SECON 2010 Accepted Papers

1 Mobility

N-Body: Social Based Mobility Model for Wireless Ad Hoc Network Research

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Accurate reproduction of real human movement patterns is necessary in simulations of mobile ad hoc networks in order to obtain meaningful performance results. Human activities are often socially organized, resulting in a certain level of tendency of forming groups. There exists a few mobility models that are taking this tendency into account; however, all these models require a certain level of understanding of the underlying social structure of the target scenario, which limits their application scope. In this paper we propose an N-body mobility model that tackles such social aspects from a different perspective. We extract the social information from real human movement traces, and reproduce them in the mobility model. We show that the N-body model is capable of capturing and synthesizing the group-forming tendency that matches to those observed from sample traces. Simulation results also show that N-Body models exhibit a similar pairwise heterogeneity in ad-hoc network performance as the sample traces do.

Small World in Motion (SWIM): Modeling Communities in Ad-Hoc Mobile Networking

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The complexity of social mobile networks, networks of devices carried by humans (e.g. sensors or PDAs) and communicating with short-range wireless technology, makes it hard protocol evaluation. A simple and efficient mobility model such as SWIM reflects correctly kernel properties of human movement and, at the same time, allows to evaluate accurately protocols in this context. In this paper we investigate the properties of SWIM, in particular how SWIM is able to generate social behavior among the nodes and how SWIM is able to model networks with a power-law exponential decay dichotomy of inter contact time and with complex sub-structures (communities) as the ones observed in the real data traces. We simulate three real scenarios and compare the synthetic data with real world data in terms of inter-contact, contact duration, number of contacts, and presence and structure of communities among nodes and find out a very good matching. By comparing the performance of BUBBLE, a community-based forwarding protocol for social mobile networks, on both real and synthetic data traces, we show that SWIM not only is able to extrapolate key properties of human mobility but also is very accurate in predicting performance of protocols based on social human sub-structures.

2 Media Access Control

Practical Multi-Channel MAC for Ad Hoc Networks

Long Le (NEC Laboratories Europe)

Multi-channel MACs have recently attracted significant attention in wireless networking research because they possess the ability to exploit multiple frequency bands in order to increase the capacity of wireless ad hoc networks. A number of multi-channel MACs have been proposed in the last few years. However, these protocols rely on two rather impractical assumptions: low channel switching latency and fine-grained clock synchronization. This paper presents Asynchronous Multi-channel Hopping Protocol (AMHP), a multi-channel MAC protocol that does not build on these two impractical assumptions. We conduct an extensive performance evaluation and compare AMHP with 802.11 MAC, Asynchronous Multi-channel Coordination Protocol (AMCP), Multi-Channel MAC (MMAC), and Slotted Seeded Channel Hopping (SSCH). The major findings of our performance evaluation are: (1) all multi-channel MACs underperform 802.11 MAC at low load but AMHP comes very close to 802.11 MAC's performance at this load, (2) all multi-channel MACs give better performance than 802.11 MAC at medium and high load, (3) SSCH attains good results in one-hop scenarios or at low loads but loses its effectiveness at high loads and in multi-hop scenarios, and (4) AMHP outperforms all other multi-channel MACs at all loads.

MCMAC: An Optimized Medium Access Control Protocol for Mobile Clusters in Wireless Sensor Networks

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Wireless sensor networks (WSNs) are developing into a promising solution for many applications, for example in healthcare. In many scenarios, there is some form of node mobility. The medium access control (MAC) mechanisms should support the expected kind of mobility in the network. Mobility is particularly complicating for contention free MAC protocols like TDMA-based protocols, because they dedicate unique slots to every node in a neighborhood. In scenarios such as body-area networking, some clusters of nodes move together, creating further challenges and opportunities. This paper proposes MCMAC (Mobile Cluster MAC), a TDMA-based MAC protocol to support mobile clusters in WSNs. The proposed protocol does not need adaptation time after movement of clusters. Several optimization mechanisms are proposed to decrease power consumption. Simulation results show that the optimizations decrease power consumption of nodes around 70% without increasing latency of data transmission compared to the non-optimized version.

Multiple Access Mechanisms with Performance Guarantees for Ad-Hoc Networks

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This paper bears on the design and the quantitative evaluation of MAC mechanisms for wireless ad-hoc networks with performance guarantees. By this, we mean mechanisms where each accepted connection obtains a minimum rate or equivalently a minimum SINR level — which is not guaranteed by CSMA/CA — and which are adapted to the wireless ad-hoc network framework, namely are decentralized, power efficient and provide a good spatial reuse. Two such access control algorithms are defined and compared. Both take the interference level into account to decide on the set of connections which can access the shared channel at any given time. The main difference between the two is the possibility or not of adjusting the transmission power of the nodes. A thorough comparison of the performance of these two mechanisms and CSMA/CA is presented, based on a mix of analytical models and simulation and on a comprehensive set of performance metrics which include spatial reuse and power efficiency. Different network topologies, propagation environments and traffic scenarios are considered. The main aim of our study is to identify which of the proposed mechanisms outperforms CSMA/CA best depending on the scenario.

Spectrum Agile Medium Access Control Protocol for Wireless Sensor Networks

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In this paper we describe the design, implementation and performance evaluation of a low-power spectrum agile medium access control protocol for wireless sensor networks. With the ever increasing popularity of wireless embedded devices and networks, spectrum is getting congested, which in turn leads to performance degradation. Since protocols are designed in isolation of each other without appropriate consideration for potential interferences and mechanisms for symbiotic coexistence, they fail to achieve the desired performance characteristics in realistic interfering environments. The performance degradation is more significant for low-power embedded networks as they remain handicapped when competing with less resource constrained networks. We design a protocol that allows sensor nodes to dynamically select an interference minimal channel for data communication. It does not pose any synchronization restrictions on the nodes and effectively handles the dynamics of the network such as new nodes joining and old nodes leaving the network. We describe the various energy efficient spectrum sensing features of the protocol on which the dynamic channel selection is based. Our experiments suggest that even in highly crowded spectrum and environments with random interferences, sensor nodes are able to communicate in a reliable and energy efficient manner.

3 Interference Management and Physical Layer Techniques

Opportunistic Interference Management Increases the Capacity of Ad Hoc Networks

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We introduce a new multiuser diversity concept with which multiple transmitters can communicate without causing significant interference to each other. The new scheme called *opportunistic interference management* significantly reduces the feedback required in distributed MIMO systems, and requires an encoding and decoding complexity that is similar to that of point-to-point communications. We show that our proposed *opportunistic interference management* scheme achieves a per-node throughput capacity of $\Theta\left(\frac{\log(T(n))}{\sqrt{n}T(n)}\right)$ in a wireless network of n nodes and communication range of $T(n) = \Omega(\sqrt{\log n})$. This represents a gain of $\Theta(\log(T(n)))$ compared to simple point-to-point communication. Hence, *opportunistic interference management* provides an alternative approach to distributed MIMO systems with significantly less feedback requirements among nodes, which makes this approach far more practical than distributed MIMO systems.

Adaptive Instantiation of the Protocol Interference Model in Mission-Critical Wireless Networks

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To exploit the strengths of both the physical and the protocol interference models and to understand the varying observations on the relative goodness of scheduling based on the two models in literature, we analyze how network traffic, link length, and wireless signal attenuation affect the optimal instantiation of the protocol model. We also identify the inherent tradeoff between reliability and throughput in the model instantiation. Our analysis explains the seemingly inconsistent observations in literature and sheds light on the open problem of efficiently optimizing the protocol model instantiation. Based on the analytical results, we propose the physical-ratio-K (PRK) interference model as a reliability-oriented instantiation of the protocol model. Via analysis, simulation, and testbed-based measurement, we show that PRK-based scheduling achieves a network throughput very close to (e.g., 95%) what is enabled by physical-model-based scheduling while ensuring the required packet delivery reliability. The PRK model inherits both the high fidelity of the physical model and the locality of the protocol model, thus it is expected to be suitable for distributed protocol design. These findings shed new light on wireless interference models; they also suggest new approaches to MAC protocol design in the presence of uncertainties in traffic and application properties.

