- [18] C. Taddia and G. Mazzini, "On the energy impact of four information delivery methods in wireless sensor networks," *IEEE Commun. Lett.*, vol. 9, no. 2, pp. 118–120, Feb. 2005.
- [19] Y. Sankarasubramaniam, O. B. Akan, and I. F. Akyildiz, "ESRT: Event-to-sink reliable transport in wireless sensor networks," in *Proc. ACM MobiHoc*, Jun. 2003, pp. 177–188.
- [20] J. Kennedy and R. C. Eberhart, "Particle swarm optimization," in *Proc. IEEE Int. Conf. Neural Netw.*, 1995, pp. 1942–1948.
- [21] A. S. Tanenbaum, *Computer Networks*, 4th Version. Englewood Cliffs, NJ: Prentice-Hall, 2003.



Yong Yuan received the B.E. and M.E. degrees from the Department of Electronics and Information, Yunnan University, Kunming, China, in 1999 and 2002, respectively. He is currently working toward the Ph.D. degree at the Department of Electronics and Information, Huazhong University of Science and Technology, Wuhan, China.

His current research interests include wireless sensor network (WSN), wireless *ad hoc* network, wireless communication, and signal processing.



Zhihai He (M'01) received the B.S. degree from Beijing Normal University, Beijing, China, and the M.S. degree from Institute of Computational Mathematics, Chinese Academy of Sciences, Beijing, in 1994 and 1997, respectively, all in mathematics, and the Ph.D. degree in electrical engineering from University of California, Santa Barbara, in 2001.

In 2001, he joined Sarnoff Corporation, Princeton, NJ, as an Member of Technical Staff. In 2003, he joined the Department of Electrical and Computer Engineering, University of Missouri, Columbia, as an Assistant Professor. His current research interests include image/video processing and compression, network transmission, wireless communication, computer vision analysis, sensor network, and embedded system design.

Dr. He received the 2002 IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS FOR VIDEO TECHNOLOGY Best Paper Award and The International Society for Optical Engineers (SPIE) visual communications and image processing (VCIP) Young Investigator Award in 2004. He is a member of the Visual Signal Processing and Communication Technical Committee of the IEEE Circuits and Systems Society and serves as Technical Program Committee member or session chair of several international conferences.



Min Chen was born in December 1980. He received B.S., M.S., and Ph.D. degrees from the Department of Electronic Engineering, South China University of Technology, Guangzhou, China, in 1999, 2001, and 2004, respectively.

He was a postdoctoral fellow with the Multimedia and Mobile Communications Lab., School of Computer Science and Engineering, Seoul National University, Seoul, Korea, from September 2004 to February 2006. He has been a postdoctoral fellow with the Communications Group, Department of Electrical and Computer Engineering, University of British Columbia, Vancouver, BC, Canada, since March 2006.