Distributed Antenna Systems: Open Architecture for Future Wireless Communications

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Chapter 1

Cross Layer Design for Wireless Sensor Networks with Virtual MIMO

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Energy efficiency, reliability and QoS provisioning are the main concerns in the design of wireless sensor networks (WSNs) to support the diverse applications. However, the design issues of energy efficiency, reliability and QoS provisioning in WSN are multifaceted problems jointly influenced by the physical, MAC, network and transport layers. Recently, some virtual MIMO schemes based on single antenna sensors have been proposed and studied to improve the energy efficiency of the wireless communication schemes. Though the initial proposal of the virtual MIMO schemes focuses on the physical layer design, the adoption of this novel technology also provides a wider design space for the schemes in the upper layers. In this chapter, a cross layer design scheme based on virtual MIMO scheme is proposed for WSN. In the design, the sensor nodes form a cooperative node set to transmit data according to the virtual MIMO scheme. Then, the virtual MIMO scheme, multi-hop routing scheme and HARQ-based retransmission schemes are jointly designed to improve
the performance of energy efficiency, reliability and QoS guarantees in terms of delay and throughput. Based on the design, we also developed the model for end-to-end QoS and overall energy consumption of the design in terms of the BER performance in each link. Then, the energy saving performance and QoS provisioning ability of the scheme are demonstrated through comprehensive simulations. At last, the chapter is concluded by identifying some open research issues on this topic.\footnote{\copyright IEEE, 2006. This is a major revision of the work published in IEEE Transactions on Vehicular Technology, Volume 53, Issue 3 (May 2006)}

\section{Introduction}

Recent years have witnessed a growing interest in deploying a sheer number of micro-sensors that collaborate in a distributed manner on data gathering and processing. Sensors are expected to be inexpensive and can be deployed in a large number to harsh environments, which implies that sensors are typically operating unattended. In addition, sensor networks are also subject to high fault rate; connectivity between nodes can be lost due to environmental noise and obstacles; nodes may die due to battery depletion, environmental changes or malicious destruction. In such an environment, reliable and energy-efficient data delivery is crucial because sensor nodes operate with limited battery power and an error-prone wireless channel. On the other hand, wireless sensor networks are expected to be used in a wide range of applications, such as target tracking, habitat sensing and fire detection, etc. The data gathering in such applications are often required to be timely. For example, when a target enters an area of interest, it may be critical to reduce the delay of sensor reports. If the reported event is not received by the sink node within a certain deadline, reported information may be obsolete and useless. Therefore, end-to-end QoS provisioning is important for such applications in WSN. In addition, different applications have different end-to-end transmission quality requirements in terms of latency and throughput.

Due to these characteristics, energy efficiency, reliability and end-to-end QoS provisioning should be jointly considered in the design of WSN. However, these design issues are multifaceted problems influenced by the physical, MAC, network and transport layers. The energy
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efficient wireless communication schemes, routing schemes, power conservation schemes and reliable transportation schemes should be jointly considered to maximize the performance in terms of energy efficiency, reliability and end-to-end QoS.

Among all the related schemes, the energy efficiency is deemed as a necessity for the wireless communication scheme in WSN, since wireless communication has been identified as the dominant power-consuming operation. In addition, the hash working environments, channel fading, interference and radio irregularity further pose challenges on the design of energy efficient wireless communication scheme for WSN. In the wireless communication schemes, MIMO techniques have been studied intensively in recent years [1, 2] due to their effectiveness for enhancing reliability, energy and bandwidth efficiency and the ability to deal with fading phenomena. The characteristics of the MIMO techniques makes them desirable for WSN. However, it is difficult to directly apply MIMO techniques in the low-cost small-sized sensors. Some virtual MIMO schemes based on single antenna sensors have been proposed and studied to improve energy saving and spectral efficiency [3, 4, 5, 6, 7, 8, 9, 10, 11, 13]. In such schemes, multiple individual single-antenna nodes will form a virtual antenna array, and each node will be viewed as an antenna in the array. These nodes will cooperate in the MIMO manner on information transmission and/or reception. Based on the virtual MIMO design, the advantages of the MIMO scheme will make the physical layer of WSN more reliable and energy efficient. On the other hand, the adoption of the virtual MIMO scheme in the physical layer also opens a wider design and optimization space for the schemes in the upper layers, such as the retransmission, distributed operation, multi-hop routing and QoS provisioning schemes.

In this chapter, the state-of-the-art of the related schemes are summarized and compared including the virtual MIMO schemes, reliable data transmission schemes and QoS provisioning schemes. Then, a cross layer design based on the virtual MIMO scheme is proposed to improve the performance of WSN in terms of energy efficiency, QoS provisioning and reliability. In the cross layer design, radio irregularity of wireless communications, multi-hop routing, retransmissions and end-to-end QoS provisioning are jointly considered with the virtual MIMO scheme.
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Firstly, we design a single-hop transmission scheme, where an adaptive cooperative nodes selection strategy is proposed to find the optimal cooperative nodes set to minimize the energy cost. In order to improve the reliability of the data transmission, three HARQ-based retransmission schemes are considered to incorporate into the virtual MIMO scheme. The average energy consumption for a successful packet transmission by the virtual MIMO scheme under three retransmission schemes are analyzed and compared. Then the retransmission scheme by hop-by-hop recovery is incorporated into the virtual MIMO scheme due to its efficiency. In analysis, the overall energy consumption for a successful packet transmission is found to depend on the average retransmission times and the energy consumption per time transmission, which can be traded off by the BER performance in transmission. Therefore, an optimal set of transmission parameters, including the BER performance, the number of cooperative nodes and the number of hops, can be found to minimize the overall energy consumption.

Based on the single-hop transmission scheme, an end-to-end transmission scheme is designed. In order to simplify the procedure of forming cooperative nodes set for the virtual MIMO scheme, the concept of clustering is adopted to organize the sensor nodes into multiple clusters and form the cluster heads as a multi-hop backbone. During the transmission, each cluster head will transmit data to its neighbor cluster through the cooperative nodes set by the virtual MIMO scheme. The energy cost for the virtual MIMO communication will be defined as the routing cost between two cluster heads in the multi-hop backbone. Then the shortest path tree (SPT) will be constructed by finding the path with minimum overall energy cost for each cluster head to transmit data to the sink. On the other hand, since the retransmission scheme is considered in each single-hop transmission, the throughput and energy consumption for packet transmission on each link in the SPT will be dependent on the BER performance. Accordingly, the queuing latency and throughput on the link will also be dependent on the BER performance, which in turn impacts the end-to-end latency and throughput. Therefore the low-level communication parameter, BER performance $P_b$ will determine the high-level QoS performance in terms of end-to-end latency and throughput. Based on this observation, the end-to-end QoS performance and the overall energy consumption are modelled by the queuing theory in terms of the BER performance of each link in the SPT. The search for the optimal BER performance for each link is modelled as
1.2 RELATED WORK

a nonlinear constrained optimization problem to minimize the overall energy consumption without violating the end-to-end QoS requirements. The particle swarm algorithm (PSO) is employed in this chapter to solve the problem.

The remainder of the chapter is organized as follows. Section 1.2 describes the related work of the design. In Section 1.3, the proposed cross layer design scheme based on the virtual MIMO is discussed in detail. Then, in Section 1.4, the energy consumption and QoS performance of the scheme are analyzed and an optimization model is developed to find the optimal parameters. Section 1.5 presents the simulation results. Then, Section 1.6 provides some conclusions and points out aspects that will be subject of future research.

1.2 Related Work

Our work is closely related to the virtual MIMO scheme design in WSN, the reliable data transfer in WSN, and end-to-end QoS provisioning in WSN. We will give a brief review of the work in these three aspects.