Deconstructing Interference Relations in WiFi Networks

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Wireless interference is the major cause of degradation of capacity in 802.11 wireless networks. We present an approach to estimate the interference between nodes and links in a live wireless network by passive monitoring of wireless traffic. This does not require any controlled experiments, injection of probe traffic in the network, or even access to the network nodes. Our approach requires deploying multiple sniffers across the network to capture

wireless traffic traces. These traces are then analyzed to infer the interference relations between nodes and links. We model the 802.11 MAC as a Hidden Markov Model (HMM), and use a machine learning approach to learn the state transition probabilities in this model using the observed trace. This coupled with an estimation of collision probabilities helps us to deduce the interference relationships. We show the effectiveness of this method against simpler heuristics, and also a profiling-based method that requires active measurements. Experimental results demonstrate that the proposed approach is significantly more accurate than heuristics and quite competitive with active measurements. We also validate the approach in a real WLAN environment.

SAND: Sectored-Antenna Neighbor Discovery Protocol for Wireless Networks

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Directional antennas offer many potential advantages for wireless networks such as increased network capacity, extended transmission range and reduced energy consumption. Exploiting these advantages, however, requires new protocols and mechanisms at various communication layers to intelligently control the directional antenna system. With directional antennas, many trivial mechanisms, such as neighbor discovery, become more challenging since communicating parties must agree on where and when to point their directional beams to enable communication. In this paper, we propose a fully directional neighbor discovery protocol called Sectored-Antenna Neighbor Discovery (SAND) protocol. SAND is designed for sectored-antennas, a low-cost and simple realization of directional antennas, that utilize multiple limited beamwidth antennas. Unlike many proposed directional neighbor discovery protocols, SAND depends neither on omnidirectional antennas nor on time synchronization. In addition, SAND performs neighbor discovery in a serialized fashion allowing individual nodes to discover all potential neighbors within a predetermined time. Moreover, SAND guarantees the discovery of the best sector combination on both communication ends allowing more robust and higher reliability links. Finally, SAND gathers the neighborhood information in a centralized location, if needed, to be used by centralized networking protocols. The effectiveness of SAND has been assessed via simulation studies and real hardware implementation.

4 Dynamic Spectrum Systems

Leveraging Cognitive Radios for Effective Communications Over Water

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Wireless communications over water may suffer from serious multipath fading due to strong specular reflections from conducting water surfaces. Cognitive radios enable dynamic spec-

trum access over a large frequency range, which can be used to mitigate this problem. In this paper, we study how to leverage cognitive radios for effective communications in wireless networks over water. We formally define the related problem as the Overwater Channel Scheduling Problem (OCSP) which seeks a channel assignment schedule such that a "good" communication link can be maintained between every Mobile Station (MS) and the Base Station (BS) all the time. We present a general scheduling framework for solving the OCSP. Based on the proposed framework, we present an optimal algorithm and several fast heuristic algorithms. In addition, we discuss an extension to the heavy traffic load case and propose two throughput-aware scheduling algorithms. We performed simulation runs based on path loss data provided by the Advanced Refractive Effects Prediction System (AREPS) and present simulation results to justify the efficiency of the proposed scheduling algorithms

Managing TCP Connections in Dynamic Spectrum Access Based Wireless LANs

Ashwini Kumar (University of Michigan, US)

Wireless LANs have been widely deployed as edge access networks in home/office/commercial buildings, providing connection to the Internet. Therefore, performance of end-to-end connections to/from such WLANs is of great importance to network applications and end-users. The advent of Dynamic Spectrum Access (DSA) technology is expected to play a major role in improving wireless communication. With DSA enabled, WLANs opportunistically access licensed channels in order to enhance spectrum-usage efficiency, and provide better network performance. In this paper, we explore issues and solutions in realizing this potential of DSA. We first identify the key issues that impact end-to-end TCP performance when a DSA-enabled WLAN is integrated with the wired cloud. Then, we propose a new network management framework, called DSASync, to eliminate or mitigate the performance issues we identified. DSASync requires no modifications to the fixed wired network or existing network stack, while ensuring traditional TCP semantics to be obeyed. DSASync uses a combination of buffering and traffic-shaping algorithms to minimize the adverse side-effects of DSA on the TCP flows. Finally, we evaluate DSASync through a prototype implementation and deployment in a testbed. The results show significant improvements in TCP performance, e.g., a 74 increase in downlink goodput, making it a promising step forward towards applying DSA technology in consumer WLANs.

Exploiting Microscopic Spectrum Opportunities in Cognitive Radio Networks

Tao Shu (University of Arizona, US); Marwan Krunz (University of Arizona, US)

In this paper, we are interested in cognitive radio networks (CRNs) whose operation does not rely on channel sensing. A spectrum server is responsible for collecting spectrum availability and location information from primary radio networks (PRNs), and broadcasting this information to cognitive radios. By subscribing to this broadcast, a CR knows about the spectrum opportunities without sensing channels. Spectrum opportunity under this paradigm presents a multi-level structure that generalizes the well-known channel-sensing-based binary structure. This multi-level structure reflects a *microscopic* spectrum opportunity for CRs, and can be exploited to increase the CRN throughput. Under this structure, we study efficient spectrum access in a multi-CR environment, with the objective of maximizing the network-wide utilization of spectrum opportunity. The difficulty of our problem

comes from the fact that different CRs may decide the same channel to be available, but at different levels. Therefore, channel access needs to be carefully coordinated. Both centralized and distributed solutions are provided, supporting different modes of operation. Numerical results verify the accuracy of our algorithms and the significant gain achieved by the multi-level framework.

A Two-Tier Market for Decentralized Dynamic Spectrum Access in Cognitive Radio Networks

Dan Xu (University of California, Davis, US); Xin Liu (UC Davis, US); Zhu Han (University of Houston, US)

Market mechanisms have been exploited as important means for spectrum acquisition and access in cognitive radio networks. In this paper, we propose a two-tier market for decentralized dynamic spectrum access. In the proposed Tier-1 market, spectrum are traded from a primary user (PU) to secondary users (SUs) in a relatively large time scale to reduce signaling overhead. Then driven by dynamic traffic demands, SUs set up the Tier-2 market to redistribute channels among themselves in a small time scale. More specifically, we use Nash bargain game to model the spectrum acquisition of SUs in the Tier-1 market and derive the equilibrium prices. We then use strategic bargain game to study the spectrum bargain in the Tier-2 market, where SUs can exchange channels with low overhead through random matching, bilateral bargain, and the predetermined market equilibrium prices. We disclose how various factors, such as availability of channels and bargain partners, matching schemes, and traffic dynamics, impact the market relationships. This work provides better understanding on the spectrum market and valuable guidelines to the primary and secondary network operators.

5 Energy I

Power Control for Mobile Sensor Networks: An Experimental Approach

JeongGil Ko (Johns Hopkins University, US); Andreas Terzis (Johns Hopkins University, US)

Techniques for controlling the transmission power of mobile devices have been widely studied in MANETs and cellular networks. However, as mobile applications for WSNs emerge, the unique characteristics of WSNs, such as severe resource constraints, suggest that transmission power control should be revisited from a WSN perspective. In this work, we take an experimental approach to examine the effectiveness of transmission power control for WSNs that involve mobility at human walking speeds. We propose two lightweight transmission power control schemes to improve energy efficiency and spatial reuse. The first is an active probing based scheme that adjusts transmission power based on (the lack of) packet losses and applies to all low-power radios, while the second scheme requires radios that offer link quality indicators (LQI) to estimate the proximity between the transmitter and receiver. We evaluate both schemes using mobile nodes in an indoor and an outdoor environment. Results show that the energy efficiency of the proposed transmission power control schemes can be very close to that of the optimal offline strategy and our schemes significantly reduce

the interference for spatial reuse. To our knowledge, this is the first work that evaluates the effect of transmission power control in mobile WSNs.

