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Preface

The Communication Systems and Networks (CSN) is an inter-disciplinary group focusing on cutting-edge research in the development of reliable and efficient delivery of information for future Internet. It encompasses several areas of study including, but not limited to, telecommunication engineering, mobile communication, sensor networks, intelligent algorithms, network security and bio-inspired networks. The thrust of the research is in the development of intelligent protocols and architectures that offer seamless support for a variety of applications and user requirements in next generation networks. Work under this group includes algorithm design, protocol development and analysis, network programming, and prototype development. The main objective of the group is to establish a world-class collaborative research environment.

BIG DATA AGGREGATION PROPOSED STRATEGIES IN WIRELESS SENSOR NETWORKS

Akshaya – IV Year

Data aggregation is one of the key challenges in big data wireless sensor networks. Data aggregation allows combining data from different sources to eliminate the redundancy, and reduce consequently the consumption of resources available in the network. Data aggregation is a subset of data fusion that involves the use of techniques that combine and gather data from multiple sources to make more effective and potentially more accurate inferences, reparations and associations. Strategies are proposed to deal with this challenge. They are mainly based on the correlation between the data aggregation, the clustering and the energy consumption challenges of big sensor data. The strategies proposed for wireless sensor networks for big data aggregation are:

A. Distributed compressive data aggregation in large-scale wireless sensor networks

The authors proposed a distributed algorithm based on local minimization to dynamically build a routing path to reduce data traffic for aggregation based on compression sampling. The primary goal is to minimize the general traffic in the hybrid data aggregation process with low overhead costs. The authors assume that the aggregation of the data is performed in cycles by correctly programming the network and that no transmission error occurs during the application of the CS source coding scheme. Therefore, the routing path in the data collection process will form an aggregation tree rooted at the BS. In addition, a node is selected as an aggregator when the size of the data it links is greater than a given M. The proposed compressive data aggregation algorithm is divided into two steps:

- Construct the data aggregation tree in a distributive way,
- Reduce the data traffic by adjusting the routing path locally.

The data aggregation tree construction is divided into two phases:

- The first phase of the construction consists in calculating the shortest distance between all the nodes and the BS. For this, a set of unvisited nodes is created and in which all the nodes except the BS are marked as unvisited. Then, for each given node and once all of its neighbors are considered, it is marked as visited, removed from all unvisited nodes and its tentative distance is recorded as the shortest distance. The process is repeated until the set of the unvisited nodes is empty or the smallest tentative distance between all the nodes in the unvisited set is equal to the infinity.

- The second phase of the construction consists of finding the edges of the tree of the shortest path: After the shortest path distance is found for all the nodes, a parent Px is assigned to each vertex x different from the BS. Once the parent of all the different nodes of the BS is determined, shortest path tree is composed of the edges between all the nodes and their parents. Once the aggregation tree is built, a distributed local minimization algorithm (LM) is used to calculate whether switching to a different neighbor can reduce data traffic. Each node performs the following steps:
  - Each node x collects the size of the received data and the identity of the parents of its neighbors with two hops by exchanging INFO messages with its neighbors.
  - For each non-child neighbor with a distance equal to or less than the BS, x measures the local data traffic change if the node x changes its parent to Ni. The new local traffic is calculated assuming node x is redirected to Ni. In the case where Ni and x have the same parent, parental traffic is counted only once. If the new traffic is less than the original traffic, x records the reduced traffic size and the ID of the neighbor.
- After all the neighbor measurements are complete, if the node x is not locked, it selects the neighbor and minimizes the local traffic and sends a LOCK message to prevent it from updating its parent. Otherwise, node x defers its action until it is unlocked by an UPDATE message to continue. Once the LOCK message is recognized by y (i.e., y is successfully locked), x updates its parent to y, and then broadcasts an UPDATE message to inform its neighbors so that they can execute this algorithm with the updated information. The UPDATE message also unlocks y so that it can continue its own calculation and update. If x does not receive an acknowledgment from y after a period of time, it waits for a random time delay and sends a LOCK message again.

The proposed approach is experienced and the simulation results demonstrate that the tree structure has a significant impact on the efficiency of compressive data aggregation. Also, the results show that the proposed solution generates much lower overhead cost than the near optimal solution, making it more suitable for WSN in practical applications.

