With over 60% of the world's population using cellphones, the need for ubiquitous and broadband wireless network connectivity has become ever more important. Limitations and the time-varying nature of resources such as network capacity and battery capacity pose significant challenges in achieving such objectives. Further, the deployment and management costs of large infrastructures impose additional constraints. With the increasing array of sensors that are becoming standard features on cellphones, these devices are also uniquely positioned to sense our surrounding environment at scale. These capabilities are also being embedded in many smart pervasive devices in a wide range of scientific disciplines. The problem of sensing at scale, however is complicated by various additional factors including renewable energy resources, wireless interference, and physical faults. My research focuses on systematically analyzing such challenges, developing the foundations, and then designing practical systems with the vision of making *ubiquitous broadband coverage and large-scale sensing a reality.*

1 Ongoing Research Themes: Results and Future Work

My ongoing research theme *Femto Networking*, addresses ubiquitous wireless broadband connectivity; *Perpetual Networking*, addresses sensor network operation in presence of time-varying renewable energy sources, and, *Sparse Networking*, addresses deployment and management costs associated with solutions based on dense infrastructures both in the context of WiFi and sensor networks.

1.1 Femto Networking

The gap between the cellular data rates and local area wireless data rates is fundamental and long-standing. Yet, a new concept called femto-cells offers promise to bridge this gap. Femto base stations are small cellular base stations that are connected to the owner's wired broadband network and are powered at the owner's expense. Most major cellular providers already have products based on similar ideas, but the use of naive resource allocation techniques and the concerns for heavy interference has limited its use to restricted sets of indoor users. With proper deployment, the femto-cells can also provide coverage over significantly large *outdoor regions* and provide service to *all* subscribers.

In order to make this *extended architecture* practically feasible, several key challenges need to be addressed. 1) Power control, OFDMA channel assignment, and association control, are inter-related problems that call for efficient and practical solutions. 2) Mobility of users will pose significant handoff overhead due to the smaller size of the femto-cells. And, 3) Advances in cognitive radio technology and a new FCC regulation to allow secondary users in licensed white spaces have made it possible to opportunistically make use of other licensed channels. As the availability of licensed channels vary in space and time, shorter range femto base-stations are more likely to be able to exploit such opportunities. While re-using the white channels as much as possible, both the cost of channel reconfiguration and the impact on incumbent users must be kept low.

Our objective is to develop the foundations for an extended femto-cell based architecture and evaluate the performance using real experimentation. Towards this objective we have designed preliminary approximation algorithms for dynamic resource allocation and are beginning to study them on a real testbed.

Expected Impact: Our *extended architecture* has the potential to re-position the cellular service providers to compete head-on with the WiFi market. If this project is successful, the ubiquity of femto-cells will become a significant advantage over the spotty coverage offered by today's scattered WiFi hotspots.

1.2 Perpetual Networking

Renewable energy enables sensor networks with the capability to recharge and provide perpetual data services. Due to low recharging rates and the dynamics of renewable energy such as solar and wind power, providing services without interruptions caused by battery runouts is non-trivial. Most environment monitoring applications require data collection from all nodes at a steady rate. Our objective is to design a solution for fair and high throughput data extraction from all nodes in presence of renewable energy sources. Specifically, we seek to compute the lexicographically maximum data collection rate for each node, such that no node will ever run out of energy. We proposed a centralized algorithm and an asynchronous distributed algorithm [9] that can compute the optimal lexicographic rate assignment for all nodes. The centralized algorithm jointly computes the optimal data collection rate for all nodes along with the flows on each link, while the distributed algorithm computes the optimal rate when the routes are pre-determined. We have proven the optimality for both the centralized and the distributed algorithms, and evaluated the performance using a TinyOS implementation on a testbed with 155 sensor nodes. We have also recently studied the problem of data collection under a utility optimization framework and have proposed distributed and localized algorithms [12].