Cloudy Computing: Leveraging Weather Forecasts in Energy Harvesting Sensor Systems

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To sustain perpetual operation, systems that harvest environmental energy must carefully regulate their usage to satisfy their demand. Regulating energy usage is challenging if a system's demands are not elastic and its hardware components are not energy-proportional, since it cannot precisely scale its usage to match its supply. Instead, the system must choose when to satisfy its energy demands based on its current energy reserves and predictions of its future energy supply. In this paper, we explore the use of weather forecasts to improve a system's ability to satisfy demand by improving its predictions. We analyze weather forecast, observational, and energy harvesting data to formulate a model that translates a weather forecast to a wind or solar energy harvesting prediction, and quantify its accuracy. We evaluate our model for both energy sources in the context of two different energy harvesting sensor systems with inelastic demands: a sensor testbed that leases sensors to external users and a lexicographically fair sensor network that maintains steady node sensing rates. We show that using weather forecasts in both wind- and solar-powered sensor systems increases each system's ability to satisfy its demands compared with existing prediction strategies.

Fair Energy-Efficient Network Design for Multihop Communications

Xin Wang (Florida Atlantic University, US)

We consider the energy-efficient network resource allocation that minimizes a cost function of average user powers for multi-hop wireless networks. A class of fair cost functions is derived to balance the tradeoff between efficiency and fairness in energy-efficient designs. Based on such cost functions, optimal routing, scheduling and power control schemes are developed. Relying on stochastic optimization tools, we further develop stochastic network resource allocation schemes which are capable of dynamically learning the traffic and channel statistics, and converging to the optimal strategy on-the-fly.

6 Energy II

Throughput and Energy Efficiency in Wireless Ad Hoc Networks with Gaussian Channels

Hanan Shpungin (University of Calgary, CA); Zongpeng Li (University of Calgary, CA)

This paper studies the problem of topology control in random wireless ad hoc networks through power assignment for n nodes uniformly distributed in a unit square. We require that the network is strongly connected and look to maximize the minimum throughput

(or capacity) link in the case that all the nodes transmit simultaneously. According to the Gaussian channel model, the throughput of a wireless link (u,v) is $B\log(1+S/N)$ bps, where B is the channel bandwidth and S/N is the signal to noise ratio. We distinguish between two types of power assignments: homogeneous (all nodes have the same power level) and heterogeneous (nodes may have different power levels) cases. For the homogeneous case we give lower and upper bounds on the minimum capacity link. In the heterogeneous case we develop an energy efficient power assignment algorithm which achieves a minimum throughput of $\Omega(B\log(1+1/\sqrt{n}\log^2 n))$ and also discuss how to implement this algorithm in a distributed fashion. Finally, we present some simulation results. To the best of our knowledge, these are the first provable bounds for capacity in wireless networks, when nodes are allowed to transmit simultaneously.

Stochastic Analysis of Energy Consumption in Wireless Sensor Networks

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Limited energy resources in wireless sensor networks (WSNs) call for a comprehensive cross-layer analysis of energy consumption in a multi-hop network. In this paper, we provide a stochastic analysis of the energy consumption in a random network environment. Accordingly, a comprehensive cross-layer analysis framework, which employs a stochastic queueing model in realistic channel environments, is developed. This framework accurately predicts the distribution of energy consumption for nodes in WSNs during a given time period. We show that when the time duration is long, the energy consumption asymptotically approaches a Normal distribution. Using the distribution of energy consumption, the distribution of node lifetime is also investigated. With the help of this probabilistic model, a case study with an anycast protocol is conducted to show how the developed framework can analytically predict the distribution of energy consumption and lifetime. Comprehensive simulations and testbed experiments are provided to validate the developed model. The cross-layer framework is also used to identify relationships between the distribution of energy consumption and network parameters, such as network density, duty cycle, and traffic rate. To the best of our knowledge, this is the first work to investigate probabilistic distribution of energy consumption in WSNs.

Energy-Efficient Transmission for Beamforming in Wireless Sensor Networks

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Energy conservation is essential in wireless sensor networks (WSNs) because of limited energy in batteries. Collaborative beamforming uses multiple transmitters to form antenna arrays; the electromagnetic waves from these antenna arrays can create constructive interferences at the receiver and increase the transmission distance. Each transmitter can use lower power and save energy, since the energy consumption is spread over multiple transmitters. However, if the same nodes are always used for collaborative beamforming, these nodes would deplete their energy much sooner and this sensing area will no longer be monitored. To avoid this situation, energy consumption for collaborative beamforming

needs to be balanced over the whole network by assigning the transmitters in turns. The transmitters in each round are selected by a scheduler and the energy carried in each node is balanced to increase the number of transmissions. We define the lifetime of a network as the number of transmissions until a certain percentage of the nodes depletes their energy. This paper proposes an algorithm to calculate energy-efficient schedules based on the remaining energy and the phase differences of their signals arriving at the receiver. Compared with an existing algorithm, our algorithm can extend the network lifetime by more than 60%.

7 Supporting Applications I

Minimum Cost Localization Problem in Wireless Sensor Networks

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Localization is a fundamental problem in wireless sensor networks. Current localization algorithms mainly focus on checking the localizability of a network and/or how to localize as many nodes as possible given a static set of anchor nodes and distance measurements. In this paper, we study a new optimization problem, minimum cost localization problem, which aims to localize all sensors in a network using the minimum number (or total cost) of anchor nodes given the distance measurements. We show this problem is very challenging and then present a set of greedy algorithms using both trilateration and local sweep operations to address the problem. Extensive simulations have been conducted and demonstrate the efficiency of our algorithms.

EcoExec: An Interactive Execution Framework for Ultra Compact Wireless Sensor Nodes

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EcoExec is a host-assisted interactive execution environment for wireless sensing systems. Users can interact with sensor nodes by viewing attributes and invoking functions via a command-line interface. Functions that are not resident in the node's firmware are automatically compiled on the host, packaged up and downloaded to the node, linked, and executed, all seamlessly and transparently to the user. By packaging these features in a dynamically object-oriented programming environment such as Python, EcoExec enables programmers to experiment with features of the wireless sensor nodes and to rapidly develop application software. Most importantly, EcoExec empowers resource-constrained wireless sensor platforms with rich functionalities that would otherwise be prohibitive, thanks to its host-assisted execution feature with code swapping over the network. Experimental results on actual wireless sensor platforms show EcoExec to perform effectively with negligible observed overhead to the user.

LTP: An Efficient Web Service Transport Protocol for Resource Constrained

Devices

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Wireless Sensor Networks (WSNs) are envisioned to become an integral part of the Future Internet. Together with countless other embedded appliances, such resource-constraint devices will form an Internet of Things (IoT) where all kinds of devices extend the Internet to the physical world. In this vision, the seamless and flexible integration of IoT devices ranging from simple sensor nodes to large scale Enterprise IT servers are the basis for novel applications and business processes not possible before. A major challenge is to master the arising challenges of scale, low resources, and heterogeneity. In the Internet and especially in Enterprise IT, heterogeneity is addressed using Service-Oriented Architectures (SOA). However, today's technologies used to realize SOAs are to heavyweight to be used in resource-constraint networks (RCNs). In this paper, we introduce a novel, versatile, and light-weight Web Service transport protocol (called Lean Transport Protocol, LTP) that allows the transparent exchange of Web Service messages between all kinds of resource-constrained devices and server or PC class systems. We describe LTP in detail and show by real-world measurements that LTP has the potential to serve as standard Web Service transport protocol in the Internet of Things.

A Dynamic Stream Merging Technique for Video-on-Demand Services Over Wireless Mesh Access Networks

Kien Hua (University of Central Florida, US); Fei Xie (University of Central Florida, US)

We propose a Dynamic Stream Merging (DSM) technique for efficient video-on-demand services to mobile users on wireless mesh networks at the edges. DSM is a new communication paradigm, in which multicast topologies are created incrementally through dynamic merging of server streams at the mesh nodes. This is accomplished without the knowledge of the server. The formation of the multicast group in this manner is fundamentally different from traditional multicast techniques which rely on centralized control at the server. We present a system prototype and give experimental results to demonstrate the feasibility of this new approach. We also give simulation results based on the NS-2 simulator to show the performance efficiency in a larger system setting.

8 Supporting Applications II

C-DMRC: Compressive Distortion Minimizing Rate Control for Wireless Multimedia Sensor Networks

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This paper investigates the potential of the compressed sensing (CS) paradigm for video streaming in Wireless Multimedia Sensor Networks. The objective is to develop a rate

adaptive video streaming protocol for compressive sensed video, integrated with a new video encoder based on compressed sensing. The proposed rate control scheme is developed with the objectives to maximize the received video quality at the receiver and to prevent network congestion while maintaining fairness between multiple video transmissions. Video distortion is minimized through analytical and empirical models and based on a new cross-layer control algorithm that jointly regulates the video quality and the strength of the channel coding at the physical layer. The end-to-end data rate is regulated to avoid congestion while maintaining fairness in the domain of video quality rather than data rate. The proposed scheme is shown to outperform traditional rate control schemes.