B. Sensor data aggregation in a multi-layer big data framework

The authors propose a multi-layer big data aggregation infrastructure as well as a priority-based Dynamic Data Aggregation Protocol (PDDA) implemented on the sensor nodes responsible for the data collection. The authors proposed a three-layer data aggregation infrastructure, where data aggregations are performed in Internet connected base stations (BSs) and large data servers. Next, the paper presents a Dynamic Data Aggregation Scheme

(PDDA) based on priorities for sensor networks because the sensors collect a large amount of redundant data.

The proposed PDDA scheme is a hybrid approach that uses clustered and tree-based approaches based on application types. The cluster approach is used to aggregate real-time emergency data that reduces the end-to-end data transmission delay since these data have the highest priority and must be transmitted with a minimum data transmission delay. The tree approach is used for non-real-time applications. Cluster- based and tree-based topologies select certain nodes as active ones that provide all network coverage. Thus, the proposed PDDA approach achieves energy efficiency and reduces data processing time and overhead at the big data server level.

The proposed data aggregation infrastructure has three layers:

(i) Data aggregation at the level of the sensors - layer 1

(ii) Data aggregation at the base station (BS) - layer 2

(iii) Data aggregation at the big data Server or No SQL Server - Layer 3 server.

The proposed PDDA system provides data aggregation priority based on the type of data captured. For example, critical applications in real time, in case of emergency, will have more priority than non-real-time applications. Sensors of layer 1 transmit data to the upper layers through the base station or the gateway nodes. However, to achieve efficient aggregation of data, the sensor networks used for the different types of applications are designed to have a different network topology. For example, for critical or real- time applications, clustering-based aggregation is used when sensors transmit data to the base station through their cluster head (CH). If the CH is far from the base station, the CH will consume more power, but it will eventually transmit data through a minimum number of hops and, as a result, should reduce data latency. In the proposed approach, a number of nodes are selected as active nodes that cover the entire network area. Then, the clusters are formed and an active node is selected as CH for each cluster. The active nodes of the cluster members detect and transmit data to the CHs while the CHs filter or reject the redundant critical data and transmit them to the gateway node so that it can transmit them to the central database or to the control station with a minimum delay.

On the other hand, for non-real-time applications, achieving energy efficiency is more important. As a result, the sensors form a tree topology and transmit data via the shortest path to the gateway node or the BS. Initially, the nodes will be identified as located at different levels of the network depending on the number of hops for the gateway node. Then, the shortest path of the gateway node to the active nodes will be created. Active nodes at the lowest level will detect the event of interest and transmit to the active nodes at the higher level. Parent nodes in this tree always perform data aggregation using different aggregation functions such as MAX, MIN, MEAN, MEDIAN, SUM, and resend to active nodes at the higher level until the data reach the gateway. This approach should result in well-distributed power dissipation on all active nodes and also a lower power consumption of the network, even if the number of hops from the sensor node to the BS is higher compared to the counterpart based on the clustering of this proposed approach. This is due to the energy consumption in a sensor node that is directly proportional to the square of the distance that a packet of data travels from one node to another. However, this approach may have a longer data transmission delay because it traverses several levels and spends time at each node of this hierarchy for data processing. Thus, the proposed PDDA approach offers a compromise between energy efficiency and data transmission delay. Normally, sensor nodes are deployed for a specific application and form their network topology based on the type of the application. However, these sensors can be reused in other applications and change their topology if the application changes. Sensors are aware of the application change by checking the data packet they are sensing and transmitting because the data packets contain the application types, which helps layers 2 and 3 to process and store data in the appropriate places.

The simulation shows that the proposed PDDA scheme dissipates less energy compared to traditional cluster and cluster data aggregation approaches. As a result, the network lifetime of the proposed scheme should be longer than that of the cluster and tree approaches. The results demonstrate that PDDA approach data transmission is inferior to that of clustering-based tree and clustering approaches. The proposed PDDA data aggregation approach selects only a few active nodes that cover the entire network, which reduces the total power consumption of the network. Involving fewer active nodes in processing and data transmission also reduces end-to-end data transmission

C. Lifting wavelet compression based data aggregation in big data wireless sensor networks

The authors aim to the energy- efficient elimination and the compression of redundant data with the objective of recovering the original data. To balance the aggregation load of a large-scale WSN, the authors propose a new energy-efficient dynamic clustering algorithm using spatial correlation, which provides a compressive and distributed data aggregation in each cluster. The authors used a fast and distributed data compression approach based on a lifting wavelet to reduce the amount of raw data. In addition, the approach offers a high recovery of raw data.

