# ENERGY-EFFICIENT WIRELESS MOBILE NETWORKING TECHNOLOGIES TO ENABLE SMART INFRASTRUCTURES

## Project Summary:

Wireless networking technologies are key to enabling the envisioned pervasive information infrastructures, such as IBM's "smarter planet" initiative, a method of integrating sensors into infrastructure and analyzing the data they produce to optimize systems like the electrical grid, transportation networks, healthcare networks, etc. Machine-to-machine communications is up and coming as an important technology that will comprise the fastest increasing component of the future Internet. Untethered and mobile access to information, summarized in the "anytime-anywhere" catch phrase is a large part of this vision, yet modern wireless communication systems hardly provide the scalability that will be required as the number of nodes, or "users" increase, especially given the rate of increase of machine-to-machine communications.

The gap between current technologies and the envisioned applications is fundamentally based on the challenges of the wireless communication medium, and the lack of sufficient treatment of *network aspects* for optimal transmission through such a medium. The delivery of high-speed data over multiuser wireless links has been facilitated by developments in Network Information Theory and advanced physical layer techniques such as MIMO communications, however, development in these fields has largely ignored the discreteness or burstiness in the arrival of data, and requirement of finite delay. It is not possible to achieving the promised wireless channel capacities by ignoring the inherent Queuing of data at nodes. The daunting difficulty in shared-processor queueing system problems is partly responsible for the lack of development in this area, combined with the lack of sufficient educational activities that combine Communication Theory and Queuing theory in curricula.

We propose to create integrated inter-disciplinary research activity focused towards advancing the understanding of the fundamental limits of wireless networks and the development of novel algorithms and techniques toward realizing the envisioned ubiquitous high-performance mobile networks of the future. Higher layer techniques of Scheduling and Buffer Management that exploit the rates achievable by advanced physical layer techniques will be developed, leading to integration to the novel protocol suites for mobile wireless networks.

## Work Packages:

**WP1. Energy-efficient wireless sensor network (WSN) testbed:** In our research laboratory, we have currently implemented a small, 10-node wireless sensor network capable of detecting the location of a ferromagnetic target using MicaZ motes. This is also the first wireless sensor network implemented at METU, and one of the few in Turkey. In this work package, we plan to
1. Expand this network to 50 nodes (with or without sensorboards),
2. Implement the energy-efficient routing algorithms that previous theoretical research in our group has produced,
3. Turn the testbed into a general-purpose WSN on which various detection, tracking, control applications in response to different sensory inputs (vibration, image, etc.) can be tested.

One doctoral student, one master's student will be working on this work package, and a number of interested undergraduates will be included.

Related publications of the Principal Investigator:

1) Keshavarzian, E. Uysal-Biyikoglu, F. Herrmann and A. Maneshwar, "Energy-efficient Link Discovery in Wireless Sensor Networks Using Optical Orthogonal Codes," Proc. IEEE/ACM INFOCOM 2004, vol. 3, pp. 1751-1761.

2) Keshavarzian, E. Uysal-Biyikoglu, D. Lal and and K. Chintalapudi, "From Experience with Indoor Wireless Channels: A Link Quality Metric That Captures Channel Memory", IEEE Communications Letters, vol. 11, no. 9, Sept. 2007, pp. 729-731.

**WP2. Scheduling and routing in WSNs: Exploiting the full capacity region of wireless channels under discrete packet arrivals and finite buffers.**

The delivery of high-speed data over wireless links has been facilitated by advanced physical layer techniques, yet higher layer issues of buffer management, scheduling, and routing need to be addressed in order to approach network capacity, and these issues are largely open, although many sub-optimal solutions have been proposed. For example, the problem of throughput maximization over a multiuser wireless link under finite queue length (finite buffer constraint) remains a challenge. In recent work, we have obtained promising results suggesting that buffer management and channel-aware scheduling problems decouple and high throughput can be obtained using simple buffer management schemes, such as partitioning the buffer, combined with channel-aware scheduling. As throughput-maximizing schemes under finite buffer constraints are not known, we will be working toward contributing both fundamental results and practical algorithms with provably good performance in this area.

Another area of contribution will be energy-efficient scheduling of data. In previous work, we have addressed energy-efficient scheduling of packets in a wireless transmitter, under a deadline constraint for the information. In the proposed work, we will be addressing the case where energy is replenished according to a stochastic process, which corresponds, for example, to a solar cell being charged.

Finally, we will be addressing these issues in a network setting, and exploring the performance limits of Greedy Maximal schemes for link scheduling, including multicast and broadcast links.

The principal researcher will collaborate on colleagues in other universities and at IBM, on this work package.