Practical Sensing for Sprint Parameter Monitoring

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Stride-related parameters of sprinters, such as split times (i.e. which is speed-related), foot contact times, stance times, stride/step length, and stride/step frequency, etc. are important factors which affect athletes' performances. Traditionally, this information is captured by biomechanics researchers and coaches using optical-based systems. However, these systems are expensive, time consuming to setup, and have limited viewing angles. Thus, existing biomechanics research work on sprinting is limited to small scale and short studies. This paper presents a practical, cost-effective, user-friendly stride-parameter sensing system - known as the SEnsing for Sports And Managed Exercise (SESAME) Integrated System (IS) C which is the first system for supporting practical and long-term biomechanics research studies in sprinting. The system includes a light-sensor-based split time monitoring system, a radio-based localisation athlete tracking system, a stride length monitoring system, and a centralised data repository. Part of the system has been commissioned at the National Indoor Athletic Centre (NIAC) at Cardiff, UK, since May 2009.

Optimizing Link Assignment to Enhance Service in Probabilistic Network

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We consider service enhancement in a wireless environment in which clients try to obtain service directly from a set of servers. Each client desires a minimum overall service success probability, which is achieved by establishing multiple connections with multiple servers. Given the service success probability of each potential client-server connection, our problem is to assign the connections such that the number of satisfied clients is maximized subject

to server capacity constraints. We define the above problem as the ”link assignment for successful service problem” (LASS). We focus on the case where there is no interference between the communication connections, so that solving this restricted version immediately gives us an upper bound for the case with interference. While LASS can be reduced to maximum matching in the deterministic case, we show that in the probabilistic case it is NP-hard. Also, an equivalent integer programming for LASS is obtained, and various heuristics are designed. Furthermore, in the special case where the underlying network graph is a tree, we show that LASS can be solved in linear time based on a simple greedy algorithm. Experimental evaluations are performed and the results demonstrate the practicality of the algorithms and the heuristics.

ANNOT: Automated Electricity Data Annotation Using Wireless Sensor Networks

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Recent advances in low-power wireless networking have enabled remote and nonintrusive access to households' electric meter readings, allowing direct real-time feedback on electricity consumption to home owners and energy providers. Fine-grained electricity billing based on appliance power load monitoring has been investigated for more than two decades, but has not yet witnessed wide commercial acceptance. In this paper, we argue that the required human supervision for profiling and calibrating appliance load monitoring systems is a key reason preventing large-scale commercial roll-outs. We propose ANNOT, a system to automate electricity data annotation leveraging cheap wireless sensor nodes. Characteristic sensory stimuli captured by sensor nodes placed next to appliances are translated into appliance operating state and correlated to the electricity data, autonomously generating the annotation of electricity data with appliance activity. The system is able to facilitate the acquisition of appliance signatures, training data and validate the monitoring output. We validate the concept by integrating the automated annotation system to the RECAP appliance load monitoring system.

9 Applications

RFID Trees: A Distributed RFID Tag Storage Infrastructure for Forest Search and Rescue

Victor K.Y. Wu (University of Illinois at Urbana-Champaign, US)

We create a distributed storage infrastructure by embedding passive RFID tags in trees, for forest search and rescue. As a hiker moves through the forest, her reader writes a unique identifier (ID) and increasing sequence numbers (SNs) to tags, called (ID,SN) pairs. This creates a digital path for searchers to follow if the hiker is lost. Since tag memory is limited, hikers must share this constrained resource to preserve their digital paths. At each tag, we consider a hiker overwriting an existing (ID,SN) pair if the tag is already full, according to one of four algorithms. In Oldest Selection (OS), the hiker deletes the oldest (ID,SN)

pair. In Random Selection (RS), the hiker randomly deletes an (ID,SN) pair. In Highest Frequency Selection (HFS), the hiker deletes the (ID,SN) pair associated with the ID that she has seen the most in previous tag encounters. In Lowest Delete Frequency Selection (LDFS), the hiker deletes the (ID,SN) pair associated with the ID that she has deleted the least in previous tag encounters. HFS performs the best, but requires hikers to remember the number of ID encounters in the past, for each hiker ID.

IPoint: A Platform-Independent Passive Information Kiosk for Cell Phones

Hooman Javaheri (Northeastern University, US); Guevara Noubir (Northeastern University, US)

We introduce iPoint, a passive device that can interact and deliver information to virtually any mobile phone equipped with a WiFi network interface and a camera. The iPoint does not need any battery but harvests energy from the phone WiFi transmissions. The iPoint delivers information to the mobile phone through a low power LCD display that can be captured and processed by a software application. We introduce a mechanism of Packet Width Modulation (PWM) to encode the phone requests in the length of WiFi packets. This allows the use of phones not equipped with RFID readers, and still allows the low power microcontroller to decode the information. In this paper, we describe the architecture of iPoint, discuss the design choices of each component, and report on the experimental evaluation of our prototype. Various Radio-Frequency energy harvesters are discussed and a WiFi tailored, modified Greinacher voltage multiplier, a highly efficient parallel full-wave rectifier, is designed, prototyped and fully characterized. A low-power micro-controller with LCD capability is optimized, interfaced, and custom made to interface with the RF Front End (RF-FE). A PWM demodulator is designed and interfaced with the microcontroller. Finally, the mobile phone application for decoding the LCD output is presented.

A Robust Push-to-Talk Service for Wireless Mesh Networks

Yair Amir (Johns Hopkins University, US); Raluca Musaloiu-E. (Johns Hopkins University, US); Nilo Rivera (Johns Hopkins University, US)

Push-to-Talk (PTT) is a useful capability for rapidly deployable wireless mesh networks used by first responders. PTT allows several users to speak with each other while using a single, half-duplex, communication channel, such that only one user speaks at a time while all other users listen. Furthermore, enabling regular PSTN phone users (e.g., cell phones) to seamlessly participate in the wireless mesh PTT session is key to supporting the heterogeneous environment commonly found in such settings. This paper presents the architecture and protocol of a robust distributed PTT service for wireless mesh networks. The architecture supports any 802.11 client with SIP-based VoIP software and enables the participation of regular phones. Collectively, the mesh nodes provide the illusion of a single third party call controller, enabling clients to participate via any reachable mesh node. Each PTT group instantiates its own logical floor control manager that is highly available and resilient to mesh connectivity changes such as node crashes and recoveries and network partitions and merges. Experimental results on a fully deployed mesh network consisting of 14 mesh nodes and tens of emulated clients demonstrate the scalability and robustness of the system.

Real-Time Recognition and Profiling of Appliances through a Single Electricity Sensor

Antonio G. Ruzzelli (University College Dublin, IE); Gregory O'Hare (University College Dublin, IE); Anthony Schoofs (University College Dublin, IE); Clement Nicolas (University of Rennes, FR)

Sensing, monitoring and actuating systems are expected to play a key role in reducing buildings overall energy consumption. Leveraging sensor systems to support energy efficiency in buildings poses novel research challenges in monitoring space usage, controlling devices, interfacing with smart energy meters and communicating with the energy grid. In the attempt of reducing electricity consumption in buildings, identifying individual sources of energy consumption is key to generate energy awareness and improve efficiency of available energy resources usage. Previous work studied several non-intrusive load monitoring techniques to classify appliances; however, the literature lacks of an comprehensive system that can be easily installed in existing buildings to empower users profiling, benchmarking and recognizing loads in real-time. This has been a major reason holding back the practice adoption of load monitoring techniques. In this paper we present RECAP: RECognition of electrical Appliances and Profiling in real-time. RECAP uses a single wireless energy monitoring sensor easily clipped to the main electrical unit. The energy monitoring unit transmits energy data wirelessly to a local machine for data processing and storage. The RECAP system consists of three parts: (1) Guiding the user for profiling electrical appliances within premises and generating a database of unique appliance signatures; (2) Using those signatures to train an artificial neural network that is then employed to recognize appliance activities (3) Providing a Load descriptor to allow peer appliance benchmarking. RECAP addresses the need of an integrated and intuitive tool to empower building owners with energy awareness. Enabling real-time appliance recognition is a stepping-stone towards reducing energy consumption and allowing a number of major applications including load-shifting techniques, energy expenditure breakdown per appliance, detection of power hungry and faulty appliances, and recognition of occupant activity. This paper describes the system design and performance evaluation in domestic environment.