The authors propose a data compression algorithm based on a distributed high-speed wavelet to compress the data captured for large-scale WSNs, which can effectively reduce the amount of transmitted data and recover the original data with great accuracy. The originality of the proposed approach lies in the following points:

- The network can be dynamically grouped by exploiting spatial correlation and user requirements rather than complete aggregation in the network.
- Spatial and temporal redundancy can be reduced by the proposed data compression algorithm.
- The proposed approach achieves a good balance between the accuracy of data retrieval and the energy consumption. Spatial correlation is used to determine the cluster members. Once the data detected in a cluster have a strong correlation, a cluster member can represent the nodes in its neighboring area with its own data and the cluster head compresses and sends only the data of its members to the base station rather than all the received data. In addition, the approach allows some cluster members to exit a cluster if their abnormal data are detected. Thus, the energy will be saved by the withdrawals of some nodes and the size of the data will be reduced by deleting the redundancy.

The main contributions of the proposed approach are as follows:

The authors propose a dynamic clustering algorithm based on the spatial correlation of data to eliminate redundancy, which can reduce the size of the redundant data and thus effectively extend the life of the network. The benefit of the dynamic clustering algorithm is analyzed in terms of complexity of time and space. The optimal number of clusters is derived based on related energy consumption. The authors rely on the use of a fast, distributed, wavelet compression technique to aggregate data at each cluster head and send the data to the base station. Prior to the transmission, the wavelet coefficients are further compressed and encoded to reduce the amount of coefficients, which can ensure the accuracy of data retrieval by occupying only a small amount of storage space.

Wavelet distributed lifting compression

The data are compressed based on the proposed data correlation clustering algorithm (CDCC) which not only provides a fast computation, but also a substantial backup of the memory space. The data received by the CH are stored as a two dimensional matrix. The matrix can be broken down into four sub-bands by in-line or column lift wavelets. The four sub bands are: a low frequency sub band and three high frequency sub bands. The most useful information is concentrated in the 8 low frequency sub-band. As a result, some frequency coefficients that contain less information can be eliminated.

In the following, the main procedures of the proposed wavelet data compression method:

First, the original data perform a first-level wavelet transformation. The wavelet transformation process is divided into three steps:

- Fractionation Process: For each row of the data matrix, the data at a given time interval are divided into an even and an odd sequence.
- Prediction Process: A prediction operator is executed on the signals at time intervals to predict the even data signal.
- Update Process: Consists of running a new update operator, which updates the original peer signal to the new peer signal.

During the process of transforming into line wavelet, the original data are replaced by a low frequency coefficient and a high frequency coefficient. The higher is the time correlation of the data the lower is the value of the high coefficient. Similarly, in the process of wavelet transformation of columns, greater spatial correlation implies a lower high frequency coefficient. When the first level wavelet transform is complete for all rows and columns, the original data are converted to a low frequency portion and three high frequency portions.

The proposed algorithm is compared to other approaches and the simulation results show that the CDCC algorithm is superior in terms of energy saving. Although the compression of the lifting wavelet is constrained by its compression ratio, its recovery accuracy may be greater than 98% if the parameters are adjusted appropriately. Indeed, experimental results demonstrate that the data correlation clustering (CDSC) - based consolidation method proposed for data aggregation outperforms other methods to extend the network lifetime and reduce the amount of transmitted data. The proposed dynamic clustering algorithm and the wavelet-based compressive data aggregation technique can achieve better performance, for example greater recovery accuracy data and considerable energy savings.

TRANSFORMING AGRICULTURE THROUGH PERVASIVE WIRELESS SENSOR NETWORKS

M.Sindhuja – IV Year

Agriculture faces many challenges, such as climate change, water shortages, labor shortages due to an aging urbanized population, and increased societal concern about issues such as animal welfare, food safety, and environmental impact. Humanity depends on agriculture and water for survival, so optimal, profitable, and sustainable use of our land and water resources is critical. At Australia's Commonwealth Scientific and Industrial Research Organization (CSIRO), we're developing a "smart farm" that applies wireless sensor network technology to animal agriculture to address these requirements. We've created a pervasive, self-configuring network of cheap, simple devices that learn about their environment and seek to control it for beneficial purposes. Sensor networks for pasture assessment knowing the state of pastures and crop fields in a farm environment are crucial for farmers. As weather patterns change, crops mature, and cattle graze pastures for food, farmers must decide when to irrigate pastures, apply fertilizer, or move cattle to another pasture. Typically, a farmer relies on a combination of experience, visual observation, and intuition as to when to make such decisions, but they will almost certainly be far from optimal. As such, the agricultural-research community has become increasingly interested in the use of sensor networks for agricultural monitoring and has undertaken numerous pilot projects.