My goal is to design a comprehensive suite of renewable energy-aware protocols so that such networks can operate *autonomously and perpetually* while providing optimum services to the end applications.

Expected Impact: Large scale outdoor deployments of sensor networks powered by renewable resources can revolutionize the way we sense environments in remote locations. Our systematic design of a suite of algorithms and protocols for supporting perpetual networking will enable many such applications.

1.3 Sparse Networking

- **Alpha Coverage: Scalable Intermittent Coverage for Mobile Users:** Vehicular Internet access via open WLAN access points (AP) has been demonstrated to be a feasible solution to provide opportunistic data service to moving vehicles. Using an in situ deployment, however, such a solution does not provide worst-case performance guarantees due to unpredictable intermittent connectivity. On the other hand, a solution that tries to cover every point in an entire road network with APs (full coverage) is not very practical due to the prohibitive deployment and operational cost. We have introduced a new notion of intermittent coverage for mobile users, called α-coverage[31], which provides worst-case guarantees on the interconnection gap while using significantly fewer APs than full coverage. We have proposed efficient algorithms to verify whether a given deployment provides α-coverage and approximation algorithms for determining a deployment of APs that will provide α-coverage. Our algorithms can also be used to supplement open WLAN APs in a region with appropriate number of additional APs that will provide worst-case guarantees on the interconnection gap.

  Recently we have extended this solution to a metric called Contact Opportunity [30] Informally, the contact opportunity for a given deployment measures the fraction of distance or time that a mobile user is in contact with some AP when moving through a certain path. Such a metric is closely related to the quality of data service that a mobile user might experience while driving through the system. We have developed approximation algorithms to compute near-optimum deployment solutions and have performed real experiments with sparse WiFi deployment to characterize the benefits of our solution.

  I plan to design an end-to-end system that provides service assurance to the mobile users from open access-points. Our solution will address how open access-points can be solicited and how a system based on acquisition of such access-points can collectively provide assured services to the mobile users. Further, I plan to develop an incentive scheme that can ensure that the owners of open access-points get a share of the revenue and therefore get enticed into supporting such services. If successful, this service can transparently complement the ubiquitous 3G or WiMAX connectivity using dual-interfaces and provide a better experience for all mobile users.

- **Trap Coverage - A Scalable Solution for Mobile Targets:** Tracking of movements such as that of people, animals, vehicles, or of phenomena such as fire, can be achieved by deploying a wireless sensor network. So far only prototype systems have been deployed and hence the issue of scale has not become as critical. Real-life deployments, however, will be at large-scale and achieving this scale will become prohibitively expensive if we require every point in the region to be covered (i.e., full coverage), as has been the case in prototype deployments. We therefore, propose a new mode of coverage called Trap Coverage [1] that scales well with large deployment regions. A sensor network providing Trap Coverage guarantees that any moving object or phenomena can move only a (known) bounded displacement before it is guaranteed to be detected by the network for any trajectory and speed. Tracking applications aside, the model of trap coverage generalizes the de-facto model of full coverage itself, by allowing for holes of a given maximum diameter. We have taken the first steps towards establishing a strong foundation for this new model of coverage by addressing some fundamental problems. We have proposed a polynomial-time algorithm to determine the level of trap coverage achieved once sensors are deployed on the ground.

My plan is to develop this elementary idea further while considering practical challenges including obstacles, inaccurate location information, and node failures. I plan to study various protocols and systems level issues in developing a full solution. Such systems can be deployed to assist law-enforcement agencies in preventing theft of tagged items over a large region. Our system was also recently demonstrated at a conference [18].

Expected Impact: Resource constraints is a hard reality that is faced by projects requiring large-scale deployments. Our efforts are the first that characterize the quality of sparse deployments and attempts to meet those metrics. If successful, this will trigger the deployment of large-scale networks.

