INTRODUCTION TO RECENT RESEARCH PROJECTS

Dr. Wei Chen, Professor
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1. Cloud Computing
2. Cooperative Cognitive Radio Networks
3. Security and Robustness in Wireless Sensor Networks
4. MIMO Technology & Cross-Layer Design of Radio Networks
5. Communication and Routing Protocols in Sensor/Mobile/Ad-Hoc Networks

Dr Wei Chen's Biography

Wei Chen, professor in Tennessee State University. She received the B.A. Degree in mathematics from Shanghai Marine Institute, China, in 1982, and M.E., and Ph.D. degrees in Computer and Information Engineering, Osaka University, Japan, in 1991 and 1994. She was an assistant professor during 1994-1998, and an associate professor during 1999-2000, at Nagoya Institute of Technology, Japan. She joined Nanzan University, Japan, in 2001, and promoted to professor in the same year. Since 2002 she has been a professor at the Department of Computer Science in Tennessee State University. She was visiting scholar in Nagoya Institute of Technology in summer of 2002, 2004, and 2006. Dr. Chen has more than 80 publications in research journals and conferences. She has led a number of scientific research projects funded by the Ministry of Education, Science, Sports and Culture of Japan, ARO, AFRL and etc. Dr. Chen received IBM Faculty Award in 2010. Her research interests include Parallel/Distributed Computing, DNA Computing, Bioinformatics, Algorithm Design and Analysis, Wireless Mobile Computing, Sensor Networks, Network Security, and Computational Geometry.

1. Cloud Computing

Topic: Market based approaches for workload balancing in cloud computing
Funding: IBM Faculty Award, 2010
PI: Wei Chen
Publications:

1. W. Chen, H. Miao, L. Hong, S. Hargrove, "Dynamic and Decentralized Approaches for Optimal Allocation of Multiple Resources in Virtualized Data Centers," *Proceedings of International Conference on Parallel and Distributed Processing Techniques and Applications* (PDPTA'11), 2011.

Summary
This research proposes dynamic and decentralized approaches for optimally allocating multiple resources in virtualized data center that has time-varying workload and heterogeneous applications. Instead of using predication based approaches or sensor measurement based approaches for resource provision, in this work, we tackle the problem with market based approaches that simplifies the control scheme and enable real-time control decision making based on each server's queue information. The proposed resource allocation scheme combines local optimization and heuristics for global optimization. In order to avoid high complexity related to multiple resources and multiple applications, we use a simple reinforcement learning method to achieve unknown optimal resource utility level. The simulation results show that our approaches can jointly maximize the throughput of the applications and minimize the usage of the resources. Furthermore, our approaches can adapt to unpredictable changes in the workload and do not require prediction or measurement of the utility level of different resources.

Virtualized Data Center Model
We consider a virtualized data center with *m* servers that host *n* types of applications, where each server hosts a subset of the applications and provides a virtual machine (VM) for each application hosted on it [9] (Fig. 1). An application may have multiple instances running across different servers in the data center. We use an indicator $a_{ij} = 1$ or 0 to indicate application *i* is hosted or not hosted on server *j* for $i \in \{1,2,...,n\}$ and $j \in \{1,2,...,m\}$. Each server has a set of resources such as CPU, disk, memory, bandwidth, etc. Application requests arrive for each application *i* according to a random arrival process. We use A_i to indicate the queue of requests arriving for each application *i*. We assume a time-slotted system. At every timeslot, the requests in A_i are admitted into each buffer Q_{ij} at virtual machine VM_{ij} via network router. We assume that buffer Q_{ij} is large enough to keep the requests that will be processed in one timeslot.

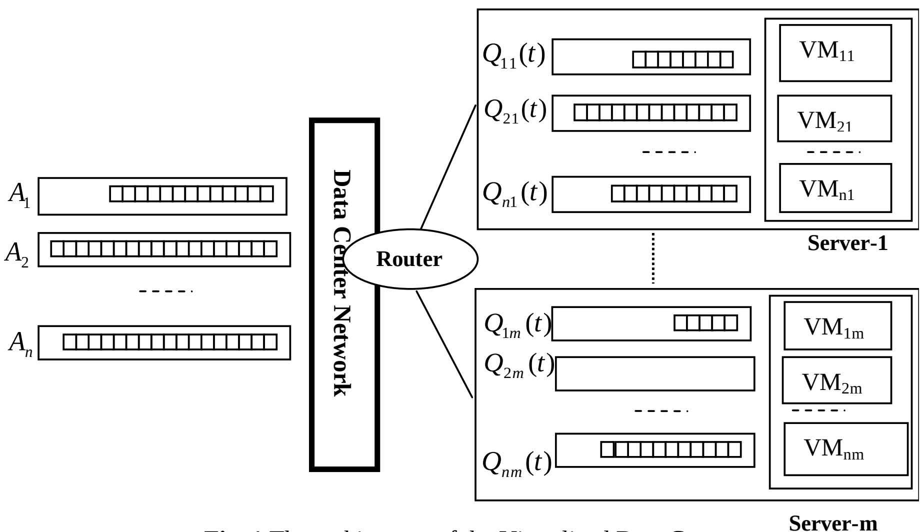

Fig. 1 The architecture of the Virtualized Data Center

Computing resources
Virtualized data centers enable consolidation of multiple applications sharing multiple resources. A customer can lease a virtual machine with a specific set of resources for a guaranteed service performance (e.g. the number of requests proceeded per second). The demands of applications are time-varying; therefore, more computing resources should be allocated on demand to an application when its workload incurs more resource demand. Among the computing resources at a server, for some resource such as power the total amount is adjustable, and for some resources such as disk, memory and bandwidth the total amount is

fixed when the server is installed.

