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# MAGIC: Mobile Auxiliary Gateways Improve Connectivity of wireless sensor networks

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**MAGIC: Mobile Auxiliary Gateways Improve Connectivity  
of wireless sensor networks**

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# **MAGIC: Mobile Auxiliary Gateways Improve Connectivity of wireless sensor networks (Project Summary)**

The increasing availability of a wide spectrum of sensors enables a variety of unprecedented applications in the areas of safety, health, and security, among others. These applications await greater connectivity of sensors, i.e., efficient, timely, and reliable transfer of their data to where the application demands.

The MAGIC project presents the vision of utilizing wireless Personal Communication Units (PCUs) — the cell phone and its evolution — as Mobile Auxiliary Gateways (MAGs) for sensor networks. Thus, in addition to providing conventional communication (audio, video, text) for human users, PCU/MAGs will provide improved connectivity to the ever expanding set of sensors and sensor networks. We envision that this approach will create a virtual, ubiquitous backbone that connects wireless sensor networks to wired networks (e.g., the Internet). We propose a unified and universal solution with a high degree of connectivity, performance, robustness, scalability, and low installation and maintenance costs that is unrivaled by the previous custom, individualized solutions for both sensors and wireless sensor networks.

The above vision entails a number of technical challenges. The MAGIC project identifies and focuses on the following five aspects: (1) A universal sensor interface for on-board management of (analog) sensor data and activities, (2) Wireless air interface including coding and power control, (3) Network protocols and routing for the combined sensor network and mobile gateway, (4) DSP algorithms for control and data management, and, very importantly, (5) Testing the MAGIC concept via a field trial demonstrator.

The field trial demonstrator will play an important role in the overall success of the MAGIC project. The demonstrator will be developed with the support of a number of companies, and will include approximately 100 PCU/MAGs. Results obtained from all the four research areas, such as power aware concepts, the universal sensor interface, newly developed protocols and routing algorithms, etc., will be validated through the field trial demonstrator. Experiments with the field trial demonstrator will assess the behavior of the proposed MAGIC architecture in a real world scenario, in addition to providing a live network that can be used for parallel research efforts.

To maximize the probability of success and broaden the impact of the MAGIC project, an Advisory Board will be created consisting of members from supporting companies and other bodies. The Advisory Board will coordinate efforts, oversee the progress of the project, and facilitate standardization and technology transfer. The previous work of the PIs and their extensive and broad backgrounds present a solid basis for the work plan, whose outline follows the five items of the technical challenges mentioned above.

**Intellectual Merits** of this project include: solution to challenging questions, of both theoretical and practical interest, relating to network protocols and modeling, coding and power control in wireless communications, energy constrained DSP algorithms, and circuits and systems for multiple analog sensors.

**Broader Impacts** of this project include: benefits to society by the development of a uniform and unified approach to sensor networks, collection and wide dissemination of data and models related to sensor networks, and promotion of education and integration of education and research via the collaborative efforts of the PIs.

# MAGIC: Mobile Auxiliary Gateways Improve Connectivity of wireless sensor networks (Project Description)

## 1 Vision and Proposed Solution

The gamut of applications utilizing sensor information stretches from the ubiquitous airbag and ABS safety modules in automobiles, to an amazing array of new applications on the horizon whose existence and operation requires efficient connectivity of sensors. For example, the automobile industry and related parties are developing networks of wireless sensors to gather and communicate data on meteorology, accident alarms, emergency localization, and road conditions. This information is to be used in automatic and semi-automatic crash avoidance, traffic shaping, and other applications.

Many other revolutionary applications also arise from the advances in wireless sensors, ranging from security monitoring in airports to monitoring hazardous conditions in factories, or detecting biological and chemical agents. The key to all these applications is *connectivity*, to transfer sensor data effectively and efficiently to where the application demands, often by wireless means. This is a difficult problem, due to the severe limitations in power, interference, and other limitations in the sensor environment. In the automobile industry as well as elsewhere, vast sums of money are earmarked for design and development of *custom*, individualized solutions for this problem.

In contrast, this proposal envisions a *unified* and universal scenario, enabled by the evolution of cell phones into wireless personal communications devices. It is envisioned that today's cell phones, pagers, and other mobile communication devices will continue to evolve in the coming decades into one or more types of Personal Communication Units (PCUs), carried by individuals in ever higher numbers. The PCU will be (1) a mobile element of the global future cellular network (made by macro, micro, and nano-cells), (2) a mobile base station for pico (personal) cell networks, (3) an electronic key for accessing proprietary information/devices, acknowledging use of services, and (4) the gateway for data transmission of general utility.<sup>1</sup> Sensors and devices placed on the PCU owner's body, properties (like bicycle, motorbike, car, house) and in the public environment will connect to the gateway either directly (single-hop) or via other sensors (multi-hop).

We advocate that, as opposed to today's individual custom solutions for sensor networking, ultimately there will be a single global network infrastructure (like the Internet today), that will enable efficient transfer of sensor information. In fact, the medium of transfer may actually include the Internet itself; thus a variety of sensors (personal, public, service related) would easily be connected to the Internet, using a universal interface that is the subject of this proposal. The advantages of such a universal sensor network infrastructure include ubiquitous coverage, scalability with the huge number of anticipated sensors, and low installation and maintenance cost.