1.2.1 The Related Work in The Virtual MIMO Design in WSN

The basic idea of the virtual MIMO scheme is extended from the virtual antenna arrays (VAA) in the design of ad-hoc oriented 4G networks [3, 4]. M.Dohler proposed the system capacity analysis, resource allocation strategy and related protocols about the application of VAA to cellular networks in [3, 4]. As for the work of virtual MIMO scheme design in WSN, Xiaohua Li [5] proposed a virtual MIMO scheme using two transmitting sensors and space-time block code (STBC) to provide transmission diversity in WSN with neither antenna-array nor transmission synchronization. The author argued that according to the scheme, the full diversity and full rate are achieved which enhances power/bandwidth efficiency and reliability. Xiaohua Li also extended the scheme for using any number of transmission sensors by the distributed STBC in [6, 7]. In [8], Xiaohua Li also proposed a blind channel estimation and equalization scheme in such virtual MIMO scheme. B. Azimi-sadjadi, et al, [9]
proposed a method in CDMA wireless multi-hop networks which groups transmission nodes into cooperative clusters to reduce the total power expenditure of transmitting nodes. S. Cui [10] analyzed a cooperative MIMO scheme with Alamouti code for single-hop transmission in WSN. S. K. Jayaweera considered the training overheads of such scheme in [11], and found that the training overheads can be modelled as proportional to the number of cooperative nodes. S. K. Jayaweera also proposed a virtual MIMO communication architecture based on the VBLAST processing [12]. J. N. Laneman also did the research work on the system capacity analysis of the virtual MIMO scheme in [13]. S. Jagannathan et al [14] investigated the effect of time synchronization errors on the performance of the cooperative MISO systems, and concluded that the cooperative MISO scheme has a good tolerance of up to 10% clock jitter. The previous work of virtual MIMO scheme focus on the MIMO schemes design in WSN and the analysis of system capacity and energy consumption. However, the previous work did not consider the impacts of the specific issues of multi-hop networking, reliable transmission and end-to-end QoS provisioning on the virtual MIMO scheme, which may result in sub-optimal system performances in terms of energy efficiency, reliability and end-to-end QoS. Our work differs mainly with the previous work in that the cross layer design of the virtual MIMO scheme is considered, which integrates the virtual MIMO scheme with the multi-hop routing scheme, retransmission scheme and end-to-end QoS provisioning.

### 1.2.2 The Related Work in the Reliable Data Transfer in WSN

As for the aspect of reliable data transfer in WSN, since the pioneer work on reliable transport protocol, PSFQ, presented in [16], there are increasing research efforts on studying the issue of reliable data transfer in WSN [16, 17, 18, 19, 20, 21]. PSFQ works by distributing data from source nodes in a relatively slow pace and allowing nodes experienced data loss to recover any missing segments from immediate neighbors aggressively. PSFQ employs hop by hop recovery instead of end to end recovery. In [17], the authors proposed RMST, a transport protocol that provides guaranteed delivery for applications requiring them. RMST is a selective NACK-based protocol that can be configured for in-networking caching and repair. An event-to-sink reliable transport (ESRT) protocol is presented in [18]. In ESRT, the sink adaptively achieves the expected event reliability by controlling the reporting frequency of
the source nodes. In [19], a protocol called ReInForM is proposed to deliver packets at desired reliability by sending multiple copies of each packet along multiple paths from sources to sink. Several acknowledgement based end-to-end reliable event transfer schemes are proposed to achieve various levels of reliability in [20]. C. Taddia [21] also proposed and compared four information delivery methods by different retransmission schemes in WSN. End-to-end and/or hop-by-hop recovery, forward error correction codes and multi-path forwarding are the major approaches to achieve the desired reliability by previous work. However, the reliable data transfer in WSN is a multifaceted problem influenced by multiple protocol layers. In our work, the retransmission schemes in MAC layer and the virtual MIMO scheme in the physical layer are jointly designed to improve the system performance in terms of energy efficiency and data reliability.

1.2.3 The Related Work in The QoS Provisioning in WSN

End-to-end QoS provisioning in WSN has so many applications, such as real-time target tracking in battle environments, emergent event triggering in monitoring applications, etc. The applications often have the QoS requirements in terms of end-to-end latency and end-to-end throughput. There are increasing research efforts on studying the issue of QoS provisioning in WSN. Sequential Assignment Routing (SAR) is the first routing protocol for WSN that includes a notion of QoS in its routing decisions [22]. SPEED [23] is an adaptive real-time routing protocol that aims to reduce the end-to-end deadline miss ratio in WSN. K.Akkaya proposed an energy-aware QoS routing protocol to support both best effort and real-time traffic at the same time [24]. The purpose is to meet the end-to-end delay constraint of the real-time traffic and maximize the throughput of the best effort traffic at the same time. K.Akkaya also used a Weighted Fair Queuing (WFQ) based packet scheduling to achieve the end-to-end delay bound in [25]. We also proposed an integrated energy and QoS aware wireless transmission scheme for WSN [26], in which the QoS requirements in the application layer, the modulation and transmission schemes in the data link layer and physical layer are jointly optimized for end-to-end QoS provisioning. In this paper, we consider the problem of energy aware QoS provisioning in another way, that is to model the end-to-end QoS performance and overall energy consumption in terms of the BER performance of each
link according to the cross layer design of the multi-hop virtual MIMO transmission scheme. Then, the search for the optimal BER performance of each link is modelled as a nonlinear constrained optimization problem.

1.3 Cross Layer Design Based on The Virtual MIMO Scheme

In this section, we will describe the proposed cross layer design scheme based on virtual MIMO in detail. First, the system architecture of the scheme is described. Then, the design of the single-hop transmission is discussed. Based on the single-hop transmission scheme, the end-to-end cross layer design is proposed.

1.3.1 System Architecture

The reference system architecture of the proposed cross layer design based on virtual MIMO is demonstrated in Fig.1.1. In the proposed architecture, 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 multiple clusters. The transmission in each hop can be divided into two main operations. First, the cluster head will broadcast the data bits to the cooperative nodes in the local cluster. We assume an AWGN channel with squared power path loss in such transmission due to the short intra-cluster transmission range. Then, the cooperative nodes will encode and transmit the data bits to the cluster head in the next hop according to the orthogonal space-time block codes (STBC). For the inter-cluster communications, we assume the transmission from each cooperative node experiences frequency-nonselective and slow Rayleigh fading. Furthermore, the long distance between any two nodes in the network with respect to the wavelength gives rise to independent fading coefficients for the cooperative nodes. The rationale behind such channel assumptions is that the inter-cluster transmission distance is much larger than the intra-cluster transmission distance and the transmission environments are more complex in the inter-cluster communication. In the design, the distance between the source cluster to the destination cluster is denoted as $d$, the number of hops is denoted as $H$, and the number of
cooperative nodes in each single-hop transmission is denoted as $J$. Since BPSK can achieve very close performance as the variable-rate modulation scheme with optimal rates, such as MQAM [12], it is used as the modulation scheme, and the bandwidth is denoted as $B$. The cluster containing the data source nodes is denoted as $S$, and the destination cluster containing the sink is denoted as $D$.

### 1.3.2 Single-Hop Transmission Scheme Design

During each single hop transmission, several cooperative nodes will be chosen to communicate with the next cluster head by the virtual MIMO scheme. In order to maximize the performance of single-hop communication between cluster heads, appropriate strategy should be designed to choose the cooperative nodes. The strategy will be discussed in this subsection. On the other hand, though the virtual MIMO scheme can obtain good BER performance in an energy aware manner, the residual BER will also reduce the reliability of the transmission. In order to improve the reliability further, the HARQ (Hybrid ARQ) scheme in the data link layer is incorporated into the hop-by-hop and end-to-end transmission.

#### Strategy to Choose Cooperative Nodes

To maximize the performance of single-hop communications between cluster heads, an appropriate strategy should be taken to choose the optimal cooperative nodes. Suppose that the current cluster head will use $J$ cooperative nodes to transmit data to its neighboring cluster head $t$ by the cooperative MIMO scheme.