Power management is one of the critical issues in an enterprise data center. Modern CPUs can be operated at different speeds at runtime by using techniques such as Dynamic Frequency Scaling (DFS) and Dynamic Voltage Scaling (DVS). The power-frequency relationship is well-approximated by a quadratic model $P(f) = P_{\min} + \xi(f - f_{\min})$ [3]. In other words, based on time-varying demand, we can adjust the power consumption by operating *CPU* at different speed and runtime using DFS or DVS. When power demand is lower than the threshold, the server can be switched to sleep mode. For some resources, such as bandwidth, more resource does not always achieve the better performance. For example, assume that application *i* in virtual machine VM_{ij} at server *j* needs to transfer data to the applications *p* in virtual machines VM_{pq} at server *q*. If the outgoing bandwidth assigned to application *i* in VM_{ij} is much larger than the incoming bandwidth assigned to application *p*, the transfer rate will be very low since large amount of the transmitted data are lost at VM_{pq} and the lost data need to be retransmitted from VM_{ij}.

Market Model and Control Objective

In the data center, a customer leases a virtual machine with a specific set of resources for the guaranteed average throughput (number of requests per second). We define the profit at each timeslot *t* for the data center according to the payments of customers and the costs of resources. Assume that virtual machine VM_{ij} at server *j* hosts application *i* at timeslot *t*. Let *R* be the set of resources at the data center. At time slot *t*, let $\bar{r}_i(t)$ and $\bar{\lambda}_i(t)$ indicate the requested amount of resource $r \in R$ and average throughput (number of requests) that the user bids for, $r_i(t)$ and $\lambda_i(t)$ indicate the real allocated amount of resource $r \in R$ and real throughput, and $que_i(t)$ indicates the number of requests in queue Q_{ij} at virtual machine VM_{ij}. The profit in server *j* at timeslot *t* can be formulized as follows:

$$profit(t) = \sum_{i=1}^{n} (pay(\bar{\lambda}_i(t)) - \sum_{r \in R} r_i(t)\text{cost}(r)) \quad \text{---------} (1)$$

where the payment model is defined in the following formula:

$$pay(\bar{\lambda}_i(t)) = \begin{cases} bid(\bar{\lambda}_i(t)) - penalty_i(t) \\ \quad \text{penalty case: if } \lambda_i(t) < \min(\bar{\lambda}_i(t), que_i(t)) \\ \quad \& \exists r \in R, r_i(t) < \bar{r}_i(t) \\ bid(\bar{\lambda}_i(t)) + award_i(t) \\ \quad \text{award case: if } \lambda_i(t) > \bar{\lambda}_i(t) \\ \quad \& \frac{1}{T} \sum_{t'=t-T+1}^{t} \lambda_i(t') \le \bar{\lambda}_i(t) \\ bid(\bar{\lambda}_i(t)) \quad \text{Others} \end{cases} \quad \text{-----------} (2)$$

In formula (2), $bid(\bar{\lambda}_i(t))$ is the payment from the customer for application *i* and the guaranteed average throughput $\bar{\lambda}_i(t)$. If $que_i(t) > \lambda_i(t)$, and $r_i(t) < \bar{r}_i(t)$ and $\lambda_i(t) < \bar{\lambda}_i(t)$, then the customer is under provisioned and the center needs to pay a penalty. If $\lambda_i(t) > \bar{\lambda}_i(t)$ and the real average throughput in time period *T* is smaller than $\bar{\lambda}_i(t)$ and the server successfully processed more requests than the requested average (the requests more than expected may caused by a sudden burst of the load), the center needs to be paid by an award. We suppose that the queues for application *i* admit the requests at the beginning of each timeslot.

Let $que_i(t)$, $que'_i(t)$ indicate the number of the requests in the queue for application *i* at the beginning of timeslot *t* and at the end of timeslot *t*, respectively. By measuring the size of the queue, we can get real performance $\lambda_i(t) = que_i(t) - que'_i(t)$. The total profit from all servers $j\ (1 \le j \le m)$ for all application $i\ (1 \le i \le n)$ at *timeslot t can be described as follows:*

$$Tprofit(t) = \sum_{j=1}^{m}\sum_{i=1}^{n}(pay(\overline{\lambda}_{ij}(t)) - \sum_{r \in R} r_{ij}(t)\text{cost}(r)) \quad \text{---}\ (3)$$

The control objective is to maximize the profit at each schedule slot by maximizing the payment from users and minimizing the cost of resources in the data center.

2. Cooperative Cognitive Radio Networks

Title: Cooperative Wireless Communication and Networked Methods for Spectrum Sharing and Interference Reducing
Funding: U.S. Air Force, November 2010 – October 2011
PI: Wei Chen
Publications:

1. Liang Hong, McKenzie McNeal III**,** Wei Chen, "Secure Cooperative MIMO Communications under Active Compromised Nodes", accepted. *Proceedings of IEEE International Workshop on Sensor Networks and Systems for Pervasive Computing,* pp. 128 – 133, 2011.
2. Wei Chen, McKenzie McNeal, Liang Hong, "Cross-Layered Design of Security Scheme for Cooperative MIMO Sensor Networks," Proceedings of *IEEE International Conference on Wireless Information Technology and Systems,* 2010.