2 Prior Research Contributions

2.1 Scalable Low Power Sensor Networking

Wireless networks of sensors have the potential to enable new applications based on different types of data that can be collected from our surrounding environment and remote locations. However, todays solutions are far from being practical as most applications that have been proposed for such networks require significant amount of energy, making it challenging to operate without periodic manual interventions. So, the critical question is: *How can we design and deploy a sensor network such that it judiciously uses energy while providing the best quality of information required by the application?*

Towards responding to this question, my research has resulted in a new and scalable coverage model for mobile targets; solutions for low energy reporting of rare events; and a MAC layer solution based on anycasting.

- **Reporting Rare Events in Sensor Networks:** Computing and maintaining network structures for energy efficient data aggregation incurs high overhead for dynamic events where the set of nodes sensing an event changes with time. Prior works on data aggregation protocols have focused on tree-based or cluster-based structured approaches. Although structured approaches are suited for data gathering applications, they incur high maintenance overhead in dynamic scenarios for event-based applications.

  We have proposed the first structure-free data aggregation technique that achieves high energy efficiency [5, 7]. As the proposed technique is opportunistic, the performance can be arbitrarily bad. We have proposed a new approach that can provide guarantees for efficient aggregation. It leverages an implicitly computed Directed Acyclic Graph (DAG) to forward packets. Specifically, a routing tree is chosen on the DAG in a dynamic fashion depending on the location of the data sources [6, 8]. This protocol was proven to aggregate data within a constant distance from the sources under the limitation of a maximum size for any event. We have also relaxed this condition using a different data structure. which uses a quad-tree and an overlapping alternative tree structure. Dynamic forwarding decisions between the two trees can ensure aggregation within a constant distance from the data sources, irrespective of the event-size. As this distance is independent of the network size, the solution is scalable. The performance of our solutions for data aggregation has been studied using simulations and experimentation on the Kansei testbed at OSU (200 sensor nodes).

- **Low Power MAC with Anycasting:** Packet retransmissions, idle listening, and overhearing, are the three main sources of energy wastage in the MAC Layer. The problem of excessive retransmissions can be avoided by observing and predicting the channel quality, and avoiding periods with poor channel quality. CSMA relies on carrier sensing to decide if retransmissions should be performed immediately. However, in cases where the poor channel quality persists, or packet losses are due to interference that is undetectable by carrier sensing, the channel assessment alone is not a good indicator of the chance of a successful transmission. To schedule retransmissions at appropriate moments, we have developed a new technique called *transmission pushbacks* [15], to reduce such losses by delaying retransmissions. This technique overcomes periods of poor channel quality while ensuring a throughput matching the incoming packet rate. In order to determine the optimal pushback period, we devise an adaptive channel prediction technique based on estimating the parameters of a simple hidden Markov model (HMM) which represents the channel. The parameters of the HMM are dynamically updated based solely on the ACK sequence for the previous packet transmissions. By considering both the packet incoming rate and the packet loss pattern, the appropriate pushback period is calculated and applied for future retransmissions.

To deal with idle listening and packet overhearing, we have developed a protocol for duty-cycled networks, called CMAC [13, 14] (Convergent MAC), that primarily uses anycasting to forward packets. CMAC can work at very low duty cycles (0.1%), and it requires no synchronization when there is no traffic. When carrying traffic, CMAC first uses anycasting to wake up forwarding nodes, and then converges gradually from route-suboptimal anycast to route-optimal unicast. Experiments on the Kansei testbed, and ns-2 simulations show that CMAC significantly outperforms other duty cycling protocols in terms of latency, throughput, and energy efficiency. More recently, we have investigated the problem of selection of the forwarding set of nodes for MAC layer anycast [10] to optimize the end-to-end delay of reporting events from all nodes.