We have concurrently focused on sensor networks as a means for providing a new level of information about the state of pastures. Our initial experiments have revolved around the use of solar-powered moisture nodes and low-resolution camera nodes for pasture assessment. Given these two complementary information sources, we can reach a new understanding of the pasture's underlying state. Measuring soil moisture our soil moisture nodes use commercially available ECH2O capacitance- based sensors that measure the surrounding soil's volumetric water content. These sensors generally don't require calibration and have an error of +/– 2 percent. The network automatically takes readings, typically at one-minute intervals, from each node and sends them back. Data is aggregated at the base to give an up-to-date moisture profile for the whole pasture.

Using a spline-interpolation technique over the individual moisture readings from each node, we estimate the function describing the whole pasture's soil moisture profile. You can clearly see the effects of irrigation at the pasture's left end (figure 2a is unirrigated, 2b is irrigated), as well as natural variation across the pasture. This is valuable input to a predictive pasture growth model. Pasture camera nodes other important parameters for farmers include surface grass coverage or grass height. We're investigating the potential for completely selfcontained, self-powered camera nodes that can send images over our low-bandwidth networks. The inset photo in figure 3 shows an example of our camera, which we created by stacking a Fleck-1 board with a custom-designed Texas Instruments DSP board and a custom CMOS camera board. You can also connect a separate MMC board to the stack for storing images. The Fleck main board, DSP board, flash memory board, and camera board work together to take an image and store it in local flash memory. A camera manager at the base preallocates time slots for each camera to send its image, which is reconstructed at the base. A program at the base interpolates missing packets. Ongoing work is investigating image-processing techniques that can take place at the node to extract the pasture's parameters, making the information more compact to transmit. We can also use cameras to observe cattle at water troughs and gates.

Cattle sensor networks

Cattle are an integral part of this dynamic system. By better understanding cattle's individual and herd behavior, grazing habits, and interactions with the surrounding environment, farmers and animal scientists can potentially select for desirable qualities that were previously hard to measure or not fully understood. In this system, animal GPS position data, taken every few minutes, was hopped in a peer-to-peer fashion to other animals when they camera in range. Subject to the amount of storage space on each device, a user could then download historical position data from multiple animals by approaching a single zebra. Researchers have since proposed more sophisticated systems for ad hoc routing of data through large networks of mobile cattle nodes.

Our work in animal sensor networks, however, has focused on extracting information (such as behavior states) that helps farmers understand how herds of cattle interact and graze pastures. This can help solve the agricultural problem of finding better ways to use limited pasture resources. Another unique focus, has been on the potential for internode communication to provide contact-log information (that is, a log of the number of times a pair of animals come into proximity of each other) without needing position information. Animal researchers can use this information to determine characteristics such as cow-calf relationships over time or trends in herd behavior.

Collars and other hardware

To attach sensor nodes to cattle, we created custom collars for them to wear. We mounted the Fleck-2 board and the expansion stimuli board inside IP55-rated plastic (ABS) boxes. These boxes fit into the pocket of a specially designed webbing collar that went around each animal's neck. The collar also had pockets for the two batteries and GPS and radio antennas. Future devices would be miniaturized, but the current collar designs are robust and well suited for experimentation. An important consideration of the collar design was protection against damage by cattle. The initial collar design had a quarter-wavelength (20 cm) whip antenna standing vertically from the top of the collar, which is optimal for communication. In practice, the cattle consistently destroyed the antenna within hours, either by rubbing against trees or cooperating with others to chew them off. Our current, non optimal solution is to lay the radio frequency antenna flat along the top of the collar.

Behavior classification

The ability to model herd and individual behavior is important in providing additional information that can help optimally manage livestock and environmental resources. A major focus of our work has been on methods for modeling cattle's individual and herd behavior on the basis of position and inertial data from the wearable Fleck-2 collar. Calibrating the inertial sensors is crucial to making the best use of this sensor information. For example, accelerometer data should range between 0–1 g. We've developed a calibration method based on the actual data from each animal that doesn't require performing specific calibration routines for each device. The method is based on building a model of the expected distribution of inertial data and fitting model parameters to each data set. By combining position information with inertial information, we can extract numerous features and use them to estimate cattle's behavior states. We can derive features such as speed, turning rate, pitch of head, and movement energy from inertial sensors. But the cattle graze pastures in a non homogeneous way, system that employs teams of sensors, people, water, pasture, animals, and perhaps robots.