Research Objective: Investigate and develop cooperative wireless communication and networked methods for cognitive radio networks that can significantly improve spectrum sharing and reduce interference. The research has two-fold purposes: using the diversity gain obtained through cooperative communication to improve system capacity and spectrum efficiency in terms of range extension, power saving and low latency; using virtual multi-antennas obtained through cooperative communication to limit or avoid interference toward cognitive radio network users, especially towards primary users. Cross-layered design with networked methods will be used to optimize network wide behavior and global performance. Collaborative dynamic spectrum access in which multiple spatial observations are combined to form an improved signal estimate is also in the research scope.

Research Approaches: Cognitive radio (CR) is a promising technology to improve the utilization of the limited spectral resources for future wireless networks by means of opportunistic spectrum access. It allows the primary and cognitive radio (secondary) networks to coexist and share the same spectrum and encourages cognitive radio users to sense the radio environment in search of the frequency band or time slot that is not being used by the primary users to exploit transmission opportunities. The main challenges to the efficient development of cognitive radio networks include primary user detection and transmission opportunity exploitation. This research will focus on the latter issue, which means that after a spectral hole is identified, secondary users must exploit the transmission opportunity so as to maximize their own performance such as transmission rate while making the interference with the primary users below a given threshold level.Though smart antenna array systems have been shown to provide extremely high spectral efficiencies and be used to limit or avoid interference, it is unrealistic to equip such systems in small-sized and/or low-cost devices. Recently, user cooperation in which distributed single-antenna nodes cooperate on data transmission/reception and relay/forward as a multi-antenna system has been increasingly regarded as a powerful technology to exploit user diversity and provide dramatic gains in reliability and capacity increase. Cooperative communication techniques with cognitive radio hold great potential to significantly improve system capacity, spectrum efficiency and network performance.

The focus of this research is to explore cooperative wireless communication and networked methods for spectrum sharing and interference reducing in cognitive radio networks. In this research, we will investigate and develop cooperative communication and networking schemes to 1) maximize the spatial diversity for the same spectrum frequency band, and 2) reduce the interference of the secondary users with the primary users.

The simplified system for this research with one primary link and four cognitive users is illustrated in Figure 1, where PT, PR, CT, CR and H denote the primary transmitter, primary receiver, cognitive transmitter, cognitive receiver and secondary helper, respectively. The developed schemes are applicable to multiple primary links and other cognitive user scenarios.

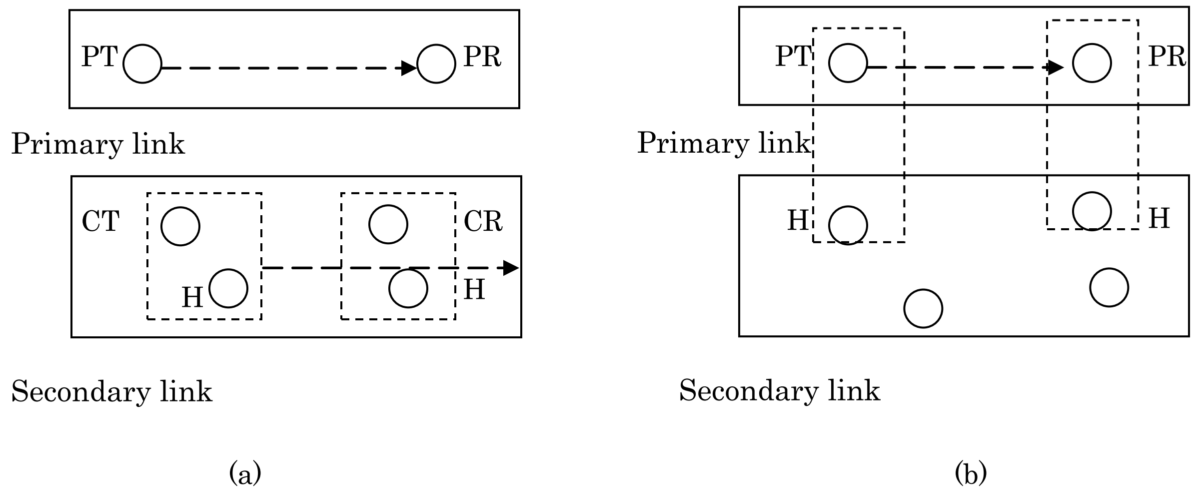

Figure 1. Simplified system for a cooperative cognitive radio: (a) cooperative transmission between secondary users; (b) cooperative transmission between primary and second users.