Denote the distance between node $j$ and its current cluster head by $d_{j1}$. Also, denote the distance and path loss for node $j$ to communicate with cluster head $t$ as $d_{jt}$ and $k_{jt}$, respectively. For each single-hop transmission, the current cluster head will broadcast a data packet to the cooperative nodes. Then, the cooperative nodes will encode and transmit the transmission sequence according to the orthogonal space-time block codes (STBC) to $t$ toward the sink node. The energy consumption for these two operations in the single-hop transmission will be modelled in the remainder of this section. Then, a novel strategy will
be developed to find the optimal set of cooperative nodes to minimize the overall energy consumption.

Let $E_{bt}(1)$ denote the energy consumption for the current cluster head to broadcast one bit to the cooperative nodes. $E_{bt}(1)$ can be broken down into two main components, the transmit energy consumption, $E_{btt}(1)$, and the circuit energy consumption, $E_{btc}(1)$.

The BER performance for BPSK is $P_b = Q(\sqrt{2r})$. Here $r$ is the Signal to Noise Ratio (SNR), which is defined as $r = \frac{P_r}{2B\sigma^2 N_f}$ [27] under the assumption of AWGN channel, where $P_r$ is the received signal power, $\sigma^2$ is the power density of the AWGN and $N_f$ is the receiver noise figure.

In the high SNR regime, we can approximate the BER performance as $P_b = e^{-r}$ by the Chernoff bound [27]. Hence, we obtain $P_r = -2BN_f \sigma^2 \ln(P_b)$. Recall that $B$ is the bandwidth of BPSK modulation scheme. As the assumption of squared power path loss, $E_{bt}(1)$ can be modelled by Eqn.(1.1).

$$E_{bt}(1) = E_{btt}(1) + E_{btc}(1) = -2(1 + \alpha)N_f \sigma^2 \ln(P_b)G_1 d_{\text{max}}^2 M_l + \frac{P_{ct} + J_P_{cr}}{B}$$

where $d_{\text{max}}$ is the maximum distance from the cooperative nodes to the cluster head, $\alpha$ is the efficiency of the RF power amplifier, $G_1$ is the gain factor at $d_{\text{max}} = 1m$, $M_l$ is the link margin, $N_f$ is the receiver noise figure, $P_{ct}$ and $P_{cr}$ are the circuit power consumption of the transmitter and receiver respectively [10].

Let $f_1(P_b) = -2N_f \sigma^2 \ln(P_b)$ and $H(d_{\text{max}}) = G_1 M_l d_{\text{max}}$. Then, Eqn.(1.1) can be rewritten as Eqn.(1.2).

$$E_{bt}(1) = (1 + \alpha)f_1(P_b)H(d_{\text{max}}) + \frac{P_{ct} + J_P_{cr}}{B}$$

According to the definition, $H(d_j)$ can be measured as follows. Let the current cluster head transmit a signal with transmit power $P_{out}$. Then, the power of the received signal at
its cluster member, node $j$, is $P_{j1} = \frac{P_{\text{out}}}{H(d_j)}$. Therefore, $H(d_j)$ can be measured as Eqn.(1.3).

$$H(d_j) = \frac{P_{\text{out}}}{P_{j1}}$$ (1.3)

From Eqn.(1.2), we can find that the energy consumption in the intra-cluster transmission, $E_{bt}(1)$, can be reduced by choosing the nearer cooperative nodes.

To analyze the energy consumption for inter-cluster transmissions based on the cooperative scheme, denoted by $E_{bt}(2)$, we refine the results in [10]. In [10] an equal transmit power allocation scheme is used as the channel state information (CSI) is not available at the transmitter. If the average attenuation of the channel for each cooperative node pair can be estimated, we can use an equal signal-to-noise (SNR) policy [28] to allocate the transmit power for its effectiveness and simplicity. The average energy consumption per bit transmission by BPSK in such a scheme can be approximated by Eqn.(1.4).

$$E_{bt}(2) = (1 + \alpha) \frac{N_0}{P_b} \sum_{j=1}^{J} \frac{(4\pi)^2 d_{jt}^{K_{tt}}}{G_t G_r \lambda^2} M_t N_f + \frac{(J P_{ct} + P_{cr})}{B}$$ (1.4)

where $N_0$ is the single-sided noise power spectral density, $P_b$ is the desired BER performance, $G_t$ and $G_r$ are the transmitter and receiver antenna gains respectively, and $\lambda$ is the carrier wavelength [10]. Eqn.(1.4) is extended from the result in [10] with the settings of different distance and path loss for each cooperative node. The training overhead and transmission rate are not considered in Eqn.(1.4), which will be considered in Section III.

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 $P_{\text{out}}$, then the power of the received signal at node $j$, $P_{jt}$, can be given by Eqn.(1.5).

$$P_{jt} = P_{\text{out}} \frac{G_t G_r \lambda^2}{(4\pi)^2 d_{jt}^{K_{tt}}} M_t N_f = \frac{P_{\text{out}}}{G(d_{jt}, k_{jt})}$$ (1.5)
where \( G(d_{jt}, k_{jt}) = \frac{P_{out}}{P_{jt}} = \frac{(4\pi)^2 d_{jt}^k}{G_t G_r \lambda^2 M_t N_f} \). Therefore, Eqn.(1.4) can be reformulated as

\[
E_{bt}(2) = (1 + \alpha) \frac{N_0}{P_b^2} \sum_{j=1}^{J} G(d_{jt}, k_{jt}) + \frac{(J P_{ct} + P_{cr})}{B} (1.6)
\]

According to Eqn.(1.6), the transmit power of node \( j \) to communicate with cluster head \( t \) can be described by Eqn.(1.7).

\[
P_{out_{jt}} = G(d_{jt}, k_{jt}) \frac{N_0 B}{P_b^2} (1.7)
\]

**The Strategy to Choose Cooperative Nodes**

Based on Eqn.(1.2) and Eqn.(1.6), the overall energy consumption for the single-hop transmission can be written as Eqn.(1.8).

\[
E_{bt} = E_{bt}(1) + E_{bt}(2) = (1 + \alpha) [f_1(P_b) H(d_{max}) + f_2(P_b) \sum_{j=1}^{J} G(d_{jt}, k_{jt})] + \frac{(J+1)(P_{ct} + P_{cr})}{B} (1.8)
\]

From Eqn.(1.8), the energy consumption for the intra-cluster transmission, \( E_{bt}(1) \) and inter-cluster transmission, \( E_{bt}(2) \) should be traded off to minimize \( E_{bt} \). \( E_{bt} \) can be minimized by choosing an appropriate set of cooperative nodes, which can minimize \( f_1(P_b) H(d_{max}) + f_2(P_b) \sum_{j=1}^{J} G(d_{jt}, k_{jt}) \). In order to simplify the distributed strategy design, the cooperative nodes should be chosen as the nodes whose \( f_1(P_b) H(d_{j1}) + f_2(P_b) G(d_{jt}, k_{jt}) \) are minimal. In addition, in order to balance the energy consumption, the selection criterion is defined as Eqn.(1.9).

\[
\beta_{jt} = \frac{E_j}{f_1(P_b) H(d_{j1}) + f_2(P_b) G(d_{jt}, k_{jt})} (1.9)
\]

where \( E_j \) is the remaining energy in the current round for node \( j \). The rationale behind definition of \( \beta_{jt} \) is that the node, which has a good tradeoff between \( E_{bt}(1) \) and \( E_{bt}(2) \) and has more remaining energy, should have a larger chance to be selected as cooperative
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node. Therefore, $J$ nodes with maximum $\beta_j$ will be chosen as the cooperative nodes to communicate with cluster head $t$.