ENHANCING ENERGY EFFICIENCY VIA COOPERATIVE MIMO IN WIRELESS SENSOR NETWORKS: STATE OF THE ART AND FUTURE RESEARCH DIRECTIONS

M.Subha Priyadarshini – IV Year

CMIMO

CMIMO is a novel approach of transmitting information by using collaboration of individual antennas; the idea behind of it can be traced back to the virtual antenna array as the ground-breaking work. In CMIMO schemes, the antennas are self-configured to form a cooperative network without any established infrastructure. The communication between the transmitter and receiver proceeds in two phases: information sharing and cooperative transmission. Through the first phase, all the nodes get the information data from the others and enable independent data transmission. In the second phase, all the nodes or selected nodes cooperate together to form a virtual MIMO system through techniques such as distributed space time block coding or repetition. The antennas handle the necessary control and communication tasks by themselves via the use of distributed algorithms without an inherent infrastructure. CMIMO schemes are highly appealing for many reasons. In contrast to conventional MIMO schemes, which relay by packaging multiple antennas in one device, CMIMO schemes break this limitation and work in a flexible way without the performance decreasing in terms of throughput. Also, due to the distributed nature, CMIMO schemes can be rapidly deployed and reconfigured. However, these advantages should not be taken to mean that CMIMO schemes are totally flat. Indeed, many CMIMO schemes require a backbone for use by the cluster head node or assistant node to form cooperative transmissions. The cluster head node and assistant node are usually selected from distributed devices, which make the implementation of the whole CMIMO system complex. Therefore, exploiting the good design structures of CMIMO without violating the fundamental requirements such as spectral efficiency, quality of service (QoS), fairness, and security has important value. The energy constraint is another vital concern in CMIMO schemes. Most existing applications for CMIMO are implemented by assuming that the individual antennas are embedded in the devices with limited energy, and the devices are dropped into a remote region. Therefore, conserving energy to maximize the lifetime is very important, and motivates the research focusing on energy efficiency. On the other hand, ensuring energy efficiency has an effect on the aforementioned fundamental requirements. Thus, finding the trade-off between energy efficiency and the aforementioned fundamental requirements is critical to design energy-efficient CMIMO. Considering the analysis in CMIMO, we may conclude that CMIMO can be a good candidate for next generation communications if we appropriately utilize its advantages and solve its drawbacks.

Energy Efficiency in CMIMO

Since the aim of using CMIMO schemes is to tailor the CMIMO design to the appropriate application for improving energy efficiency, it is useful to discuss the energy efficiency in the CMIMO design. Several fundamental factors need to be considered in energy-efficient CMIMO design. In what follows, we consider the spectral efficiency, QoS, fairness, and security as the fundamental factors and discuss their effects on energy efficiency in CMIMO design. Reducing the energy consumption to increase energy efficiency sometimes can result in lower spectral efficiency due to the reduction of the transmission diversity. Usually, the transmission diversity is related to the modulation constellation size and dimension of the transmitted symbol. Therefore, the appropriate techniques such as adaptive modulation and index modulation techniques need to be considered. In the index modulation technique is taken into account in CMIMO design. The results show that significant energy efficiency is achieved compared to the traditional way under the same spectral efficiency. QoS is a factor interacting with energy efficiency and needs to be guaranteed in most cases. Apparently, the QoS improvement mechanism is contradictory to the energy efficiency requirements because good QoS usually requires big energy consumption. However, for a given QoS, energy efficiency can be achieved by adapting the modulation scheme at the cost of increasing the transmission power. Some systems are energy efficiency preferred, whereas some are power preferred. The type of reference depends on the system itself. If the system is energy efficiency preferred, the property of big power can be neglected. The optimal modulation constellation sizes are derived to achieve energy efficiency under the given bit error ratio (BER) requirement. The results show that by adapting the modulation to choose the optimal modulation constellation size, the energy efficiency is obtained. Fairness for a communication system refers to the degree to which a fair share of system resources is utilized. For instance, in cognitive-radio-based wireless networks, a certain amount of spectrum should be assigned regardless of the ambient environment. In many cases, increasing energy efficiency causes unfair sharing of the system resources. Therefore, it aims to allocate resource as fairly as possible while keeping energy efficiency. The authors propose a cognitive CMIMO by considering the radio resource being fairly utilized, and the results show good performance in terms of energy efficiency. For CMIMO-based wireless sensor a network, security is usually not mandatory but desired. In a normal security-based environment, more energy is needed during the transmission due to the additional processing at both the transmitter and receiver. Spending more energy will decrease the energy efficiency. However, in some special environments such as the military environment, secure transmission can improve energy efficiency by avoiding the additional energy due to misdetection and retransmission. Hence, considering security or not to improve energy efficiency in wireless sensor networks is highly dependent on the operating environment. In the following section, we discuss more energy efficiency issues of the recent advanced techniques in CMIMO design.