To improve system capacity and spectrum efficiency in terms of range extension, power saving and low latency using the spatial diversity for the same spectrum frequency band, two different scenarios will be considered in the research, 1) cooperative transmission between secondary users, where secondary users form virtual antenna array to increase the secondary throughput and reliability; 2) cooperative transmission between primary and second users, where primary users and secondary users form virtual antenna array to increase the primary throughput and reliability. The rationale behind such a decision is that the helping primary users finish their transmissions as quickly as possible will, in turn, lead to more transmission opportunities for secondary users. The cooperative transmission scheme brings in new challenges of resource allocation and grouping. Joint node-selection and spectrum-allocation schemes will be investigated and designed so that the throughput of the cooperative cognitive radio network under the quality of service (QoS) requirement of the primary link will be maximized. Specifically, the transmitter broadcasts a message to a set of secondary users, which can serve as a set of helper. A new distributed clustering algorithm will be developed in this research to let the cognitive users that correctly decode the message create or reconfigure a virtual antenna array to forward the message to the receiver. The trade-off between the two scenarios in Figure 1 will be taken into account. In general, an optimal clustering algorithm is a NP-hard problem. A sub-optimal algorithm with significant reduction on computational complexity will also be developed using a heuristic solution. After forming the virtual antenna array, the channel will be allocated to increase the system performance.

To reduce the interference of the secondary users with the primary users in the scenario (a) in Figure 1, cooperative antennas at the secondary transmitters will be used to put nulls in the antenna radiation beamforming pattern of secondary transmitters along the direction indentified as the primary receivers, thus enabling the share of frequency and time resources with no additional interference. Specifically, in order to reduce the interference of secondary users with the primary users, the secondary users must be aware of the approximate location of the primary users. This knowledge can be acquired during primary user detection stage. The primary user distribution map with the locations of the primary users relative to the cognitive users with direction will be forwarded to the secondary user based on request. The best weight vector of the zero-forcing beamforming will be developed to put nulls in the antenna radiation beamforming pattern of secondary transmitters along the direction indentified as the primary receivers, while putting the beam of the virtual antenna array aimed at the receiver direction to maximize the receiving power. In the literature, most works were largely based on the assumption of perfect channel state information (CSI) which is usually difficult to achieve in practice. In this project, a more general setting that optimize the transmit beamforming with the aid of imperfect CSI will be considered. Iterative algorithms will be developed to efficiently obtain the robust optimal beamforming solution.

It is essential to optimally assign cooperative antennas for achieving both purposes. Cross-layered design with networked methods will be used for optimal network-wide behavior and global performance. The MAC protocol will be designed to coordinate physical-layer operations among multiple nodes and achieve reliability, energy saving and latency reduction at each virtual MIMO link. The approach will adaptively achieve optimal multiplexing gain and/or diversity gain based on current physical parameters of virtual MIMO nodes/links such as the diameter of the virtual MIMO nodes, number of cooperative nodes in the virtual MIMO nodes, length of the virtual MIMO links, and the strategy that the primary nodes used to cooperate transmission and reception between virtual MIMO nodes and etc. Collaborative dynamic spectrum access schemes will also be developed to improve signal estimation for spectrum sensing.

The following research tasks are expected to be performed in order to achieve the above stated goals and objectives:

1. Develop and theoretically analyze the optimal join node-selection and spectrum-allocation schemes
2. Develop and theoretically analyze the sub-optimal join node-selection and spectrum-allocation algorithm that can significantly reduce computational complexity
3. Develop and theoretically analyze zero-forcing beamforming algorithm with imperfect CSI information
4. Develop and theoretically analyze iterative algorithm that can efficiently obtain the robust optimal beamforming solution
5. Develop the MAC protocol using cross-layered design to coordinate physical-layer operations

3. Security and Robustness in Wireless Sensor Networks

Topic: Robust Networking Architectures and Security Schemes for Heterogeneous Sensor Networks (DTRA's Student Research Associate Program)

Funding: DTRA (subcontract from Pennsylvania State University), January 2009 – May 2011

PI: Wei Chen

Publications:

1. M. McNeal, W. Chen, S. Shetty, S. Aungst, "Security-Oriented Robust Networking Architecture and Key Management for Heterogeneous Wireless Sensor Networks," *Proceedings of International Conference on Wireless Networks (ICWN'11)*, 2011.

Summary

Current communication protocols used for Wireless Sensor Networks (WSNs) have been designed to be energy efficient, decrease redundancy in sensed data, increase the lifetime of the sensor network, and reduce the number of transmissions across the network. But one major issue that must be addressed is security of sensed data and communication channels between sensor nodes. Due to the limited capabilities of sensor nodes, e.g. power, memory, transmission range, and processing power, designing security-based communication protocols present a difficult challenge. The current commonly used encryption schemes require too much processing power and memory to be used by the sensor nodes. Security for WSNs requires a unique scheme and protocol to protect the data and functionality of the network. The overall goal of this work is to develop a security system for heterogeneous WSNs that feature security-oriented robust networking architecture (Figure 1) and secure communication scheme (Figure 2). We propose that the security should begin with the network architecture in defining the roles of each sensor node. These defining roles provide a measure of security through a hierarchical communication protocol and aid in the distribution of an efficient key management scheme that uses both public key and symmetric key cryptography. The simulation results show that by using the proposed networking architecture and key management scheme a small amount of keys is preloaded before deployment and stored after key setup to achieve secure connectivity throughout the entire network.