To Incorporate HARQ-based Retransmission Schemes

Though the virtual MIMO scheme can obtain good BER performance in an energy aware manner, the residual BER will also reduce the reliability of the transmission. In order to improve the reliability further, the HARQ scheme in the data link layer is incorporated into the data transmission among cluster heads. HARQ is the widely accepted technique to mitigate the link error. The basic idea of HARQ is to combine the ARQ schemes and FEC to reduce the average retransmission times for a successful packet transmission. In HARQ scheme, a FEC code is used to detect and correct the bit errors in the packet [29, 30]. If the number of bit errors surpasses the error-correcting capability of the FEC code, a request is sent to the sender to retransmit the packet. Currently, most HARQ schemes can be classified into two types. In HARQ-I schemes, all the transmission attempts of a packet are identical FEC codewords containing redundant bits for both error detection and error correction. The error-correcting capability of the FEC part of the scheme can be designed so that most of the erroneously received packets can be corrected, which reduces the number of retransmissions. Generally speaking, the HARQ-I schemes are best suited for channel environments where the level of noise and interference is fairly constant. On the other hand, the HARQ-II schemes rely on the basic concept of incremental redundancy [31]. In the HARQ-II schemes, the parity bits for error correction are sent only when they are needed. On the first transmission attempt, only parity bits for error detection are appended to the message. If errors are detected in the received packet, it is stored in a buffer and a retransmission is requested. The retransmission is not the original packet but a block of parity-check bits formed based on the original message and an error-correcting code. When this block is received, it is used to correct the errors in the previously stored erroneous packet. Many proposed HARQ techniques belong to this type, such as diversity combining [32], code combining [33] and code puncturing [34], etc. Since the HARQ-II schemes have the flexibility in adapting the additional parity bits to changing channel conditions, they are more suitable for the time-varying channels.
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As for the scenario of WSN, the sensor nodes are too function limited to carry out the HARQ-II scheme. In addition, the positions of the sensor nodes are fixed, the level of noise and interference is relatively constant. So the HARQ-I scheme is more suitable for WSN. In order to improve the reliability, a simplified HARQ scheme is considered in our design. In the simplified HARQ scheme, the linear block code and stop-and-wait ARQ scheme are combined together to correct the errors and reduce the average retransmission times. Then, the HARQ scheme is incorporated into the following retransmission schemes, similar to the information delivery methods in [21], for the packets transmission among cluster heads.

1. The intermediate cluster heads only perform as digital repeaters and the packet is decoded only at $D$, retransmissions are requested to $S$, which is just the end to end recovery scheme.

2. The intermediate cluster heads decode the packet and stop a further forwarding of a wrong packet, retransmissions are requested to $S$.

3. The intermediate cluster heads decode the packet and stop a further forwarding of a wrong packet, retransmissions are requested to the previous cluster head, which is just the hop by hop recovery scheme.

In order to compare the performance of the three retransmission schemes, the amount of energy consumption per successful packet transmission is defined as the criterion for comparison.

In the rest of this section, the amount of energy consumption per successful packet transmission by the virtual MIMO scheme under these three retransmission schemes are modelled and compared.

Denote $E_{\text{code}}$ as the energy consumption of the baseband signal processing to perform encoding process, $E_{\text{enc}}$ and decoding algorithm, $E_{\text{dec}}$. The $E_{\text{code}}$ of different BCH codes can be found in [35]. Other energy consumption in baseband signal processing is ignored. Denote the employed linear block code as $(n, m, n_1)$, in which $m$ information bits will be encoded
into a symbol word with \( n \) bits, and the word error probability can be computed as in [21].

\[
P_w(P_b) = \sum_{i=n_1+1}^{n} \binom{n}{i} P_b^i (1 - P_b)^{n-i}
\]  \hspace{1cm} (1.10)

where \( P_b \) is the BER performance.

We denote the encoded symbol word as a packet, so the packet size is just \( n \) bits.

On the other hand, as training overhead will be introduced by MIMO for channel estimation and the number of required training symbols is proportional to the number of transmit antennas [11], we suppose that the block size of the STBC code is \( F \) symbols and in each block we include \( pJ \) training symbols. According to these assumptions, the framework of the data transmission can be shown in Fig.1.2.

As shown in Fig.1.1, the main operations in each hop include the transmission in local cluster and the transmission between clusters by the virtual MIMO scheme.

Under the assumption of AWGN channel with squared power path loss, the average transmit energy consumption per bit in local cluster can be described by Eqn.(1.11).

\[
E_{b0} = rd_0^2 + \frac{P_{ct}}{B}
\]  \hspace{1cm} (1.11)

where \( d_0 \) is the transmission distance in the local cluster, \( P_{ct} \) is the transmit circuit power consumption and \( r \) is a constant based on the circuit design which can be calculated by Eqn.1.1. Since there are \( J \) cooperative nodes receiving the bit at the same time, the average receive energy consumption per bit can be described as \( \frac{JP_{cr}}{B} \), where \( P_{cr} \) is the receive circuit power consumption.

Therefore, the overall energy consumption per packet transmission in local cluster can be described by

\[
E_0(d_0, J) = nr d_0^2 + \frac{n P_{ct}}{B} + \frac{n J P_{cr}}{B}
\]  \hspace{1cm} (1.12)

According to [10], the average transmit energy consumption per bit transmission by the
STBC-encoded virtual MIMO scheme can be described by

$$E_b = (1 + \alpha) \frac{JN_0(4\pi)^2 d^k M_i N_f}{P_b^2} + \frac{JP_{ct}}{B}$$

(1.13)

where $\alpha$ is the efficiency of the power amplifier, $N_0$ is the single-sided noise power spectral density, $d_j$ is the inter-cluster distance of the $j$th hop, $M_i$ is the link margin, $N_f$ is the receiver noise figure, $G_t$ and $G_r$ are the transmitter and receiver antenna gains respectively, $\lambda$ is the wavelength.

Denote $C_2 = \frac{(1+\alpha)(4\pi)^2 N_0 M_i N_f}{G_t G_r \lambda^2}$, then $E_{b_1} = \frac{J}{P_b^2} C_2 d^k_j + \frac{JP_{ct}}{B}$. The cluster head in next hop also consumes $\frac{P_{cr}}{B}$ energy to receive the bit. Taking into account the training overhead, the total energy consumption per packet transmission in the $j$th hop can be described by

$$E_1(P_b, d_j, J) = \frac{nF}{F - pJ} \left( \frac{J}{P_b^2} C_2 d^k_j + \frac{JP_{ct}}{B} + \frac{P_{cr}}{B} \right)$$

(1.14)

Based on Eqn.(1.12) and Eqn.(1.14), we can model the overall energy consumption of the multi-hop virtual MIMO scheme under the three retransmission schemes.

In retransmission scheme 1), the intermediate cluster heads only repeat the packet, and the packet is only decoded at $D$. Therefore, the energy consumption for one time packet transmission can be described by

$$E = E_{code} + H E_0(d_0, J) + \sum_{j=1}^{H} E_1(P_b, d_j, J)$$

(1.15)

During the transmission, a bit arrives wrong at $D$ if an odd number of errors occur in the path, then the end-to-end BER performance can be described by [21].

$$P_{bd}(P_b) = \sum_{i=0}^{[\frac{H-2}{2}]} \binom{H}{2i + 1} P_b^{2i+1} (1 - P_b)^{(H-2i-1)} + (H \mod 2) P_b^H$$

(1.16)
The word error probability can be computed as \[ P_{e1} = P_w(P_{bd}) \] (1.17)

Then, the average retransmission times for a successful packet transmission can be described as \[ \frac{1}{1 - P_{e1}}. \]

Therefore, the overall energy consumption per packet transmission by retransmission scheme 1) can be described by

\[
E_{e1} = \frac{1}{1 - P_{e1}} \left[ E_{\text{code}} + HE_0(d_0, J) + \sum_{j=1}^{H} E_1(P_b, d_j, J) \right]
\] (1.18)

In the retransmission scheme 2), the intermediate cluster head will decode the packet, the wrong packet will be dropped and the source cluster head will be requested to retransmit. Then, the word error probability per hop can be described as \( P_{w}(P_b). \) The end-to-end word error probability can be described by

\[ P_{e2} = 1 - [1 - P_{w}(P_b)]^H \] (1.19)