Recent Advances in CMIMO

Diversity Gain in CMIMO Schemes

By cooperating with the neighboring wireless nodes, CMIMO can efficiently reduce the transmission energy, but this benefit comes at the cost of higher circuit energy consumption. Since the transmission energy of wireless nodes is proportional at least to the square of the distance, the transmission energy dominates the total energy consumption for a long transmission distance. On the other hand, when the transmission distance is short, circuit energy becomes the major contributor in the total energy consumption. Therefore, in the case of long transmission distance, more cooperative nodes should be used to reduce the transmission energy consumption via antenna diversity, while in the case of short transmission distance, fewer cooperative nodes are preferred to reduce the circuit energy. Moreover, the authors also show that there is an optimal modulation constellation size for each transmission distance. By considering this factor, the energy consumption performance of CMIMO can be further improved.

Multiplexing Gain in CMIMO Schemes

Vertical-Bell Labs Layered Space-Time (VBLAST)-virtual MIMO is yet another classical CMIMO, which provides multiplexing gain by allowing a virtual antenna array to transmit *N* independent data streams. The core technique of this scheme is to point a data gathering node that can cope with more computational complexity than other normal nodes at the receiver. At the transmitter, each of the nodes broadcasts its data to the other nearby nodes by means of a time-division multiple access scheme. After that, each node has data from all the others to transmit through space time coding techniques. At the receiver, the data gathering node receives data from the transmitter, which allows realization of real MIMO capability with only transmitter side local communications. Using this method, significant energy reduction is achieved.

Data Aggregation Gain in CMIMO Schemes

The CMIMO with data aggregation technique is a way in which the correlated data size can be significantly reduced according to the correlation factor . The underlying philosophy is to reduce the amount of redundant data depending on the data similarity at the transmitter. Specifically, the sensor nodes send the information data to their cluster head, and then the cluster head aggregates the collected data and sends them back to all the sensor nodes in that cluster. Thus, all the sensor nodes at that cluster have the same aggregated information data. After that, the sensor nodes transmit the received aggregated data to the sensor nodes that are located in the receiving cluster, and then sensor nodes at the receiving cluster transmit the received data to their cluster head for joint detection. By considering data aggregation, the transmitted data amount is significantly reduced, and so is the total energy.

Indexing Gain in CMIMO Schemes

CMIMO-spatial modulation (CMIMO-SM) is a novel CMIMO transmission scheme based on the SM technique. The adoption of SM makes CMIMO systems operate without inter-channel interference (ICI). In CMIMO-SM, each node at the transmitter side broadcasts its information data to all the other nodes inside the transmitting cluster using different time slots as the first stage. In the second stage, after each sensor node receives all the other information data, the data sequence is transmitted via the MIMO channel. Note that, for each time instant, the transmitted data sequence is split into two parts: the multiple quadrature amplitude modulations (MQAM)/ multiple phase shift keying (MPSK) modulated symbol part and the antenna index part. Only the modulated symbol part is transmitted, while the antenna index part is reserved for the selection of active transmit antenna and will be detected at the receiver as hidden information. Therefore, for the same spectral efficiency, fewer bits are transmitted in CMIMO-SM compared to CMIMO. Additionally, CMIMO-SM requires a single RF chain, unlike plain CMIMO. Overall, the total energy consumption, including transmission energy and circuit energy, is reduced in CMIMO-SM when compared to that in CMIMO.