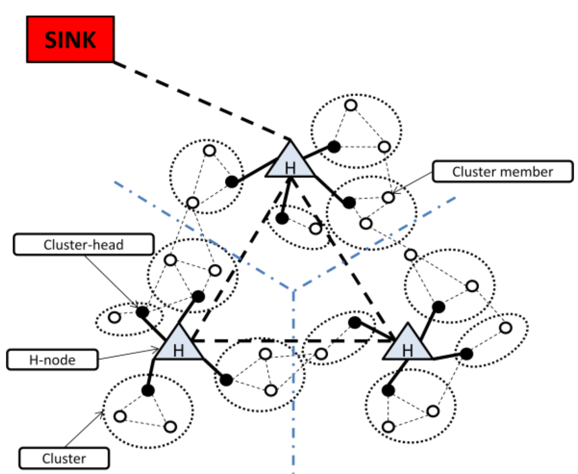

Figure 1 - Hierarchical Cluster-based HWSN architecture

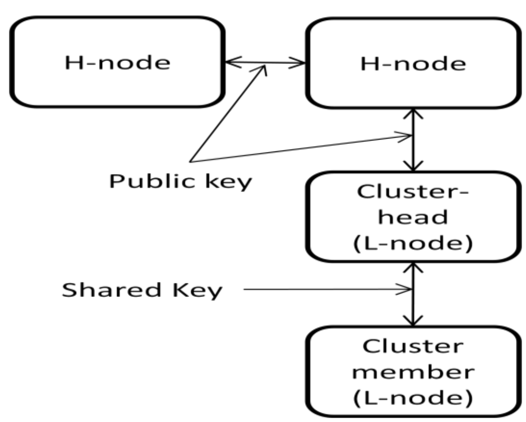

Figure 2 - Secure routing hierarchy for cluster-based HWSN

4. MIMO Technology & Cross-Layer Design of Radio Networks

Topic 1: A Cross-Layered Perspective of Cognitive Networks – Building MIMO Radios into Design of Cognitive Networks
Funding: U.S. Air Force (Oct.2009 – Sep. 2010)
PI: Wei Chen

Topic 2: Heterogeneous Cognitive MIMO Networks: From Spectral Efficiency to Global Optimization
Funding: U.S. Air Force (Oct.2008 – Sep. 2009)
PI: Wei Chen

Topic 3: Cross-Layer Design of Channel-Adaptive Transceiver jointing with MAC and Networks
Funding: U.S. Air Force (Sep.2006 – Aug. 2008)
PI: Wei Chen

Publications:

1. W. Chen, H. Miao, L. Hong, "Cross-layer Design for Cooperative Wireless Sensor Networks with Multiple Optimizations," *International Journal of Networking and Computing,* Vol. 1, No. 1, pp. 63-81, 2010.
2. Wei Chen, Heh Miao, Liang Hong, Jim Savage, Husam Adas, "Cross Layer Design of Heterogeneous Virtual MIMO Radio Networks with Multi-Optimization," *Proceedings of 12th Workshop on Advances in Parallel and Distributed Computing Models in IEEE International Parallel & Distributed Processing Symposium*, 2010.
3. W. Chen, H. Miao, L. Hong, S. Zein-Sabatto, H. A. Adas, K. Suzan, "Distributed Resource Management and Parallel Routing for Data Acquisition in Heterogeneous Sensor Networks,"

Summary of Topic 1

Research Objective: Investigate and design a network of cognitive MIMO radios in a cross-layered manner for two-fold purposes: leverage MIMO induced spectacular increase to network-wide optimization on throughput, QoS, and network lifetime; second, explore optimal control topology and distributed algorithms for cognitive radio with minimal coordination among the nodes to provide the additional spatial degrees of freedom from MIMO antenna arrays for controlling the interference generated by the cognitive users.

Prior Work: We have worked on joint design of link scheduling, MAC and routing protocol for the networks of heterogeneous MIMO radios. We investigated the tradeoff of data rate, energy, transmission distance, error rate, and other physical constraints in MIMO radio systems. By optimally using diversity gain and multiplex gain, our design successfully leveraged MIMO induced gains into the network-wide optimization on throughout, QoS, and network lifetime. The work has been summarized and published in the Proceedings of International Conference on Wireless Networks, WORLDCOMP, 2008. Currently, we are considering to generalize our work to the networks of virtual MIMO radios in which distributed individual single-antennas cooperate on investigate information transmission as a multiple antenna array.

Proposed Work: Based on our prior work, we propose to develop a network consisting of cognitive radios equipped with physical/virtual MIMO antenna systems. Since it is unrealistic to equip multiple antennas physically at each terminal device considering the size, power consumption and cost of the terminal devices, we must introduce virtual MIMO technology into low-cost small nodes such that distributed individual single-antennas cooperate on investigate information transmission as a multiple antenna array. It is essential to develop distributed algorithms which allow low-cost small nodes to self-form virtual MIMO nodes in optimal way. After it, we can generalize our prior work to a virtual MIMO network. On the other hand, we will work on develop control topology for cognitive radios to provide the additional spatial degrees of freedom from MIMO antenna arrays and investigate decentralized algorithms to avoid or minimize the interference generated by the primary users.