Denote \( P_h \) as the probability for the packet transmitted \( h \) hops before dropped. Then, \( P_h \) can be described by [21],

\[ P_h = P_w(P_b)[1 - P_w(P_b)]^{(h-1)} \] (1.20)

The energy consumption in the \( jth \) hop transmission can be described by

\[ E_{\text{code}} + E_0(d_0, J) + E_1(P_b, d_j, J) \]

Therefore, the overall energy consumption per packet transmission by retransmission
CHAPTER 1. CROSS LAYER DESIGN FOR WIRELESS SENSOR NETWORKS WITH VIRTUAL MIMO

scheme 2) can be described by

\[ E_{s2} = \sum_{h=1}^{H} \left\{ h[E_{\text{code}} + E_0(d_0, J)] + \sum_{j=1}^{h} E_1(P_b, d_j, J) \right\} \times P_h + (1 - P_{e2}) \times \left[ H E_{\text{code}} + H E_0(d_0, J) + \sum_{j=1}^{H} E_1(P_b, d_j, J) \right] \] (1.21)

In the retransmission scheme 3), the intermediate cluster head will decode and buffer the packet, the wrong packet will be dropped and the previous cluster head will be requested to retransmit. Then, the word error probability per hop can be described as \( P_w(P_b) \). The average transmission times for each hop can be described as \( \frac{1}{1 - P_w(P_b)} \). The energy consumption in the \( j \)th hop transmission can be described by

\[ E_{\text{code}} + E_0(d_0, J) + E_1(P_b, d_j, J) \]

Then, the overall energy consumption per packet transmission by retransmission scheme 3) can be described by

\[ E_{s3} = \frac{1}{1 - P_w(P_b)} \times \left\{ H[E_{\text{code}} + E_0(d_0, J)] + \sum_{j=1}^{H} E_1(P_b, d_j, J) \right\} \] (1.22)

As shown in Eqn.(1.18), (1.21) and (1.22), the overall energy consumption per packet successful transmission should be traded off between the energy consumption per time transmission and the average transmission times. So an optimal BER performance, \( P_b \) should be found to minimize the overall energy consumption per packet successful transmission.

Figure 1.3 shows the relationships between the overall energy consumption per packet transmission and BER performance by the three retransmission schemes, in which the distance of each hop is assumed to be the same. The investigated system parameters are shown in Tab.1.1. The employed linear block code is BCH(63,39,4).

From Fig.1.3, we can see that there exists an optimal \( P_b \) for three schemes with minimum overall energy consumption. The optimal \( P_b \) for the retransmission scheme 1) is the least one, and the optimal \( P_b \) for the retransmission scheme 3) is the largest one. For scheme 1) only \( D \)}
Table 1.1: The System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$r$</td>
<td>$10pJ/bit/m^2$</td>
</tr>
<tr>
<td>$d_0$</td>
<td>$10m$</td>
</tr>
<tr>
<td>$d$</td>
<td>$2km$</td>
</tr>
<tr>
<td>$H$</td>
<td>$10$</td>
</tr>
<tr>
<td>$C_2$</td>
<td>$4.0605e-12$</td>
</tr>
<tr>
<td>$P_{ct}$</td>
<td>$98.2mw$</td>
</tr>
<tr>
<td>$P_{cr}$</td>
<td>$112.6mw$</td>
</tr>
<tr>
<td>$F$</td>
<td>$200$</td>
</tr>
<tr>
<td>$p$</td>
<td>$2$</td>
</tr>
<tr>
<td>$J$</td>
<td>$5$</td>
</tr>
<tr>
<td>$E_{code}$</td>
<td>$(445 + 752) \times 39nJ$ [35]</td>
</tr>
</tbody>
</table>

will decode the packet and retransmissions are requested to $S$. So one transmission will start from $S$ and end at $D$, which will cost much energy for retransmission. So the optimal $P_b$ will be small to reduce the number of retransmission times, which is at the cost of more energy consumption per time transmission. For scheme 3) the retransmission will be requested to the previous cluster head, one retransmission will not cost so much energy. So the optimal $P_b$ will be some large to reduce the energy consumption per hop transmission, which is at the cost of more retransmission times. We also can find at the corresponding optimal $P_b$, the retransmission scheme 3) will cost the minimum energy consumption. Figure 1.4 and 1.5 show the optimal $P_b$ and minimum overall energy consumption varying with distance under the different settings of $H$ and $J$ by the three schemes.

From Fig.1.4 and 1.5, we can draw the conclusion that the retransmission scheme 3) can achieve the minimum energy consumption under different distance in three schemes. The optimal $P_b$ for scheme 3) under different distance is about 0.03 in the investigated system parameters. Figure 1.6 also shows the optimal number of hops varying with distance under the different setting of $J$ by the three schemes.

From Fig.1.6, we can find the optimal $H$ by the three schemes are almost linearly increasing with the total distance, which makes the one-hop distance by three schemes almost fixed. The optimal $H$ by scheme 3) makes the one-hop distance almost fixed as 40$m$. Figure 1.7 also shows the optimal $J$ varying with distance under the different setting of $H$ by three schemes. From Fig.1.7, we can find the optimal $J$ is almost fixed as 3 by scheme 3).

Based on these analysis, we adopt the retransmission scheme 3) and the joint optimal parameters $(H, J, P_b) = (\frac{d}{40}, 3, 0.03)$ in design.
1.3.3 End-to-end Transmission Scheme Design

Based on the design of the single-hop transmission, the end-to-end transmission scheme will be designed. In the end-to-end transmission scheme, radio irregularity of wireless communications, multi-hop routing, retransmissions and end-to-end QoS provisioning are jointly considered with the virtual MIMO scheme. In order to simplify the procedure of forming cooperative nodes set in the virtual MIMO scheme, the clustering protocol, LEACH protocol, is used to organize the sensor nodes into multiple clusters. Then, the LEACH protocol is extended to enable cluster heads form a multi-hop backbone, and the single-hop design in the previous section is incorporated into each hop transmission. As assumed in the LEACH protocol, each node has a unique node’s ID. The transmit power of each node can be adjusted, and the nodes are all time synchronized. Similarly, the operations of the proposed scheme are broken into rounds. Each round consists of three phases: cluster formation phase, during which the clusters are organized and the cooperative MIMO nodes are selected; routing phase, during which routing table is constructed; transmission phase, during which data are transferred from the nodes to the cluster head and forwarded to the sink according to the routing table.

Cluster Formation Phase

In this phase, each node will elect itself to be a cluster head with a probability $p$ as specified in the original LEACH protocol. After the cluster heads are elected, each cluster head will broadcast an advertisement message (ADV) by transmit power $P_{out}$ using a non-persistent CSMA MAC protocol. The message contains the head’s ID. If a cluster head receives the advertisement message from another head $t$ and the received signal strength (RSS) exceeds a threshold $th$, it will take cluster head $t$ as a neighboring cluster head and record $t$’s ID. As for the non cluster head, node $j$, it will record all the RSSs of the advertisement messages, and choose the cluster head whose RSS is the maximum. Then, it will calculate and save $H(d_j)$, $G(d_{jt}, k_{jt})$, $\beta_{jt}$ and $P_{out\_jt}$ by Eqns. (1.3), (1.5), (1.7) and (1.9). Then node $j$ will join the cluster by sending a join-request message (Join-REQ) to the chosen cluster head. This message contains the information of the node’s ID, the chosen cluster head’s ID and...
After a cluster head has received all join-request messages, it will set up a TDMA schedule and transmit this schedule to its members as in the original LEACH protocol. If the sink receives the advertisement message, it will find the cluster head with the maximum RSS, and send the sink-position (Sink-POS) message to the cluster head and mark the cluster head as the target cluster head (TCH).