2.2 Data Streaming over Wireless Networks

Media streaming over wireless networks is a challenging task due to the limited capacity of wireless networks. Although new applications such as IPTV and video-on-demand are available for wired at-home users, such services are barely becoming available for the mobile users. The demand for such applications for mobile users is clear from the success stories of YouTube and Verizon's vCast services. However, multimedia services over PDAs and cell-phones are slow and often suffer from poor quality. These reasons along with the high cost of multimedia services has resulted in limited use of such services. So, the key question is: *How can we support such resource-hungry real-time applications over wireless networks in a scalable fashion?*

To address this question, my research has explored solutions for infrastructured WiFi networks, and mesh networks. I am also investigating how open access-points at homes can be leveraged to provide predictable high data-rate services to supplement the coverage from 3G and WiMAX networks for mobile users. My contributions to this problem along with pointers to my future plans are outlined below.

- **Scalable Multicast Data Streaming over Wireless Networks:** In recent years, numerous large-scale Wireless LANs (WLAN) have been deployed all over the world. However, the shortage of non-interfering channels makes it a challenge for WLANs to efficiently support real-time multicast services. We have studied the problem of association control in the case of multicast flows in order to optimize different objective functions such as maximizing the number of accepted flows, balancing the multicast load among the access-points (APs) and reducing the total load on all APs [3, 4]. For these problems we have designed approximation algorithms and evaluated them using simulations. We have also studied the problem of efficient packet-by-packet scheduling of real-time multicast flows [2]. For mitigating interference, we allow APs to transmit simultaneously only if they are mutually non-interfering and our objective is minimizing the fraction of time used by the APs for servicing the multicast flows. We introduce two multicast strategies, the association strategy in which each user is restricted to receive flows only from its associated AP and the non-association strategy in which a user may also decode transmissions from other APs in its vicinity. Under both the strategies, the scheduling problem of minimizing the multicast service time is NP-hard and we have developed simple approximation algorithms with provable performance bounds. Our simulations clearly demonstrate that the proposed algorithms yield efficient multicast scheduling.

  In case of mesh networks the optimization must also consider the traffic in the backbone wireless network. We have proposed a new metric [11] that considers the overall network load which includes the traffic in the backbone as well as the traffic on the last wireless hop to the user. By associating based on this metric rather than RSSI (Received Signal Strength Indicator), we have shown that significant reduction in interference can be obtained.

- **Mesh-based Sensor Network Backbones:** In the ExScal[1] project, (funded by DARPA/NEST) a 1000 node sensor network was demonstrated in operation for the purpose of detection, classification and tracking in Avon Park, Florida in December 2004. For this project, we designed several networking services for the sensor network backbone of 200 nodes [20, 19, 29, 28].

  We have designed Sprinkler, a reliable data dissemination service for wireless embedded devices which are constrained in energy, processing speed, and memory. Sprinkler embeds a virtual grid over the network whereby it can locally compute a connected dominating set of the devices to avoid redundant transmissions and a transmission schedule to avoid collisions. Sprinkler transmits O(1) times the optimum number of packets in O(1) of the optimum latency; its time complexity is O(1). Sprinkler is tolerant to fail-stop and state corruption faults. Thus, Sprinkler is suitable for resource-constrained wireless embedded devices. We evaluated the performance of Sprinkler in terms of the number of packet transmissions and the latency, both in an outdoor and indoor environment. Based on outdoor and indoor testbed experiments, we showed that Sprinkler is not only energy efficient as compared to existing schemes, but it also has less latency. Further, the energy consumption of nodes and the latency grows linearly as a function of newly added nodes as the network grows in size.

  In the context of IEEE 802.11b network testbeds, we have examined the differences between unicast and broadcast link properties, and shown the inherent difficulties in precisely estimating unicast link properties via the use of broadcast beacons even if the length and transmission rate of beacons are the same as that of data packets. To address the difficulties in link estimation, we proposed to estimate unicast link properties directly via data traffic itself without using periodic beacons. To this end, we designed a data-driven routing protocol Learn on the Fly (LOF). LOF chooses routes based on ETX/ETT-type metrics, but the metrics are estimated via MAC feedback for unicast data transmission instead of broadcast beacons. Using a realistic sensor network traffic trace and an 802.11b testbed of 195 Stargates, we have experimentally compared the performance of LOF with that of beacon-based protocols, represented by the geography-unaware ETX and the geography-based PRD. We found that LOF reduces end-to-end MAC latency, enhances energy efficiency, and improves network throughput, which demonstrate the feasibility and the potential benefits of data-driven link estimation and routing.