Summary of Topic 2

Research Objectives: It is widely recognized that the use of a MIMO (Multiple-Input Multiple-Output) antenna architecture can provide for a spectacular increase in the spectral efficiency of wireless communications. With improved spectrum utilization as one of the primary objectives of cognitive radio, it is logical to explore building the MIMO antenna architecture into the design of cognitive radio that offers the ultimate in flexibility, which is exemplified by four degrees of freedom: carrier frequency, channel bandwidth, transmit power, and multiplexing gain [1]. In this research, we consider a cognitive network consisting of a network of devices with MIMO radios. While the research on a conventional cognitive network explores the channel capacity by utilizing both unused and underused spectrum, we focus on the aspect of exploring spectral efficiencies provided by MIMO radios. In a cognitive MIMO network, a user will first detect an unused or underused spectrum, then gets extra spectral efficiency by using MIMO antenna arrays with the detected channel. So far, MIMO antenna architecture induced spectacular increase has been used for increasing data rate, extend transmission range or reduce error rate; however, the superior capabilities of MIMO technology; can be leveraged only through appropriately designed higher multiple network layers [2].

The goal of this project is to investigate and develop a cognitive MIMO network that can fully use MIMO antenna architecture induced spectral efficiency for achieving global multiple-optimization on network throughput, network lifetime, communication reliability and other QoS requirements. We will specifically consider the case that the network consists of a large number of small devises such as MICA motes with MIMO radios. The project will have the following objectives**:**

- Investigate and identify the capabilities of MIMO antenna structure and its relevance to higher multiple network layers with underlying hardware resources, especially when the network is formed by inexpensive and resource limited devices such as MICA motes. Establish the coordination and control of parameters among the multiple layers. Outline the design trade-offs of the cognitive MIMO networks and their cross-layer behaviors.
- Develop adaptive, dynamic and distributed approaches which can efficiently utilize the MIMO radio spectrum at various network layers for achieving global multiple-optimization on network performance, network lifetime, communication reliability and other QoS reqirements. To achieve this objective, spectrum-aware, energy-aware and service-aware will be embedded in all layers of the network stack.

Research Approaches:

(1) Modeling of MIMO Links with Physical Layer

A MIMO transceiver employs digital adaptive transmitting and receiving antenna arrays. Each pair of transmitter and receive antenna arrays provides a signal path from the transmitter to the receiver. By sending signals that carry *the same information streams* through different paths, multiple independently faded replicas of data symbol can be obtained at the receiver end; hence, more reliable reception is achieved. This diversity gain can be used to provide range extension or reduce error rate. On the other hand, if the path gains between individual transmit-receive antenna pairs fade independently, the channel matrix is well conditioned with high probability, multiple parallel spatial channels called multiplexing gain are created. By transmitting *independent information streams* in parallel through the spatial channels, the data rate can be incurred. The model will have to precisely describe the relations between the above MIMO gains and data rate, error rate, transmission range, energy consumption and other more physical resources.

(2) Building Parameters and Metrics of Multiple Network Layers

The model for MIMO links and Physical layer will be used to establish the coordination and control of parameters among the multiple layers in bottom-up fashion. The metrics for the performance of each aspect will be investigated. The design trade-offs of cognitive MIMO networks and their cross-layer behaviors will be outlined. The parameters, metrics, and trade-offs will have to reflect the goal of global optimization and be able used for spectrum-aware, energy-aware and service-aware network design.

(3) Cross-Layered Embedding MIMO technology into Cognitive Networks

Efficiently utilize the MIMO radio spectrum at multiple network layers for achieving the goal of global optimization: (i) Design architecture and algorithms for MAC and routing protocols which are spectrum-aware, energy-aware and service-aware. MIMO antenna arrays will be adaptively used via MAC and routing layers to achieve multiplexing gain for high date rate and/or diversity gain for low energy consumption, low error rate and long communication range depending on the network status and communication requirements. (ii) Develop a distributed resource allocation system which works with a service manager at base station for optimally assigning hardware and network resources based on application and service requirements.

Summary of Topic 3

Research Objectives: This research aims at structure and algorithm design of a channel-adaptive MIMO transceiver from the perspective of MAC protocols and routing layer protocols for a battle field mobile ad-hoc network with low power consumption, high functional performance, and minimum overall system cost. In a network centric battle field, one-to-many and many-to one transmission are more important transmission patterns. MIMO uses multiple transmitters and receivers within wireless devices for much stronger bandwidth performance and the spatial degrees of freedom in MIMO communication can be leveraged to support one-to-many and many-to one transmission.

Research Approaches: This research will investigate designing MIMO wireless communication systems based on partial channel knowledge. To be able to realize the MIMO spectrum efficiency, adaptive channelization will be used to guarantee the access to all active users in a way that leaves no idle channels. Bea forming with adaptive antenna arrays is the most promising means for increasing data rates of wireless systems, since it enables channel reuse by several users in a cell through space division multiple access (SDMA). In SDMA, multiple beams are formed towards different users, each beam by a dedicated transceiver. However, the use of adaptive antenna arrays at the physical layer mandates significant modifications for higher layers. Joint consideration of beamforming and higher layer issues is required in order to fully exploit the benefits of SDMA. To overcome the difficult in channelization in an ad hoc network with dynamic and distributed user activities due to the lack of a central node (i.e., a base station), physical layer transceiver will be designed jointly with MAC protocols and routing layer protocols.

The research will have two concentrations. The first is to investigate the capabilities of MIMO links, and identify the relevance to MAC protocols and routing layer protocols. MAC protocols can be single-channel MAC and multi-channel and routing layer protocols can be flat and hierarchical. The second is to design and develop physical layer transceiver structure and algorithms which enable fully using of channels based on partial channel state information, and minimize transmit-power and maximize data rates by capturing the relevance with MAC protocols and routing layer protocols.