CMIMO-SM with randomly distributed nodes (CMIMO-SMR), is a recently proposed clever modification of CMIMO-SM to improve the flexibility while maintaining its advantages such as ICI-free and energy-efficient transmission. In CMIMO-SMR, the cluster head node and assistant node are jointly set up by means of a cooperative technique in each cluster to obtain diversity. Specifically, the randomly distributed nodes form clusters; and in each cluster there are a cluster head, an assistant node, and several nodes. The cluster head and assistant node have a preassigned index by use of 1 and 0, respectively, to represent them. In the cluster, each node decides if it works as a cluster head for each round according to the rounds in which the node has been a cluster head. After that, the nodes inside the cluster inform the selected cluster head that they will operate as normal nodes or the assistant node by transmitting an extra bit along with the information data. According to the received signal strength (RSS) of the acknowledgment from the other nodes, the cluster head selects the assistant node from the interested candidates. Once the formation of the cluster is done, the nodes only transmit information data to the cluster head and the assistant node. After that, the cluster head and the assistant node transmit the received information data by use of SM. Compared to CMIMO-SM, CMIMO-SMR has less operation inside the cluster and lower circuit energy consumption at the receiver due to the existence of the cluster head and assistant node. Thus, total energy reduction is achieved.

Hop in Multihop-CMIMO Schemes

When the transmission distance is far, CMIMO is often presented in the context of multihop architectures. The authors derive an optimal hop length expression for multihop-CMIMO-based linear networks, where the sensor nodes form clusters using CMIMO-SM to transmit the information. The optimal length is derived mathematically by considering the transmitted load. Specifically, a cluster close to the destination forwards more load than another cluster far away from the destination; thus, the hop length for the cluster that is close to the destination should be small. The opposite way can be explained for the big hop length. In this way, for each hop length, there is a matched optimal value for it to achieve the minimum energy consumption.

When the intermediate hops act only forwarding information data rather than transmitting their own information data, an optimal number of hops that can be used to minimize the total energy consumption of the whole network can be found by solving the optimization problem. Specifically, the total energy consumption is dependent on the number of hops and can be treated as a convex function. The optimal number of hops can be achieved by taking the first-order derivative of the total energy function with respect to the number of hops and setting it to zero. Because the number of hops is defined over integer values, the adjacent value, which is with regard to the minimum total energy consumption, can be selected as the optimal number of hops.

Communication Modes Adaptation in CMIMO Schemes

In cooperative communications, it is possible to form CMIMO mode, cooperative single-input multiple-output (CSIMO) mode, and cooperative multiple-input single-output (CMISO) mode via the collaboration of nodes. In wireless sensor networks, the energy reduction can be achieved by adapting the communication modes for each transmission hop. A novel communication mode adaptation algorithm is introduced to improve energy efficiency in wireless sensor networks. For each hop, the adaptation of communication modes is considered and determined by optimizing the parameters such as the number of transmitters, receivers, and cooperation nodes to achieve the minimum energy consumption. The experiment results show that significant energy reduction can be obtained by using the communication modes adaptation algorithm.

Radio Resource Management in CMIMO Schemes

Radio resource management is one effective way to reduce energy consumption of wireless systems . The goal of the research on radio resource management is to efficiently utilize the radio resource of the whole network by use of traffic-aware and cognitive radio techniques. The cognitive CMIMO where the local broadcasting phase and distributed MIMO access phase operate in the cognitive and licensed bands, respectively. In the broadcasting phase, each active node broadcasts its own message with a transmit power, whereas an inactive node becomes a participant of the CMIMO only when it can successfully decode the message transmitted from the nearest active node. It shows that the energy efficiency can be increased by tuning the bandwidth ratio for a given spectral efficiency range.

Sleeping Strategy in CMIMO Schemes

In CMIMO networks, it is not always reasonable to assume that all nodes simultaneously participate in the transmission or are active in certain scenarios. Therefore, sleep mode is an effective tool for energy saving. We propose the design of CMIMO schemes to decide whether a node with a single antenna should be active to become a part of CMIMO under an energy constraint requirement so as to achieve better system performance. In particular, under large-scale CMIMO-based networks, the number of cooperating nodes is high. In this case, if all the nodes participate and keep active in the cooperation stage, the local energy consumption, especially the circuit energy consumption, will increase. On the other hand, the cooperation of large active nodes makes the cooperative transmission consume less transmission energy in the long haul due to the added spatial diversity. Therefore, there is a trade-off between the number of active nodes and total energy consumption. This active nodes selection can be done via making a node sleeping strategy, and then the total energy consumption of CMIMO networks can be optimized by use of the sleeping strategy.