After the clusters are formed, each cluster head will select corresponding optimal $J$ cooperative nodes for cooperative MIMO communications with each of its neighboring cluster heads. As stated in Section II.A, $J$ nodes with maximum $\beta_{jt}$ will be chosen to communicate with a neighboring cluster head $t$. If no such $J$ nodes can be found for $t$, $t$ will be removed from the neighbor list, since too much energy is consumed for communicating with $t$. After selecting the cooperative nodes, the total energy per bit transmission for communications with $t$, $E_{bt}$, can be derived by Eqn. (1.4). Then, $E_{bt}$, the ID set of the cooperative nodes for each neighboring cluster head will be stored. At the end of this phase, the cluster head will broadcast a cooperate-request message (COOPERATE-REQ) to each cooperative node, which contains the ID of the cluster itself, the ID of the neighboring cluster head $t$, the IDs of the cooperative nodes, and the index of the cooperative nodes in the cooperative nodes set for each cluster head $t$. Each cooperative node that receives the cooperate-request message (COOPERATE-REQ) will store the ID of $t$, the index and the transmit power $P_{outjt}$ and send back a cooperate-ACK message (COOPERATE-ACK) to the cluster head.

We assume the nodes are locally time synchronized in each cluster at the end of this phase. This could be achieved by having each cluster head 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 inter-symbol interference (ISI). An accurate synchronization algorithm should be implemented to have very fine synchronization within each cluster, which will cost significant energy consumption. However, as stated in [14], the clock jitter as large as 10% of the bit time do not have much effect on the BER performance for the cooperative MISO scheme. So we do not implement the accurate synchronization algorithm to save energy.
Routing Table Construction

To construct the routing table, the basic ideas of distance-vector based routing will be used. Each cluster head will maintain a routing table, in which each entry contains Destination Cluster ID, Next Hop Cluster ID, IDs of Cooperative Nodes, Mean Energy Consumption Per Bit. Initially, only the neighbor cluster heads will have a record in the routing table. Then each cluster head will simply inform its neighbor cluster heads of its routing table. After receiving route advertisements from neighbor cluster heads, the cluster head will update its routing table according to route cost and advertise to its neighbor cluster heads the modified routes. After several rounds of route exchange and update, the routing table of each cluster head will converge to the optimal one. Then, TCH will flood a target announcement message (TARGET-ANNOUNCEMENT) containing its ID to each cluster head to enable the creation of the paths to it.

Data Transmission

In this phase, cluster members will transmit first their data to the cluster head 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 cluster head 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 cluster head 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 cluster head will forward the data packets to the TCH by multiple-hops routing. In each single-hop communication, if there exist \( J \) cooperative MIMO nodes, the cluster head 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. The cluster head will buffer and encode the data packet according to the linear block coding. Then the encoded data packet is broadcasted. Once the corresponding cooperative nodes receive the data packet, they will encode the data packet by orthogonal STBC, and transmit the data to the cluster head in the next hop as an individual antenna with transmission power.
1.4. THEORETICAL ANALYSIS OF THE CROSS LAYER DESIGN

$P_{\text{out,ij}}$ in the MIMO antenna array. In the cooperative MIMO scheme, the transmission delay and channel estimation scheme proposed in [5] can be used in decoding. After receiving the packet, the cluster head 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 a NACK message to the previous cluster head to retransmit the packet, otherwise it will send an ACK message to the previous cluster head to remove the buffered packet. The stop-and-wait ARQ scheme is used for the retransmission requirements. The reason not to use other ARQ schemes, such as selective repeat ARQ scheme, is that the transmission distance is so near in WSN that the propagation latency can be ignored. So the throughput by the stop-and-wait ARQ scheme is almost the same as other ARQ schemes. Due to its simplicity, it is more suitable to use in WSN.

In order to improve the energy efficiency of the protocol, the communication parameters, including $k_c$, $J$ and $P_b$, should be chosen as the joint optimal one. The choice of $k_c$ should make the inter-cluster distance approximately 40m in the system parameters settings in Tab.1.1.

1.4 Theoretical Analysis of The Cross Layer Design

In this section, we will analyze the energy consumption and end-to-end QoS performance of the scheme. Then, an optimization model is developed to find the optimal parameters based on these analyses.

1.4.1 Energy Consumption and End-to-end QoS Performance Analysis

As the scheme design in Section 1.3, during transmission each cluster head will find the minimum energy consumption of relaying data packet among other cluster heads to the sink. The multi-hop data transmission topology among cluster heads can be treated as a short path tree (SPT), which is shown in Fig.1.8. The BER performance, $P_b$, on each link will determine the packet throughput, which can be treated as the packet service rate $\mu$ for
the sender of the link. Therefore, the queuing latency and throughput of the node can be modeled by the BER performance, $P_b$, according to the queuing theory. Based on the result, the end-to-end latency and throughput can also be modeled in terms of the $P_b$s of all links.

According to the assumptions in Section 1.3, the mean time to transmit a packet can be described as $t_f = \frac{nF}{B(F-pF)}$. Since the stop-and-wait ARQ scheme is used for the retransmission requirements, the throughput can be described as Eqn. (1.23) if the propagation latency, the processing latency and the ACK packet transmission latency are ignored [37].

\[
G = \frac{1 - P_w(P_b)}{t_f} \quad (1.23)
\]

From the view point of the network layer, the throughput of the stop-and-wait ARQ scheme can be viewed as the packet service rate, which can be described as $\mu = \frac{1 - P_w(P_b)}{t_f}$ packets/s. Suppose the packets arrive according to the Possion process and the packet arrival rate is denoted as $\lambda$. 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, respectively. The existing solutions by the queuing theory can be used directly to compute $P_0$, $P_N$ and $W$ [38].

Now we are ready to model the end-to-end 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 cluster heads in the SPT, and edge set $E_T$ denotes the set of directed communication links between each pair of cluster heads in the SPT. $V$ can be grouped into two subsets, the set of leaf cluster heads (denoted as $V_s$) and the set of internal cluster heads (denoted as $V_r$). As for the leaf cluster head, such as $S_1$ in Fig.1.8, it only receives the packets from its cluster members. However, the internal cluster head, such as $R_1$ in Fig.1.8, not only receives the packets from its members but also the packets from its children cluster heads in SPT. Then, the packet arrival rate can be described by

\[
\lambda_i = \begin{cases} 
\lambda_c, & (i \in V_s) \\
\sum_{j \in N_i} \mu_j(P_{bj})(1 - P_0(\mu_j(P_{bj}), \lambda_j)) + \lambda_c, & (i \in V_r)
\end{cases} \quad (1.24)
\]
where \( N_{si} \) is the set of children cluster heads in SPT, \( \lambda_c \) is the intra-cluster packet arrival rate and \( \mu_j(P_{bj}) = \frac{1-P_w(P_{bj})}{t_f} \). To simplify the analysis, we assume \( \lambda_c \) are the same for all clusters, which can be estimated by the number of nodes and the desired number of clusters. However, the extension to the scenario with different \( \lambda_c \) is simple.

Therefore, the probabilities of the queue being empty, being full and the mean sojourn time of a packet transmission for cluster head \( j \) 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 cluster head \( j \) to the sink in SPT, the end-to-end latency and throughput for \( j \) can be described by

\[
La_j = \sum_{i \in L_j} W(\mu_i(P_{bi}), \lambda_i) \\
Th_j = \prod_{i \in L_j} (1 - P_N(\mu_i(P_{bi}), \lambda_i))
\] (1.25)

The mean end-to-end latency and throughput for the whole network can be described by

\[
La(\{P_{bj}\}) = \frac{\sum_{j \in V_s \cup V_r} \lambda_j La_j}{\sum_{j \in V_s \cup V_r} \lambda_j} \\
Th(\{P_{bj}\}) = \frac{\sum_{j \in V_s \cup V_r} \lambda_j Th_j}{\sum_{j \in V_s \cup V_r} \lambda_j}
\] (1.26)

Strictly speaking, we only considered the QoS performance of the inter-cluster communication in Eqn.(1.26). We have considered the QoS performance of the intra-cluster communication in [26], which will not be discussed here due to the limited space.