5. Communication and Routing Schemes in Wireless Sensor/Mobile/Ad-Hoc Networks

Topic: Communication Scheme and Routing Protocols for Battle Field Sensor Fusion
Agent: Center of Excellence for Battle Field Sensor Fusion
Funding: Army Research Office (Oct. 2004 - Sep. 2009)
Co-PI: Wei Chen
Publications:

1. J. Uchida, A.K.M. Muzahidul Islam Y. Katayama, W. Chen, and K. Wada, "Construction and Maintenance of A Novel Cluster-based Architecture for Ad Hoc Sensor Networks," *Journal of Ad Hoc and Sensor Wireless Networks,* Vol. 6, Number 1-2, pp. 1-31, 2008.
2. J. Uchida, W. Chen, K. Wada, "Acknowledged Broadcasting and Gossiping in Ad Hoc Radio Networks," *Journal of Theoretical Computer Science,* No. 377, pp 43-54, 2007.
3. A.K.M. Muzahidul Islam, Y. Katayama, W. Chen, W. Wada, "A novel cluster-based architecture and routing protocols for dynamic ad-hoc radio networks,"*Journal of Electrical Engineering, The Institution of Engineers, Bangladesh,* vol. EE33, No. I & II, 2006.
4. W. Chen, H. Miao, L. Hong, S. Zein-Sabatto, H. A. Adas, K. Suzan, "Distributed Resource Management and Parallel Routing for Data Acquisition in Heterogeneous Sensor Networks," *Proceedings of 1st International Conference on Sensor Networks and Application,* 2009
5. W. Chen, H. Miao, W. Koichi, "Autonomous market-based approach for resource allocation in a cluster-based sensor network," *Proceedings of the IEEE Symposium on Computational Intelligence in Multicriteria Decision-Making*, 2009.
6. Saleh Saleh Zein-Sabatto, Vinayak Elangovan, Wei Chen and Richard Mgaya, "Localization strategy for large-scale airborne deployed wireless sensors," *Proceedings of the IEEE Symposium on Computational Intelligence in Multicriteria Decision-Making,* 2009.
7. W. Chen, M. Heh, "A framework for hierarchical resource management in structured sensor networks," *Proceedings of the 8th International Conference on Application and Principles of Information Science,* Okinawa, Japan, 2009.
8. W. Chen, H. Miao, F. Gregory, "Multiple-Optimizing Wireless Sensor Networks with MIMO Technology," *Proceedings of International Conference on Wireless Networks*, WORLDCOMP, 2008.
9. W. Chen, H. Miao, L. Hong, S. Zein-Sabatto, H. A. Adas, K. Suzan, "Distributed Resource Management and Parallel Routing for Data Acquisition in Heterogeneous Sensor Networks," *Proceedings of 1st International Conference on Sensor Networks and Application,* 2009
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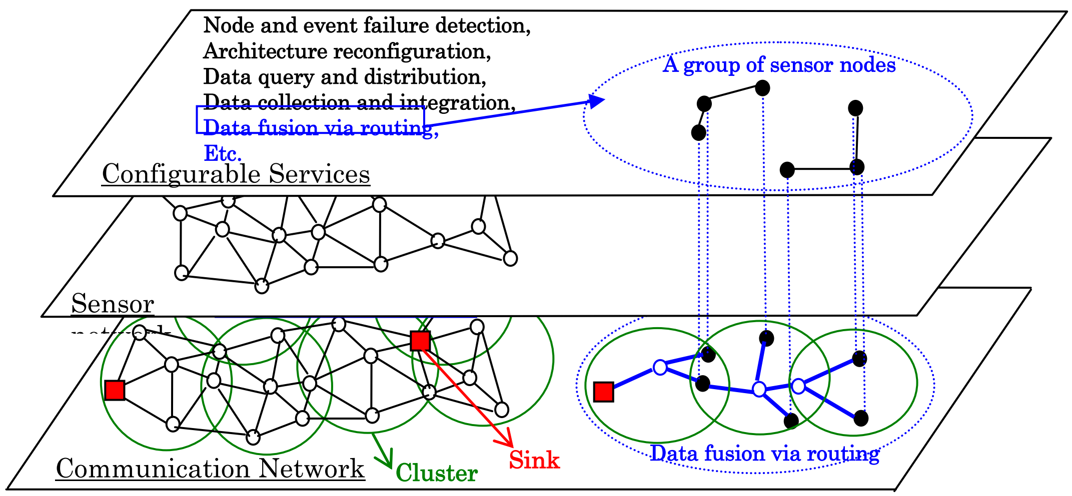
11. Richard H. Mgaya, Saleh Zein-Sabatto, Amir Shirkhodaie, Wei Chen, "Vehicle Identifications Using Acoustic Sensing", *Proceedings of IEEE Southeast Conference*, 2007.
12. W. Chen, M.A.K.M. Islam, M. Malkani, A. Shirkhodaie, K. Wada, M. Zein-Sabatto, "A Novel Cluster-based Architecture and Fast Broadcast for Dynamic Sensor Networks," Proceedings of the 9th Japan-Korea Joint Workshop on Algorithms and Computation, pp. 127-134, 2006.
13. M.A.K.M. Islam, W. Chen, K. Wada, "Routing Protocol on a Novel Cluster-based Architecture for Dynamic Ad Hoc Radio Networks", *Proceedings of 5th International Information and Telecommunication Technologies Symposium,* 2006.
14. J. Uchida, I. Muzahidul, Y. Katayama, W. Chen, K. Wada, "Construction and Maintenance of A Cluster-based Architecture for Dynamic Radio Networks," *Proceedings of the 39th Hawaii International Conference on System Sciences*, pp.1-10, 2006