Joint Selecting Gain in CMIMO Schemes

Joint selection is a good candidate to reduce the energy consumption of wireless systems . In multihop-CMIMO networks, the energy consumption is more complex due to the complex transmission environments. CMIMO can exploit the spatial diversity to reduce the transmission energy under a given BER. Therefore, larger hop length should be used to reduce the number of hops. On the other hand, when the hop length is large, the energy consumption of long-haul transmission will dominate the overall energy consumption. Thus, more nodes are required to enlarge the spatial diversity, which will benefit the transmission energy. This analysis means that not only the hop length, but also the numbers of hops influence the total energy consumption. In a joint selected scheme is proposed in CMIMO systems for energy reduction. In this scheme, the hop length and the number of cooperating nodes are jointly selected under the high node density condition. The simulation results indicate that significant energy saving is obtained by using the joint selected scheme.

Challenges in Cooperative MIMO

Despite the significant developments that have been achieved in CMIMO, in practical environments, CMIMO still faces several challenges.

Cross-Layer Design

Cross layer design for energy efficiency improvement is important in CMIMO-based transmission. The key design challenge is the performance guarantee when several layers are considered together. There have been many works at different layers in CMIMO networks for energy efficiency. However, their efforts mainly focus on isolated layer design, thus ignoring important interdependencies. Such isolated layer design results in poor performance, especially in real environments when energy and delay are constraints. To overcome this problem, a cross-layer design that supports integration across multiple layers of the protocol is required.

Power Control

Power control is a potent way to improve the performance of CMIMO transmissions. Due to multipath fading, the channel changes randomly. Power control can be used to compensate the random channel, reduce the transmit power, meet the delay constraint, and minimize the probability of link outage. For example, when the CMIMO transmission experiences a deep fading channel, much power should be used to maintain the required signal-to-noise ratio (SNR); when a hard delay constraint requirement is given, the power for transmission of a packet should be increased to improve the probability of successful transmission. For all these purposes, power control in the CMIMO environment needs to be investigated.

Channel Estimation

To improve the BER performance and optimize the power allocation in CMIMO systems, channel estimation is indispensable. Although there have been many works on real MIMO channel estimation, the channel estimation in CMIMO is a challenging task because the antenna elements of CMIMO are not integrated. Moreover, because of the frequent changing of cooperated candidates, the timing requirement of channel estimation is very strict. To achieve accurate channel estimation, there remain many open issues, such as how to utilize only partial channel state information to estimate the whole CMIMO channel, and how to characterize the relation of multiple links at the system level appropriately.

Topology Design in Multihop-CMIMO

Existing topology schemes in CMIMO are mainly developed for linear networks. Specifically, the linear network is categorized into all transmission and single-transmission networks. In these CMIMO-based networks, the optimal values such as the optimal number of hops or optimal hop lengths are calculated for the purpose of total energy saving. Their solutions mainly rely on Lagrange function or derivation. However, in fact, the nodes in CMIMO networks are usually distributed, and the linear topology may not always be suitable. Therefore, the optimal solutions in terms of hops and hop lengths for CMIMO-based random topology are needed. There have been some methods, such as energy awareness optimal relay selection (EAORS) , for solving the energy efficiency problem. However, it is not used in the CMIMO scenario yet. Thus, adopting such methods into CMIMO can be a good way to solve the topology problem.

Adaptive Resource Allocation

In CMIMO systems, adaptive resource allocation can provide robust performance while meeting application-specific requirements. The working principle is to achieve better transmission performance via adaptation of the transmission schemes inlcuding constellation size, coding scheme, power level, and so on. The authors design an adaptive modulation by changing the modulation constellation size for compensating SNR variations. The transmit power can be adapted by changing the modulation constellation size to meet the BER requirements caused by the variations of SNR. However, in real CMIMO systems, how to facilitate and motivate CMIMO to be adaptive is challenging. In other words, mechanisms to facilitate the adaptation need to be investigated.

Service Differentiation

In CMIMO, energy saving should exploit not only the traffic load variations by considering the node sleeping strategy, but also the variations of QoS requirements. Specifically, in CMIMO-based wireless networks, some applications require short delay, whereas some applications are delay-tolerant. Therefore, it is reasonable to differentiate the types of traffic and make the energy consumption scale with the corresponding traffic type. Such service-differentiation-based CMIMO can be a potential candidate for energy reduction.