On the other hand, the overall energy consumption of all cluster heads can be described by

\[
E_a(\{P_{bj}\}) = \sum_{j \in V_s \cup V_r} \frac{1}{1 - P_w(P_{bj})} [E_{code} + E_0(d_0, J) + E_1(P_{bj}, d_j, J)]
\] (1.27)

1.4.2 Parameters Optimization

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 end-to-end QoS requirements, which
Table 1.2: The Optimization Model

Objective: \( \min E_a(P_{ Bj}) \). Refer to Eqn.(1.27) for the expression of \( E_a(P_{ Bj}) \).

Subject to:

- The requirement on mean end-to-end latency, \( L_a(P_{ Bj}) \leq \tau_{ app} \).
- The requirement on mean end-to-end packet loss ratio, \( T h(P_{ Bj}) \leq th_{ app} \).
- \( P_{ bmin} \leq P_{ Bj} \leq P_{ bmax} \).

Expected solution: Find the optimal \( \{ P_{ Bj} \} \).

are shown in Tab.1.2.

By solving the optimization model, we can obtain the optimal \( \{ P_{ Bj} \} \) to provide the end-to-end QoS requirements by minimum overall energy cost. However, the problem shown in Tab.1.2 is a nonlinear constrained optimization problems, which is difficult to solve especially when the number of \( P_{ Bj} \) is large. Due to its efficiency in solving such optimization problems, we use the Particle Swarm Optimization (PSO) algorithm to find the optimal solution. PSO algorithm is proposed by James Kennedy and R. C. Eberhart in 1995 [36], motivated by social behavior of organisms such as bird flocking and fish schooling. In the PSO algorithm, the local search method and global search method are combined to find the optimal solution. 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 is 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 transmission, the sink node will determine the optimal \( P_{ Bj} \) for each link in the SPT and transmit \( P_{ Bj} \) to the related cluster head via the control packet. After receiving the control packet, within its cluster, the cluster head will broadcast a transmit power adjustment packet including \( P_{ Bj} \) and the ID of its parent cluster head in the SPT. After receiving the adjustment packet, the cooperative nodes corresponding to the ID of the parent cluster head will adjust the transmit power by the \( P_{ Bj} \) according to Eqn.(1.7). This procedure requires the knowledge on the topology information of the SPT and the channel gains of each link. We assume that each cluster head will report the following information to the sink, such as the ID of its parent cluster head and the channel gains between itself and its parent cluster head in the SPT during the Routing Table Construction phase. To implement the optimization
procedure in a more distributive manner is one of our research interests in the future work.

1.5 Simulation and Numerical Results

In this section, we evaluate the energy saving performance and QoS provisioning of the proposed cross layer design based on virtual MIMO. Our experiments are organized as follows: Firstly, we demonstrate the energy saving performance of the proposed scheme in the phenomena of fading and radio irregularity; Secondly, we investigate the QoS provisioning performance of the design based on the optimization of \( \{P_{bj}\} \) of each link by the optimization model proposed in Section 1.4. In the simulations, the related system parameters are the same as shown in Tab.1.1.

1.5.1 Energy Saving Performance of The Cross Layer Design

In order to evaluate the energy saving performance of the proposed cross layer design, we simulate the operation of the cross layer design in multiple rounds, record its’ energy consumption and compare to other schemes. The procedure of this simulation will be discussed in this section.

In the simulations, 400 nodes are randomly deployed on a 200 × 200 field. The location of the sink is randomly chosen in each round. Each node begins with 400J of energy and an unlimited amount of data packets to send to the sink. When the nodes use up their limited energy during network operation, they can not transmit or receive data any longer.

During the simulation, we tracked the accumulated number of packets transferred to the sink, the amount of energy and duration required to deliver the data to the sink, and the percentage of nodes alive. We are interested in the transmission quality and energy saving performance of the proposed scheme. The performance of the proposed Multi-Hop MIMO-LEACH scheme is compared with the original LEACH and the multi-hop LEACH scheme, in which cooperative MIMO communications is not implemented. The optimal value of \( k_c \)
for the original LEACH is determined by the model in [15]. We also develop a similar model to find the optimal $k_c$ for the multi-hop LEACH scheme, which will not be discussed here due to the limited space. In the investigated scenario, the optimal $k_c$ for the original LEACH protocol, the multi-hop LEACH scheme and the proposed scheme, are found and set to 3, 41 and 27, respectively. The optimal $J$ for the proposed scheme is found to be 3.

Due to the aggregation operation, the number of effective received packets by sink [15] is deemed as the number of “real” packets after aggregation. Specifically, if no aggregation carries out, the number of effective received packets equals to the number of successfully received packets. If the aggregation operation in transmission is *information lossless*, the number of effective received packets is just the number of total packets transferred by the source nodes. We believe that the number of effective received packets is a good application-independent indication of the transmission quality.

Fig. 1.9 and 1.10 show the total number of effective packets received at the sink over time and the total number of effective packets received at the sink per a given amount of energy.

Fig. 1.9 shows that during its lifetime the LEACH protocol can obtain better latency performance compared to the multi-hop LEACH scheme and the proposed MIMO LEACH scheme. The reason is that the multi-hop operation in the multi-hop LEACH scheme and the Multi-hop MIMO-LEACH scheme will increase the latency, and thus result in a less number of data packets sent to the sink for a given period of time. However, the better latency performance of the LEACH protocol comes from the more energy consumption compared to the other two schemes. Especially, in the fading channel environment, LEACH protocol will consume much more energy due to its single-hop transmission from the cluster heads to the sink, which will result in less network lifetime and less total number of transmitted packets. Fig. 1.10 shows that, with the same amount of energy consumption, the Multi-hop MIMO-LEACH scheme can transmit much more data packets compared to the LEACH protocol and the multi-hop LEACH scheme. From these simulation results, we can find that the Multi-hop MIMO-LEACH scheme is more suitable for the application scenarios which have high requirements on network lifetime but low requirements on latency.

Fig. 1.11 shows the percentage of nodes alive over time. From Fig. 1.11, we can find that
the proposed Multi-hop MIMO-LEACH scheme can improve the network lifetime greatly. If we define the network lifetime of WSN as the duration of more than 70% of network nodes are alive, it can be observed that the network lifetime of WSN with the original LEACH protocol, the multi-hop LEACH scheme and the proposed Multi-hop MIMO-LEACH scheme are about $0.7 \times 10^4$, $8.2 \times 10^4$ and $11 \times 10^4$s, respectively. The improvement on network lifetime obtained by the Multi-Hop MIMO-LEACH scheme is significant.

However, the percentage of nodes alive over time is not always a good indication to the energy saving performance of a protocol. For example, during the same time, though one protocol is worse than other protocols in terms of the energy saving performance, it will still consume less energy if it transmits less packets than other protocols. Thus, its lifetime is likely longer. In order to further investigate the energy saving performance, we also simulate the performance in terms of the percentage of nodes alive per amount of effective data packets received at the sink, which is shown in Fig. 1.12. From Fig. 1.12, we find that the proposed Multi-hop MIMO-LEACH scheme needs significantly less energy to transmit the same amount of data packets. Therefore, the improvement on network lifetime obtained by the Multi-hop MIMO-LEACH scheme is significant.

On the other hand, the impacts of the parameters, including the number of cluster heads, $k_c$ and the number of cooperative nodes, $J$, are also investigated in the simulation. Fig. 1.13 and 1.14 show the percentage of nodes alive over time in different settings of $k_c$ and $J$.

From the simulation results including those shown in Fig. 1.13 and 1.14, we can find that the energy saving performance of the proposed scheme is impacted by the setting of these parameters. As for the number of cluster heads ($HeadNum$), a large value of $HeadNum$ will reduce the distance for each single hop transmission, which will reduce the transmit energy consumption; A large $HeadNum$ also generates a wide search space for the routing table construction, which will also reduce the transmit energy consumption further. However, larger is $HeadNum$, more number of hops in transmission to the sink is needed, which causes more circuit energy consumption for relaying the data packets. Therefore, the number of cluster heads should be chosen to trade off the transmit energy consumption and circuit energy consumption. As for the number of cooperative nodes, a certain number of cooperative nodes
can form the effective independent multi-path transmission so as to energy-efficiently combat the fading effects. However, too many cooperative nodes will result in large circuit energy consumption, which will cause large overall energy consumption. Therefore, the number of cooperative nodes should also be chosen to trade off the transmit energy consumption and the circuit energy consumption.