10 Scheduling

Coexistence-Aware Scheduling For Wireless System-on-a-Chip Devices

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Today's mobile devices support many wireless technologies to achieve ubiquitous connectivity. Economic and energy constraints, however, are driving the industry to implement multiple technologies into a single radio. This system-on-a-chip architecture leads to competition among networks when devices toggle across different technologies to communicate

with multiple networks. In this paper, we study the impact of such network competition using a representative scenario where devices split their time between WiMAX and WiFi connections. We show that competition with WiMAX significantly lowers WiFi's throughput, but this performance degradation is largely unnecessary, and can be attributed to the fact that WiMAX's transmission scheduling does not consider competing networks. We propose PACT, a new coexistence-aware WiMAX scheduling policy that cooperates with WiFi links hosted by its users without compromising its own transmission requirements. We derive PACT's design using an analytical model of network competition, and apply it to design practical WiMAX scheduling algorithms for various traffic classes. We evaluate PACT using OPNET's realistic models for WiFi and WiMAX. Using real network topologies, our experiment results show that PACT significantly improves WiFi performance by up to 17 fold without affecting the WiMAX user experience.

Transmission Scheduling for Routing Paths in Cognitive Radio Mesh Networks

Brendan Mumey (Montana State University, US); Xia Zhao (Montana State University, US); Jian Tang (Montana State University, US); Richard S. Wolff (Montana State University, US)

Nodes in a cognitive radio mesh network may select from a set of available channels to use provided they do not interfere with primary users. This ability can improve overall network performance but introduces the question of how best to use these channels. This paper addresses the following specific problem: given a routing path P, choose which channels each link in P should use and their transmission schedule so as to maximize the end-to-end data flow rate (throughput) supported by the entire path. This problem is relevant to applications such as streaming video or data where a connection may be long lasting and require a high constant throughput. The problem is hard to due the presence of both intraflow and interflow interference. We have developed a new constant-factor approximation algorithm for this problem. If certain natural conditions on the path are met, the performance guarantee is 1/4 of optimal. It has been shown by simulation results that the end-to-end throughput given by the proposed algorithm is often within 90% or better of optimal.

Scheduling for Scalable Energy-Efficient Localization in Mobile Ad Hoc Networks .

Jeremy Gribben (University of Ottawa, CA); Azzedine Boukerche (Univ. of Ottawa, CA); Richard W. Pazzi (University of Ottawa, CA)

Existing localization schemes in wireless ad hoc networks rely on redundant measurements from multiple devices with known positions in order to reduce error. However, when node density is high this can result in excessive localization messages with minimal improvement on position accuracy. In this work we present a scheduling algorithm to select a subset of active reference nodes to be used in localization, which has the effect of reducing message overhead, increasing network lifetime, and improving localization accuracy in dense mobile networks. We investigate the Cramer-Rao Lower Bound (CRLB) and existing single-hop localization techniques to determine the optimal average node density to ensure sufficient estimation accuracy. The correctness and effectiveness of the proposed scheme is evaluated through extensive simulation results, which show that in dense networks localization messages are greatly reduced and network lifetimes are more than doubled, while maintaining high estimation accuracy. Furthermore, computational time of localization algorithms is reduced, which effectively decreases accumulated error due to computation latency when locating a mobile device.

On the Uplink Capacity of Hybrid Cellular Ad Hoc Networks

Serdar Vural (University of Surrey, UK); Lap Kong Law (University of California, Riverside, US); Srikanth V. Krishnamurthy (University of California, Riverside, US); Michalis V. Faloutsos (University of California Riverside, US)

Towards increasing spatial reuse, cellular networks may be augmented with ad hoc connectivity. In the resulting hybrid network, the coverage area of the base station (BS) is reduced and the users within this area relay packets from/to the users outside. With this approach, shorter range, higher-rate links are used; this favors an increase in spatial reuse and thus, the achievable capacity. However, multi-hop relaying overhead can hurt capacity. In this paper, we analytically compute the uplink capacity, defined as an upper bound on the achievable throughput under max-min fairness. To gage the tightness of the bound, we seek to find the optimal transmission schedule for delivering the packets from the nodes in a cell to the BS. In general, constructing the optimal uplink schedule is NP-hard. We develop a heuristic approach and show via simulations that the resulting performance is close to the derived capacity bound. Our results suggest that (a) the hybrid network can achieve up to a 200 % increase in the uplink capacity compared to a pure cellular network, and (b) the simulated throughput is close to the analytically computed capacity showing that our bound is tight.

11 Deployment I

Two-Tiered Constrained Relay Node Placement in Wireless Sensor Networks: Efficient Approximations

Dejun Yang (Arizona State University, US); Satyajayant Misra (New Mexico State University, US); Xi Fang (Arizona State University, US); Guoliang Xue (Arizona State University, US); Junshan Zhang (Arizona State University, US)

The sensor nodes in a wireless sensor network sense the environment and transmit data cooperatively over multiple hops to the base stations. To prolong network lifetime, researchers have proposed to deploy some relay nodes in the network such that the sensors transmit the sensed data to a nearby relay node, which in turn delivers the data to the base stations. In this paper, we study two-tiered constrained relay node placement problems, where the relay nodes can only be placed at some pre-specified candidate locations. To meet the connectivity requirement, we study the connected single-cover problem where each sensor node is covered by a relay node, and the relay nodes form a connected network with the base stations. To meet the survivability requirement, we study the 2-connected double-cover problem where each sensor node is covered by at least two relay nodes, and the relay nodes form a 2-connected network with the base stations. We propose novel polynomial time approximation algorithms for these problems. For the connected single-cover problem, our algorithms have O(1) approximation ratios. For the 2-connected double-cover problem, our

algorithms have O(1) approximation ratios for practical settings and O(ln n) approximation ratios for arbitrary settings.

Placement and Orientation of Rotating Directional Sensors

Giordano Fusco (Stony Brook University, US); Himanshu Gupta (SUNY, Stony Brook, US)

We analyze several new problems that arise from the use of rotating directional sensors. The coverage region of a rotating directional sensor is restricted to a certain direction, and its orientation varies at constant speed. For already placed rotating directional sensors, we consider three problems for which the goal is to minimize the dark time (i.e. uncovered time) of all point in the area. We also consider the problem of placement and orientation of the minimum number of sensors, so to reduce to zero the dark time of all points. In addition, we study barrier coverage problems, in which the goal is to detect all intruders (or the largest number of them) that are trying to cross the monitored area. We show that these problems are NP-hard and some of them also NP-hard to approximate. We provide approximations algorithms that are easy to decentralize, and hence allow the sensors to self organize themselves.

Utility-Based Gateway Deployment for Supporting Multi-Domain DTNs

Ting He (IBM T. J. Watson Research Center, US); Nikoletta Sofra (Imperial College London, US); Kang-Won Lee (IBM T. J. Watson Research Center, US); Kin K. K. Leung (Imperial College, UK)

Due to technology or policy constraints, communications across network domains usually require the intervention of gateways, and their proper deployment is crucial to the overall performance. In this paper, we study the placement of static gateways in mobile DTNs with multiple domains. Given a limited gateway budget, the problem is to select deployment locations to optimize certain performance. The challenge is that different domains may possess heterogeneous properties. To ensure general applicability of solution, we propose a unified framework based on utility optimization, and solve utility computation and placement optimization separately. To handle heterogeneity, we decompose utility computation into individual domains and derive closed-form expressions based on key domain characteristics with focus on the routing scheme. Moreover, we develop quadratic-complexity optimization algorithms to provide an efficient solution which has guaranteed performance under certain uniformity conditions. Although certain assumptions have been made in developing the solutions, evaluations based on synthetic data and real DTN traces both show that the proposed solutions can achieve near-optimal performance at much lower complexities, and the results are robust with respect to the routing schemes and the mobility patterns. Compared with utility-agnostic deployments, our solutions significantly improve the end-to-end performance.