2.3 Ad-hoc Networking: Architecture and Routing Infrastructure

- **Unified Architecture for Ad-hoc and Cellular Networks:** In third-generation (3G) wireless data networks, providing service to low data-rate users is required for maintaining fairness, but at the cost of reducing the cell's aggregate throughput. We have proposed the Unified Cellular and Ad Hoc Network (UCAN) architecture [16, 17] for enhancing cell throughput while maintaining fairness. In UCAN, a mobile client has both 3G interface and IEEE 802.11-based peer-to-peer links. The 3G base station forwards packets for destination clients with poor channel quality to proxy clients with better channel quality. The proxy clients then use an ad hoc network composed of other mobile clients and IEEE 802.11 wireless links to forward the packets to the appropriate destinations, thereby improving cell throughput. We have refined the 3G base station scheduling algorithm so that the throughput gains are distributed in proportion to users' average channel rates, thereby maintaining fairness. With the UCAN architecture in place, we have proposed novel greedy and on-demand protocols for proxy discovery and ad hoc routing that explicitly leverage the existence of the 3G infrastructure to reduce complexity and improve reliability. We have also proposed secure crediting mechanisms to motivate users that are not actively receiving to participate in relaying packets for others. Through both analysis and extensive simulations with HDR and IEEE 802.11b, we have shown that the UCAN architecture can increase individual user's throughput by more than 100 percent and the aggregate throughput of the HDR downlink by up to 50 percent.

- **CEDAR: Core Extraction based Distributed Ad-hoc Routing:** We proposed the first solution for routing in ad-hoc networks based on virtual infrastructures called cores [22, 26, 25, 27]. A core is a connected subgraph whose nodes form a dominating set of the network. We have developed distributed solutions to efficiently compute and maintain a core of the network. The core enables routing protocols

[1] http://ceti.cse.ohio-state.edu/exscal

to use only a subset of nodes in the network for route management and avoid the use of broadcast relays. We have also shown how the core can be used to enhance the performance of existing routing protocols such as DSR and AODV.

2.4 Data Transport over Local Area and Wide-Area Wireless Networks

- **TCP Fairness over Wireless Local Area Networks:** As local area wireless networks based on the IEEE 802.11 standard see increasing public deployment, it is important to ensure that access to the network by different users remains fair. While fairness issues in 802.11 networks have been studied before, we focus on TCP fairness in 802.11 networks [21] in the presence of both mobile senders and receivers. Through analysis, simulation, and experimentation we extensively evaluate the interaction between the 802.11 MAC protocol and TCP. We identified four different regions of TCP unfairness that depend on the buffer availability at the base station, with some regions exhibiting significant unfairness of over 10 in terms of throughput ratio between upstream and downstream TCP flows. We have also proposed a simple solution that can be implemented at the base station above the MAC layer that ensures that different TCP flows share the 802.11 bandwidth equitably irrespective of the buffer availability at the base station.

- **WTCP: Wireless Transmission Control Protocol:** Wireless wide-area networks (WWANs) are characterized by very low and variable bandwidths, very high and variable delays, significant non-congestion related loss, asymmetric uplink and downlink channels, and occasional blackouts. Additionally, the majority of the latency in a WWAN connection is incurred over the wireless link. Under such operating conditions, most contemporary wireless TCP algorithms do not perform very well. We have designed the WTCP protocol [23, 24], that addresses rate control and reliability over commercial WWANs such as CDPD. WTCP is rate based, uses only end-to-end measurements, performs rate control at the receiver, and uses inter-packet delays as the primary metric for rate control. We have performed experiments with a real CDPD network and simulations in ns-2.

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