**Related publications of the Principal Investigator:**

1) A. Sridharan, C.E. Köksal, E. Uysal-Biyikoglu, "A Greedy Link Scheduler for Wireless Networks with Gaussian Multiple Access and Broadcast Channels", IEEE/ACM INFOCOM 2010, San Diego, CA, March 2010.

2) O. Ozel, E. Uysal-Biyikoglu, "Distributed Control of Transmit Power for Energy Efficiency in Wireless Networks with Multiple Access Points ", Wireless Communications and Mobile Computing, Wiley, to appear, 2010.

3) Swannack, E. Uysal-Biyikoglu and G. Wornell, ``Low-complexity Multi-user Scheduling for Maximizing Throughput in the MIMO Broadcast Channel," Proc. Forty-Second Allerton Conference on Communication, Control and Computing, Monticello, IL, September 2004, pp. 440-449.

4) Swannack, E. Uysal-Biyikoglu and G. Wornell, "Finding NEMO: Near Mutually Orthogonal Sets and Applications to MIMO Broadcast Scheduling," 2005 International Conference on Wireless Networks, Communications and Mobile Computing, Volume 2, 13-16 June 2005, Maui, Hawaii, Page(s): 1035 - 1040.

5) E. Uysal-Biyikoglu, B. Prabhakar, and A. El Gamal, ``Energy-efficient Packet Transmission over a Wireless Link," IEEE/ACM Trans. Networking, vol. 10, Aug. 2002, pp. 487-499.

6) B. Prabhakar, E. Uysal-Biyikoglu and A. El Gamal, ``Energy-efficient Transmission over a Wireless Link via Lazy Scheduling," in Proc. IEEE/ACM INFOCOM 2001, pp. 386-394.

7) El Gamal, C. Nair, B. Prabhakar, E. Uysal-Biyikoglu and S. Zahedi, ``Energy-efficient Scheduling of Packet Transmissions over Wireless Networks," Proc. IEEE/ACM INFOCOM 2002, pp. 1773-1782.


**WP3: The Development of a Wireless Multicast Tree Formation Algorithm and Routing Protocol**

The problem of finding the most efficient wireless multicast tree (WMT)- that is, the multicast routing tree requiring the minimum number of transmissions- is related to the Steiner Tree problem, and is NP-complete. In recent research, we have exhibited a computationally efficient multicast tree construction algorithm that achieves close to optimal number of forwarding nodes (NFN), where the optimal is determined by an exhaustive search on tested instances. Our algorithm, named SWIM (for Source-Initiated Wireless Multicast) is optimal for unicast. Moreover, for the broadcast problem, the resulting tree size (NFN) is observed to be within several hops of the optimal. As its goal is minimizing NFN, SWIM forms one shared tree from sources to the multicast destinations;

yet, it inherently also creates a multicast mesh structure by maintaining alternative branches at every tree node. This provides robustness to link failures.

The principal researcher and one master's student will be working on developing the SWIM algorithm and implementing it as a routing protocol.

**Related publications of the Principal Investigator:**

1) S. Akyürek, Elif Uysal-Bıyıkoğlu, B. Neymanov, "SWIM: A Low Complexity Distributed Algorithm for Computing Near-Optimal Wireless Multicast Trees in Mesh Networks", May 2009 (under revision for publication in IEEE Trans. Mobile Communications.)

**Expected Outcomes and Merits:**

The proposed research will contribute to the development of expertise in the field of wireless networks, and establish collaboration between METU researchers with different groups in IBM: in addition to IBM in Turkey, we plan to collaborate with Dr. Murtaza Zafer and Dr. Mayank Sharma from IBM's Watson Lab. The results will be disseminated as conference and journal publications. The cross-fertilization of ideas of IBM and METU researchers will contribute to the dynamics of educational activities in METU. Specifically, masters and Ph.D. level theses, as well as course curricula, will be informed by issues that are of interest to IBM.

**<u>Project Budget:</u>**

**Equipment:**
In order to form the expanded WSN testbed in WP1, an estimated 12,000 USD over the total project duration is required.

**Travel:**
To facilitate the dissemination of results, travel to conferences and workshops will be required. Specifically, two person x conferences per year is planned, which corresponds to an annual travel budget of 4,000 USD, and a total travel budget of 16,000 USD.

**Personnel:**
As indicated in the above work packages, we plan to support two graduate students over a duration of 4 years, corresponding to about 24,000 USD per year, and 96,000 USD in total. An annual 6000 USD contribution to the salary of the PI will be requested.

**Consumables, Facilities, Discretionary funds:**

A total of 4000 USD to the purchase of consumables as well as improvement of laboratory facilities is requested.