Project Summary

Intelligent sensor network communication modeling

Adaptive network architectures, communication protocols and algorithms suitable for battle field sensor fusion will be developed in dynamic, efficient, scalable, traffic and fault tolerant, self-organization, situation aware, and power saving sensor network. The developed techniques will support the following fundamental network functions and data fusion tasks and network functions: Node and event failure detection; dynamic network formation; architecture reconfiguration; data query and data distribution; data collection and integration; data fusion via routing protocols; group communication and group reconfiguration.

An adaptive architecture of a sensor system will conceptually consist of three bottom-up layers (See the following figure): a communication network layer, a sensor network layer, and a configurable service layer. The communication network layer is responsible for routing and disseminating the information. It is larger than sensor network layer because it includes additional nodes such as soldiers and vehicles. The nodes of this layer form a wireless ad hoc network, in which some nodes called as sinks (which can be ground-based sites, unmanned airborne vehicles, etc) are used as the gateways between the sensor system and the outside world. The service layer provides cluster-based routing protocols and algorithms, with which sensor groups can be self-organized dynamically to finish different data fusion tasks and network functions with less power, less traffic congestion, high speed, and strong fault-tolerance.



A set of communication protocols, algorithms and technologies will be proposed to support distributed data/information fusion.

- **Synchronization scheme**. Sensor synchronization is a critical issue for a meaningful sensor fusion. The existing technologies such as a global clock based on the GPS is an unlikely solution because it requires expensive and energy-consuming electronics to precisely synchronize with a satellite's while sensor devises have hardware limitations and the inherent energy constraints. In this research, novel synchronized data exchange schemes will be designed, in which only a few of devices called as anchors will be synchronized via the GPS or some other mechanisms and other sensors will be synchronized with the anchors via multi-hop communication on the sensor network. Dynamic global clocks of sensor networks based on snapshot, time stamp and other synchronization technologies will also be designed for the case that the GPS like systems cannot be used at all.
- **Localization scheme**. Sensor localization is crucial issue in location based services or location aware sensing networks. Among the existing technologies, Time of Arrival technology based on the GPS systems is commonly used as means of obtaining range information via signal propagation time, which is an unlikely solution to sensor network devises with the same reason stated above. Time Difference of Arrival technique (estimating the distance between two communicating nodes) using ultrasound-require dense deployment has been used as a localization solution for infrastructure-based wireless sensor network, but it is less suitable of low-power infrastructure-free ad hoc sensor network. In this research, suitable self-calibration schemes will be designed, in which only a few of devices called as anchors will be equipped with location information obtained via the GPS or some other mechanisms, and other sensors will get location information by estimating their relative positions to these anchors

via multi-hop communication on sensor network. In the case that GPS like systems can not be used, the schemes will provide the relative locations which actually give the good enough solutions for most applications.

- **Routing protocols and algorithms for communication primitives.** Communication primitives such as broadcasting, gossiping, group communication, network counting and leader selection are the atomic networking functions. Many routing protocols and algorithms developed on mobile wireless ad ho radio network can be used for sensor network. In a large degree, they decide the performance and efficiency of whole sensor system. Comparing with infrastructure-based wireless computer networks, infrastructure-free wireless ad hoc sensor networks face more problems because of their communication limitations and the inherent energy constraints. To solve the problems, the sensors will be self-organized dynamically to a cluster-base hybrid architecture, where the heads and the gateway nodes of the clusters form a communication backbone which supports speedy communication. Routing protocols and deterministic/randomized algorithms will be designed for each communication primitive.
- **Event-driven mechanism.** Event-driven mechanism is extremely important for saving power and extending the lifetime of sensor networks. Under such mechanism, Sensor nodes will be woken up only when they are involved in an event. Novel autonomous algorithms will be designed to wake the targeted sensors up/put the targeted sensors to sleep by using cluster-based hybrid architectures and efficient broadcasting, gossiping, and other communication algorithms.
- **Reconfiguration mechanism.** Reconfiguration mechanism is necessary for a dynamic mobile sensor network. The evens like node move-in/move-out and fault-node deleting always asks an architecture reconfiguration. In this research, the reconfiguration algorithms matching the designed cluster-based hybrid architectures will be designed. Although in the worst case, a reconfiguration changes the whole architecture, but the proposed approaches will limit it as local as possible.

The testing and evaluation of the proposed communication protocols and algorithms will be held on our experimental simulation test bed. A set of performance metrics such as network settle time (time required for a collection of sensor nodes to self organize and transmit the first message), Network join time (time for node move in/out), network fault detecting time, network recovery time (time for recovery the network from failures), network synchronization and localization time, network/group broadcasting/gossiping time, power consuming of each task, data transmission failure rate, and etc., will be used to measure the efficiency and effectiveness of sensor network communication.