Optimized Operation for Infrastructure-Supported Wireless Sensor Networks

Eun-Sook Sung (Samsung Electronics, KR); Miodrag Potkonjak (University of California at Los Angeles, US)

Due to the energy-constrained nature of wireless sensor networks (WSNs), a variety of com-

munication protocols which rely on cluster-based topologies to enhance network capacity or to prolong network operational lifetime have been well studied heretofore. In this paper, we instead study a comprehensive perspective that searches for an optimal operation that considers backbone node placement and communication scheduling methods, as well as network connectivity properties. Specifically, we aim to answer the following three questions: how many backbone nodes are necessary, where to position these nodes, and which backbone nodes can communicate simultaneously to maximally serve the networks. We study the scalability of our approach and its dependency on parameters such as network size and density and present simulation results.

12 Deployment II

Divide and Conquer: Localizing Coverage Holes in Sensor Networks

Harish K Chintakunta (North Carolina State University, US); Hamid Krim (North Carolina State University, US)

Sensor Networks are inherently complex networks, and associated problems where analysis of some global features becomes more important than local ones, often arise. Localizing the holes in the overall coverage is one such problem. We present here, a distributed algorithm in a generalized combinatorial setting to localize holes in the coverage, with no a priori localization information for the nodes. We follow a divide and conquer approach, strategically dissecting the network so that the overall topology is preserved, while simultaneously minimizing the computational complexity. The detection of holes is enabled by first attributing a combinatorial object called a "Rips Complex" to each network segment, and by then checking for the triviality of the first homology class of this complex. Our estimate approaches the location of the holes exponentially with each iteration leading to a very fast convergence coupled with optimal usage of valuable resources such as power and memory. We demonstrate the effectiveness of the presented algorithm with simulations.

Relay Placement for Reliable Base Station Connectivity in Polymorphous Networks

Ying Huang (University of Illinois at Urbana-Champaign, US); Yan Gao (University of Illinois at Urbana and Champaign, US); Klara Nahrstedt (University of Illinois at Urbana-Champaign, US)

With emerging demand for online surveillance and management, persistent and reliable connectivity to base stations (BSs) is indispensable so that network operators, which have access to all BSs, can collect measurements from all wireless terminals in the field, monitor their status and respond to critical incidents in real-time. However, disconnected networks make reliable BS connectivity problematic. Many papers have studied the problem of placing the minimum number of relays to retain connectivity. However, none of them considered polymorphous networks, which have multiple topologies, due to terminal movement, unsynchronized wakeup schedule and packet forwarding policy. Our paper makes the first attempt towards the study of relay placement problem in polymorphous networks. We propose two heuristic algorithms, topology stitch algorithm and topology iterative algorithm, which are built upon constrained relay placement algorithms for monomorphous networks with a single topology. Also, we propose the weigh-and-place algorithm (WPA), which optimizes relay placement across topologies with balanced load based on integer programming formulation. Evaluation shows that WPA places a smaller number of relays than the other two heuristic algorithms and achieves good load balance among multiple BSs.

Connected Barrier Coverage on A Narrow Band: Analysis and Deployment

Yen-Ting Lin (University of Wisconsin Madison, US); Kewal K Saluja (University of Wisconsin, Madison, US); Parmesh Ramanathan (University of Wisconsin at Madison, US)

Barrier coverage indicates the capability of a deployed wireless sensor network to detect intruders crossing the sensing field, and it has been widely studied in recent years. Most of the existing works are asymptotic and focusing on the critical conditions (sensor density, sensing radius, etc.) to achieve barrier coverage. However these results are not very useful in practice since the sensing field generally has finite region. Also, the critical conditions may not be adequate for making deployment decisions if sensor cost and deployment cost are taken into consideration. In this paper we analyze the probability of achieving connected barrier coverage on a finite narrow band while sensors with given sensing/communicating radius are randomly deployed with given density. Moreover, we apply our analytical result and propose a cost efficient deployment strategy that uses minimal number of sensors to achieve connected barrier coverage within at most k iterations. Both the correctness of the analysis and the performance of the proposed deployment strategy are evaluated via simulations.

Back-Tracking Based Sensor Deployment by a Robot Team

Greg Fletcher (University of Ottawa, CA); Xu Li (University of Ottawa, CA); Amiya Nayak (SITE, University of Ottawa, CA); Ivan Stojmenovic (University of Ottawa, CA)

We propose a novel localized carrier-based sensor placement algorithm, named Back-Tracking Deployment (BTD). Mobile robots (carriers) carry static sensors and drop them at visited empty vertices of a virtual square, triangular or hexagonal grid in a bounded 2D environment. A single robot will move forward along the virtual grid in open directions with respect to a pre-defined order of preference until a dead end is reached. Then it back tracks to the nearest sensor adjacent to an empty vertex on its backward path. The robot resumes regular forward moving and sensor dropping from there. To save movement steps, the back tracking is performed along a locally identified shortcut. We extend the algorithm to support multiple robots, which move independently and asynchronously. Once a robot reaches a dead end, it will back-track, giving preference to its own path. Otherwise it will take over the back-track path of another robot, by consulting with neighboring sensors. We prove that BTD terminates in finite time and produces full coverage when no sensor failures occur. We also describe an approach to handle sensor faults. Through extensive simulation we show that BTD far outperforms the only competing algorithm LRV [2] in robot moves and robot messages.

13 Dissemination

Rapid Convergecast on Commodity Hardware: Performance Limits and Optimal Policies

Haibo Zhang (KTH - Royal Institute of Technology, SE); Fredrik Osterlind (Swedish Institute of Computer Science, SE); Pablo Soldati (Royal Institute of Technology, SE); Thiemo Voigt (Swedish Institute of Computer Science, SE); Mikael Johansson (Royal Institute of Technology, SE)

The increased industrial interest in wireless sensor networks demands a shift from optimizing protocols for energy-efficient reporting of sporadic events to developing solutions for high-rate real-time data collection and dissemination. We study time-optimal convergecast under the communication constraints of commodity sensor network platforms, and propose a novel convergecast model in which packet copying between the microcontroller and the radio transceiver is separated from packet transmission, thereby improving channel utilization and system throughput. Based on this model, we establish tight lower bound on the number of time slots for convergecast in networks with tree routing topology, and present both centralized and distributed algorithms for generating time-optimal convergecast schedules. Our scheme is also memory-efficient as each node needs to buffer at most one packet at any time. We evaluate our scheme in simulation and on real hardware, and show that our scheme can achieve a throughput of 203 kbit/s (86.4% of the theoretical upper bound) and up to 86.24% improvement compared with traditional TDMA-based convergecast. With optimal routing tree and maximum MAC layer payload, convergecast in a network with 20 sensor nodes can be completed in only 100 ms.

Disruption-Tolerant Spatial Dissemination

Bo Xing (University of California, Irvine, US); Sharad Mehrotra (University of California, Irvine, US); Nalini Venkatasubramanian (University of California, Irvine, US)

Spatial dissemination is a specific form of information dissemination that enables mobile users to send information to other mobile users who are or will appear at a specific location (a user-defined region). Such geo-messaging services are on the rise; they typically are built upon centralized solutions and require users to have reliable access to a stable backend infrastructure for storing and communicating content. In this paper, we develop a distributed solution to spatial dissemination, that can work without the need for such an infrastructure. Our solution utilizes the concepts from disruption-tolerant networking to build a flexible/best-effort service that leverages the intermittent ad-hoc connectivity between users. We propose Sticker, a spatial dissemination protocol that aims to maximize delivery reliability without incurring significant storage/transmission overheads. Sticker employs the store-carry-and- forward model, and strives to optimize dissemination performance by addressing three sub-problems - replication, forwarding and purging. Our experiments show that, Sticker achieves delivery ratios that are close to the maximum possible values; as compared to existing techniques, it either cuts down storage/transmission overheads by over 50%, or greatly enhances both delivery reliability and storage efficiency.