1.5.2 QoS Provisioning Performance of The Cross Layer Design

In Section 1.4, we have proposed an end-to-end QoS model in terms of the BER performance of each link in the SPT. We also propose to use the PSO algorithm to find the optimal BER performance of each link to minimize the overall energy consumption without violating the end-to-end QoS requirements. In this section, the numerical results will be presented. The structure of the SPT in experiments is shown in Fig. 1.15, where $S_1$, $S_2$, $S_3$ and $S_4$ are the source cluster heads; $R_1$ and $R_2$ are the internal cluster heads; the number shown on each link is the distance of the link; $P_{bi}$ is the BER performance of link $i$, and the intra-cluster packet arrival rates $\lambda_c$ for all cluster heads are 40 pps. $N_p$ is set to be 10000 and $N_{iter}$ is set to be 100 in the simulation. In the experiments, we search the optimal BER performance of each link by PSO algorithm to minimize the overall energy consumption with varied end-to-end QoS requirements.

Figure 1.16 to 1.19 show the convergence of the minimum overall energy consumption, end-to-end latency, end-to-end throughput and $P_{bs}$ during the search process of PSO algorithm. The desired end-to-end latency and end-to-end throughput are 0.04s and 0.80 respectively. From Fig. 1.16 to 1.19, we can find the algorithm can converge in about 30 iterations, so the convergence speed is fast. Therefore, the PSO algorithm is efficient to solve our problem. The optimal $P_{b5}$, $P_{b6}$ are less than $P_{b1}$ to $P_{b4}$, the reason is that the internal links should have smaller optimal BER to make the throughput larger than the throughput of the children links in SPT for end-to-end QoS provisioning.

We also did the experiment to search the minimum energy consumption and optimal $P_{bs}$ with time-varying end-to-end QoS requirements. In the experiment, the desired end-to-end
latency is varied from 0.008s to 0.038s, and the desired end-to-end throughput is fixed as 0.8, then 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 

$$\eta_E = \frac{E_{\text{ref}} - E_{\text{opt}}}{E_{\text{ref}}} \times 100\%,$$

where $E_{\text{ref}}$ and $E_{\text{opt}}$ are the overall energy consumptions by a random setting and optimal setting of $P_b$s. Figure 1.20 and 1.21 show the actual end-to-end latency and end-to-end throughput acquired by the algorithm. Figure 1.22 shows the energy saving performance varied with the desired end-to-end latency. Figure 1.23 shows the optimal $P_b$s varied with the desired end-to-end latency.

Furthermore, in order to investigate the energy saving performance and end-to-end QoS provisioning of the protocol in a large-scale network. We also did the simulation to search the optimal $P_b$s by PSO algorithm in the scenario of large-scale network, in which 400 sensor nodes are randomly deployed over a $200m \times 200m$ area and the nodes are clustered into 22 clusters. The intra-cluster packet arrival rates $\lambda_c$ for all cluster heads are 60pps. The topology of the network is shown in Fig.1.24.

Figure 1.25 to 1.27 show the convergence of the minimum overall energy consumption, end-to-end latency and end-to-end throughput during the search process of PSO algorithm.

For the network shown in Fig.1.24, we also did the experiments to search the minimum energy consumption with time-varying end-to-end QoS requirements. In the experiment, the desired end-to-end latency is varied from 11.8ms to 14.8ms, and the desired end-to-end throughput is fixed as 0.78. Figure 1.28 and 1.29 show the actual end-to-end latency and energy saving performance varied with the desired end-to-end latency.

From the experimental results, it can be seen that by adjusting the $P_b$ of each link, the actual end-to-end QoS performances are varied with the end-to-end QoS requirements. And the significant energy saving performance can be acquired by adjusting the optimal BER performance.
1.6 Conclusion and Open Issues

In this chapter, we propose a cross layer design based on virtual MIMO scheme to increase the energy efficiency and provide the end-to-end QoS guarantee. In the scheme, radio irregularity of wireless communications, multi-hop routing, retransmissions and end-to-end QoS provisioning are jointly considered with the virtual MIMO scheme. In the cross layer design, the concept of clustering is adopted to organize the sensor nodes into multiple clusters and form the cluster heads as a multi-hop backbone. Then, the virtual MIMO scheme is incorporated into each single-hop transmission between each pair of cluster heads. In each single-hop transmission, three HARQ-based retransmission schemes are considered to incorporate into the virtual MIMO scheme. The average energy consumption for a successful packet transmission by the virtual MIMO scheme under the three retransmission schemes are analyzed and compared. Then the retransmission scheme by hop-by-hop recovery is incorporated into the virtual MIMO scheme due to its efficiency. Then, an adaptive cooperative nodes selection strategy is also designed in the protocol. Based on the single-hop transmission scheme, the end-to-end transmission scheme is designed which jointly integrate virtual MIMO scheme, multi-hop routing scheme and retransmission scheme to improve the performance of energy efficiency, reliability and QoS guarantees. Based on the cross layer design, we also developed the model for end-to-end QoS and overall energy consumption of the design in terms of the BER performance in each link of the SPT. A nonlinear constrained programming model is also designed to find the optimal BER performances for all the links in the SPT. 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. The numerical results show that by adjusting the BER performance of each link, the actual end-to-end QoS performance can be varied with the requirements and the energy can be saved significantly.

In the future work, we are interested in incorporating the network layer retransmission schemes into the multi-hop virtual MIMO protocol. In addition, a distributed protocol will be developed to adjust the BER performance of each link in the SPT to provide the end-to-end QoS guarantee while minimize the overall energy consumption.
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References


[34] J. Hagenauer, “Rate-compatible punctured convolutional codes and their applications,”


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Figure 1.1: Multi-hop virtual MIMO Scheme

Figures 1.2: The Framework of The Transmission Symbols

Figure 1.3: Overall Energy Consumption Versus BER Performance
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Figure 1.4: The Optimal BER Performance Varying with Distance by Three Schemes

Figure 1.5: The Minimum Overall Energy Consumption Varying with Distance by Three Schemes

Figure 1.6: The Optimal Number of Hops Varying with Distance by Three Schemes
Figure 1.7: The Optimal J Varying with Distance by Three Schemes
Figure 1.8: The Short Path Tree of The Cluster Heads

Figure 1.9: Total amount of effective packets received at the sink over time.
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Figure 1.10: Total amount of effective packets received at the sink per given amount of energy.

Figure 1.11: Percentage of nodes alive over time.

Figure 1.12: Percentage of nodes alive per amount of effective data packets received at the sink.
Figure 1.13: The impact of the number of cluster heads on energy saving performance.
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Figure 1.14: The impact of the number of cooperative nodes on energy saving performance.

Figure 1.15: The topology of the SPT in experiments
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Figure 1.16: The minimum energy consumption versus iterations

Figure 1.17: The acquired end-to-end latency versus iterations

Figure 1.18: The acquired end-to-end throughput versus iterations
Figure 1.19: The BER performance of each link versus iterations
Figure 1.20: Actual end-to-end latency versus desired end-to-end latency

Figure 1.21: Actual end-to-end throughput versus desired end-to-end latency
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Figure 1.22: Energy saving performance versus desired end-to-end latency

Figure 1.23: The optimal BER performance of each link versus desired end-to-end latency

Figure 1.24: The topology of the large-scale network
Figure 1.25: The minimum energy consumption versus iterations
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Figure 1.26: The acquired end-to-end latency versus iterations

Figure 1.27: The acquired end-to-end throughput versus iterations
Figure 1.28: Actual end-to-end latency versus desired end-to-end latency

Figure 1.29: Energy saving performance versus desired end-to-end latency