Secondis: An Adaptive Dissemination Protocol for Synchronizing Wireless Sen-

sor Networks

Federico Ferrari (ETH Zurich, CH); Andreas Meier (ETH Zurich, CH); Lothar Thiele (ETH Zurich, CH)

Reliability and predictability of the timing behavior have shown to be major issues for wireless sensor network deployments. Real-time requirements presented by several applications can be fulfilled by implementing communication schemes that lower possible sources of non-determinism of the timing behavior, assuming that the nodes are synchronized. The predictability of current synchronization protocols, however, cannot be verified, due to potential interferences with other activities. In this paper we propose Secondis, a dissemination protocol that periodically synchronizes and orchestrates activities in the network, providing three main benefits. (1) The synchronization task is performed in short time windows, where no interferences can occur, independently of any available communication structure. (2) The synchronization is energy efficient, and (3) robust against link and node failures. Secondis provides probabilistic bounds about its predictability, by means of a probabilistic model checker analysis. It proposes a novel adaptive flooding scheme based on the observation that only a subset of the nodes is important for the propagation. The behavior is analyzed in simulation, using realistic models of the wireless channel and hardware clocks.

14 Data Gathering and Aggregation

A Scalable Scheme for Preventing Feedback Implosion in a Large-Scale Multi-Tier Sensor Network

Reuven Cohen (Technion, IL); Alex Landau (IBM Research, IL)

We consider a huge hierarchical sensor network consisting of millions of sensors arranged in clusters for scalability and cost-performance. We address the problem of how a centralized gateway can estimate the number of sensors affected by a certain event. We propose a scheme for solving this problem in the most efficient way in terms of communication cost, and a complete mathematical analysis of the estimation error. We show that the error of the new scheme is very small even if the number of sensors experiencing an event is several million.

RDAS: Reputation-Based Resilient Data Aggregation in Sensor Network

Carlos Perez-Toro (USPTO, US); Rajesh Krishna Panta (Purdue University, US); Saurabh Bagchi (Purdue University, US)

Data aggregation in wireless sensor networks is vulnerable to security attacks and natural failures. A few nodes can drastically alter the result of the aggregation by reporting erroneous data. In this paper we present RDAS, a robust data aggregation protocol that uses a reputation based approach to identify and isolate malicious nodes in a sensor network. RDAS is based on a hierarchical clustering arrangement of nodes, where a cluster head analyzes data from the cluster nodes to determine the location of an event. It uses the redundancy of multiple nodes sensing an event to determine what data should have

been reported by each node. Nodes form part of a distributed reputation system, where they share information about other nodes performance in reporting accurate data and use the reputation ratings to suppress reports from malicious nodes. RDAS is able to perform accurate data aggregation in the presence of individually malicious and colluding nodes, as well as nodes that try to compromise the integrity of the reputation system by lying about other nodes behavior. We show that RDAS is more resilient to security attacks with respect to accuracy of event localization than the baseline data aggregation protocol with no security feature.

Data Aggregation in Body Sensor Networks: A Power Optimization Technique for Collaborative Signal Processing

Hassan Ghasemzadeh (University of Texas at Dallas, US); Roozbeh Jafari (University of Texas at Dallas, US)

Body sensor networks (BSNs) have proved their viability to greatly improve quality of medical care by providing continuous and in-home monitoring solutions. Highly constrained nature of the platform demands a design that efficiently utilizes limited resources of the system. Energy optimization techniques are especially desirable as the system lifetime is constrained by small batteries that power sensor nodes in a BSN. In this paper, we introduce a novel data-centering routing model to minimize communication energy, taking collaborative nature of signal processing for healthcare applications into consideration. Transmission energy for a path is determined as a compromise between the path length and the amount of data being transmitted along the path. Data produced by different nodes are aggregated to form packets of large size that consume smaller energy per bit. We formulate the problem as a minimum concave cost multicommodity flow problem and propose two approaches to find both optimal and approximate solutions. We evaluate performance of our energy minimization techniques on a variety of synthesized signal processing task graphs, as well as a real application for evaluating human postural control system. The results show an average of 35% energy saving with our proposed routing against a simple shortest path approach.

Cross-Layer Optimization of Correlated Data Gathering in Wireless Sensor Networks

Shibo He (Zhejiang University, CN); Jiming Chen (Zhejiang University, CN); David K. Y. K. Y. Yau (Purdue University, US); Youxian Sun (Zhejiang University, CN)

We consider the problem of gathering correlated sensor data by a sink node in a wireless sensor network. We design efficient distributed protocols to maximize the network lifetime subject to nodal energy constraints. Many existing approaches address the routing layer only, but the routing often interacts with physical-layer power control and MAC-layer link access. We present a first effort to maximize the network lifetime by jointly considering the three layers. We first solve the joint power control and routing problem, by assuming that the link access probabilities are known. We show that the problem is convex and propose a distributed algorithm, JRPA, as solution. When the link access probabilities are unknown, we then generalize the problem to encompass all three layers of routing, power control, and link random access. The general problem is non-convex; a duality gap exists when the Lagrangian dual method is employed. We propose an efficient heuristic algorithm, JRPRA, to solve the general problem. Numerical results show that JRPRA is

highly effective; particularly, even without the best link access probabilities pre-determined for JRPA, JRPRA achieves extremely competitive performance. Our results also show the convergence of the algorithms and their advantages over existing solutions.

15 Routing I

Using BGP in a Satellite-Based Challenged Network Environment

Roman Chertov (University of California, Santa Barbara, US); Kevin C Almeroth (University of California, Santa Barbara, US)

Once, satellites were considered an important option for creating global Internet access. However, for a period of time, satellites were supplanted by other ground-based technologies. More recently, satellites have been proposed as an integral component in highly dynamic challenged environments where large numbers of mobile devices connect through satellite-based terminals. Routing within groups of mobile devices is performed by one of the myriad of wireless routing protocols, but over the space/ground link, BGP is the protocol of choice. In this work, we conduct a high fidelity experimental study of link intermittency on the space/ground link and its effect on BGP peering sessions between ground and satellite routers. Our results show that a routing architecture that does not correctly adapt to the particular characteristics of satellite links performs very poorly. By contrast, a correctly tuned routing architecture can survive prolonged outages intermixed with short periods of link connectivity.

Connectivity-Driven Routing for Cognitive Radio Ad-Hoc Networks

Anna Abbagnale (University of Rome, IT); Francesca Cuomo (University of Rome La Sapienza, IT)

We design a routing scheme based on an extension of the algebraic connectivity for cognitive radio ad hoc networks. We observe that a cognitive radio network topology and its connectivity are highly influenced by the behavior of primary users. Even if the physical proximity of nodes would give rise to a connected topology, the primary user behavior could impact the network connectivity. In graph theory the second smallest Laplacian eigenvalue, i.e., the algebraic connectivity, has numerous relationships with the graph characteristics, including connectivity, diameter, mean distance of vertexes. We then propose to compute the algebraic connectivity in a cognitive scenario by deriving the average Laplacian matrix of the network, averaged over the random activity of the primary users, and compute the algebraic connectivity. On the basis of this mathematical model we build up an utility function which is shown to be effective for capturing some key characteristics of networks paths and can be used to compare them for routing purposes. We then design a routing scheme which, by modeling a path with a graph and its Laplacian, captures the connectivity characteristics of the path itself and suitably selects the best route in a uncertain and high variable connectivity scenarios.

Multi-Constrained Anypath Routing in Wireless Mesh Networks

Xi Fang (Arizona State University, US); Dejun Yang (Arizona State University, US); Pritam Gundecha (Arizona State University, US); Guoliang Xue (Arizona State University, US)

Anypath routing has been proposed to improve the performance of unreliable wireless networks by exploiting the spatial diversity and broadcast nature of the wireless medium. In this paper, we focus on anypath routing subject to K constraints, and present a polynomial time K-approximation algorithm. When K = 1, our algorithm is the optimal polynomial time algorithm for the corresponding problem. When K ¿= 2, the corresponding problem is NP-hard. We are the first to present an O(1)-approximation algorithm. Furthermore, our algorithm is as simple as Dijkstras shortest path algorithm, and is therefore suitable for implementation in actual wireless routing protocols.

Distributed Routing, Relay Selection, and Spectrum Allocation in Cognitive and Cooperative Ad Hoc Networks

Lei Ding (State University of New York at Buffalo, US); Tommaso Melodia (State University of New York at Buffalo, US)

Throughput maximization is one of the main challenges in cognitive radio ad hoc networks, where the availability of local spectrum resources may change from time to time and hop-by-hop. Cooperative transmission exploits spatial diversity without multiple antennas at each node to increase capacity with reliability guarantees. This idea is particularly attractive in wireless environments due to the diverse channel quality and the limited energy and bandwidth resources. With cooperation, source node and relay node cooperatively transmit data to the destination. In such a virtual multiple antenna transmission system, the capacity of the cooperative link is much larger than that of the direct link from source to destination. In this paper, we will study decentralized and localized algorithms for joint dynamic routing, relay assignment, and spectrum allocation under a distributed and dynamic environment.

16 Routing II

Connectivity in Wireless Underground Sensor Networks

Zhi Sun (Georgia Institute of Technology, US); Ian F. Akyildiz (Georgia Institute of Technology, US)

This paper investigates the probabilistic connectivity of the Wireless Underground Sensor Networks (WUSNs). Due to the unique channel characteristics and the heterogeneous network architecture of the WUSNs, the connectivity analysis is much more complicated than in the terrestrial wireless sensor networks and ad hoc networks. To our knowledge, this connectivity problem in WUSNs was not addressed before. In this paper, a mathematical model is developed to analyze the probabilistic connectivity in WUSNs, which captures the effects of environmental parameters such as the soil moisture and soil composition, and system parameters such as the operating frequency, the sensor burial depth, the sink antenna height, the density of the sensor devices, the tolerable latency of the networks, and the number and the mobility of the above- ground sinks. The lower and upper bounds for the connectivity probability are derived analytically. Simulation studies are performed,

where the theoretical bounds are validated, and the effects of several environmental and system parameters on the performance of these networks are investigated.

Exploiting Heterogeneity in Mobile Opportunistic Networks: An Analytic Approach

Chul-Ho Lee (North Carolina State University, US); Do Young Eun (North Carolina State University, US)

Heterogeneity arises in a wide range of scenarios in mobile opportunistic networks and is one of key factors that govern the performance of packet forwarding algorithms. While the heterogeneity has been empirically investigated and exploited in the design of new forwarding algorithms, it has been typically ignored or marginalized when it comes to rigorous performance analysis of such algorithms. In this paper, we develop an analytical framework to *quantify* the performance gain achievable by exploiting the heterogeneity in mobile nodes' contact dynamics. In particular, we derive a delay upper bound of a heterogeneity-aware forwarding policy per a given number of message copies and obtain its closed-form expression, which enables our quantitative study on the benefit of leveraging underlying heterogeneity structure in the design of forwarding algorithms. We then analytically show that less than 20% of total (unlimited) message copies is only enough under various heterogeneous network settings to achieve the same delay as that obtained using the unlimited message copies when the networks become homogeneous. We also provide independent simulation results including real trace-driven evaluation to support our analytical results.

Trajectory-Aware Communication Solution for Underwater Gliders Using WHOI Micro-Modems

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The predictable trajectory of underwater gliders can be used in geographic routing protocols. Factors such as drifting and localization errors cause uncertainty when estimating a glider's trajectory. Existing geographic routing protocols in underwater networks generally assume the positions of the nodes are accurately determined by neglecting position uncertainty. In this paper, a paradigm-changing geographic routing protocol that relies on a statistical approach to model position uncertainty is proposed. Our routing protocol is combined with practical cross-layer optimization to minimize energy consumption. Our solution's performance is tested and compared with existing solutions using a real-time testbed emulation that uses underwater acoustic modems.

Cost Efficiency of Anycast-Based Forwarding in Duty-Cycled WSNs with Lossy Channel

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Anycasting has been proposed recently as an efficient communication method for asynchronous duty-cycled wireless sensor networks. However, the interdependencies between end-to-end communication cost and the anycasting design parameters have not been sys-

tematically studied. In this paper, a statistical end-to-end cost model is presented to capture the end-to-end latency and energy consumption of anycasting operation under a realistic wireless channel model. By exploring the relationship between the end-to-end cost efficiency and the forwarding decision dependent anycasting design parameters, two anycasting forwarding metrics are proposed for fully distributed forwarding decision. By exploring the relationship among the preamble length, the size of the forwarding set and the achievable end-to-end cost efficiency, a series of preamble length control guidelines are proposed for low and extremely low duty-cycled WSNs. According to our analytical results and simulation validation, the proposed forwarding metrics help reduce the end-to-end latency and energy consumption by about 55% for anycasting with moderate preamble length, compared with the existing heuristic forwarding metrics. The proposed preamble length control guidelines help reduce, by more than half, the end-to-end energy and latency costs in low and extremely-low duty-cycled WSNs.

17 Management

Fair Payments for Outsourced Computations

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Initiated by volunteer computing efforts, the computation outsourcing problem can become a compelling application for networked set-top-boxes and mobile devices. In this paper we extend such environments with the ability to provide secure payments in exchange for outsourced CPU cycles. Previous contributions in wired networks have almost exclusively tackled only one side of the problem – offering incentives for volunteer participation and preventing worker laziness. This makes sense in static environments where reputable outsourcers have little to gain from incorrectly rewarding honest participation. However, this assumption is no longer valid in ad hoc environments, where unique identities are difficult to provide and anyone can outsource computations. In this paper we propose a solution that simultaneously ensures correct remuneration for jobs completed on time and prevents worker laziness. Our solution relies on an offline bank to generate and redeem payments; the bank is oblivious to interactions between outsourcers and workers. In particular, the bank is not involved in job computation or verification. Our experiments show that the solution is efficient: the bank can perform hundreds of payment transactions per second and the overheads imposed on outsourcers and workers are negligible.

QoI-Aware Wireless Sensor Network Management for Dynamic Multi-Task Operations

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This paper considers the novel area of quality-of-information (QoI)-aware network management of multitasking wireless sensor networks (WSNs). Specifically, it provides an investigation of new task admission and resource utilization mechanisms for controlling the individual QoI provided to new and existing tasks using real-time feedback-based monitoring mechanisms. The paper describes three key design elements in support of the above: (a) the QoI satisfaction index of a task, which quantifies the degree to which the required QoI is satisfied by the WSN; (b) the QoI network capacity, which expresses the ability of the WSN to host a new task with specific QoI requirements without sacrificing the attained QoI levels of other existing tasks, and (c) an adaptive, negotiation-based admission control mechanism that reconfigures and optimizes the usage of network resources in order to optimally accommodate the QoI requirements of all tasks. Finally, extensive results are presented for assessing the performance of the proposed solution for the case of an intruder detection application scenario.

Traffic Inference in Anonymous MANETs

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The open wireless medium in a mobile ad-hoc network (MANET) enables malicious traffic analysis to dynamically infer the network traffic pattern in hostile environments. The disclosure of the traffic pattern and its changes is often devastating in a mission-critical MANET. A number of anonymous routing protocols have been recently proposed as an effective countermeasure against traffic analysis in MANETs. In this paper, we propose a novel traffic inference algorithm, called TIA, which enables a passive global adversary to accurately infer the traffic pattern in an anonymous MANET without compromising any node. As the first work of its kind, TIA works on existing on-demand anonymous MANET routing protocols. Detailed simulations show that TIA can infer the traffic pattern with an accuracy as high as 95%. Our results in this paper highlight the necessity for cross-layer designs to defend a MANET against traffic analysis.

Bluetooth Coexistence with 4G Broadband Wireless Networks

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Multi-radio devices equipped with both Bluetooth and 4G broadband wireless technologies such as WiMAX or LTE are expected in the market soon. The spectrum available for 4G networks include the 2.3 GHz and 2.5 GHz frequency bands, both at close proximity to the 2.4 GHz ISM band where Bluetooth radio operates in. Several common usage cases require the simultaneous operations of co-located Bluetooth and 4G radios. However, State of Art filter/antenna technologies are unable to support co-located 4G transmissions and Bluetooth receptions at the same time. In this paper, we discuss a simple time domain coexistence solution that has low complexity and is easy to implement. Experiment results using off-the-shelf Bluetooth/WiMAX radios show that the proposed solution can well support common coexistence usage cases.