To realize the envisioned scenario, we propose the following approach: we will design an integrated Universal Sensor Interface (USI) to accommodate various types of (analog) sensors. The USI will be equipped with short range wireless transmission capabilities. In conjunction with this USI, the heart of this proposal is an architecture with *Mobile Auxiliary Gateways* (MAGs) that *Improve* the *Connectivity* of the sensor network, hence the project name: MAGIC.

MAGIC is an improved information transfer infrastructure for sensor networks. MAGIC utilizes *mobile* gateways that interconnect the sensor to the Internet. We propose to research, design, build, and test a sensor network system where mobile PCUs (or today's cell-phones) act as "base stations" for sensor networks in their proximity. Some sensors may be attached and wired directly to the PCU-MAG. Some other sensors may be wireless connected within short reach, using radio frequency (RF) or infrared (IR) links. Other sensors may even use multi-hop and ad-hoc connectivity to communicate with the nearest PCU-MAG (see Figure 1).

The mobile PCU is thus used to accommodate a miniaturized mobile auxiliary gateway for sensor networks that

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<sup>1</sup>Simple elements of this vision are already in place: in Europe one may routinely make vending machine purchases or pay for a car wash via a cell phone.

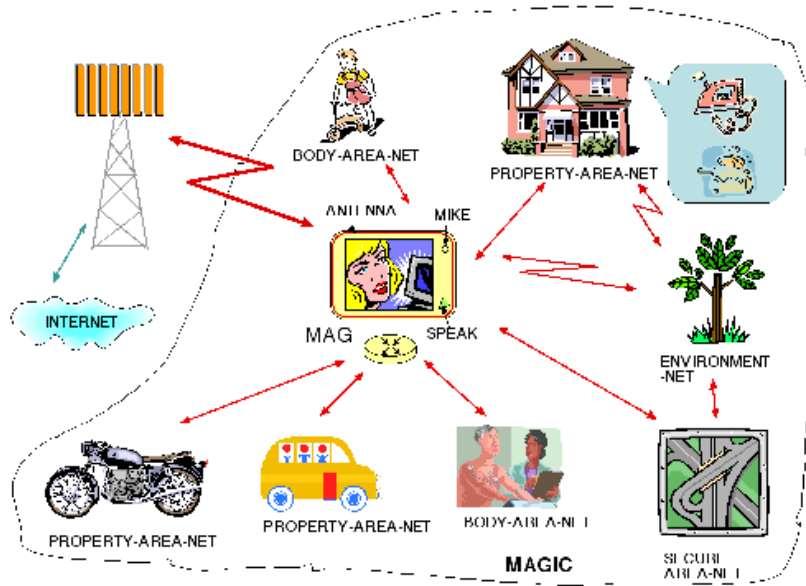


Figure 1: MAGIC applications

will improve the connectivity provided to sensors to reach the Internet. Given the current coverage of wireless cellular network, and the large number of cellular users (either in general, or within a certain group organization), these potential gateways are already virtually *ubiquitous* in urban environments, where the largest amounts of sensor data are likely to be gathered and transmitted.

Some of the key points that give this MAGIC architecture unprecedented power and abilities are described in the following.

- The mobile PCUs in a cellular environment, be they handsets, PDAs, laptops, or other wireless-enabled devices, usually have much higher power at their disposal than sensor networks, allowing them the kind of asymmetric behavior towards the sensor that a mobile receives from a conventional base station.
- The greater capacity and reliability afforded by the mobile gateway comes also from the fact that cellular handsets, PDA's, etc., are *mobile*. They move around the network and therefore by the virtue of coming near to various sensors over the course of time, they can provide a degree of connectivity that is not possible by a static network alone. It has been demonstrated and proven [1] that mobility increases the capacity of packet-switched wireless networks.
- The MAGIC concept will allow a more gradual application of wireless sensor networks. Conventional sensor networks will not function until the density of sensors (over space) is up to a certain threshold. This is due to the fact that communication over long hops is impractical. By introducing mobile gateways, it is possible for sensor networks to be functional (to varying degrees) with a relaxed constraint in sensor density. This also makes the network more robust to decay and power loss of individual sensors.
- MAGIC-enabled PCUs may offer added value to the user (e.g., monitoring the health of the user via a "body area network") as well as creating new applications and profitable services for the access providers. Such applications will make the latest technology more useful and essential, thus boosting the currently stagnant sales in this sector.

The MAGIC architecture has many advantages beyond what was mentioned above, however, due to space limitations it is not possible to describe them all in full detail. In the following, we briefly mention some of these additional advantages: easy connectivity to a variety of (analog) sensors via the USI; global coverage due to the wide acceptance of cell phones; increased capacity of the sensor networks due to reduced number of hops to the closest mobile gateway; minimal installation cost for the network infrastructure because ubiquitous cell phones are used as gateways - no need to install gateways in the fields, with power supply, protection from rain, etc.; low-cost maintenance, as the gateway does not require to be monitored in the field, space need not be rented, no damage done at equipment on the curb, failure detection and repair done by PCU owner; long lifetime of sensors, as energy consumption at the sensor is traded for energy consumption at the gateway (recharged by the owner regularly).

Some further advantages include: network robustness is improved due to the number of cell phones in operation - much like the Internet, loss of a few nodes will not result in perceptible loss in capacity. The MAGIC platform is self-deployed: data and monitoring is often needed where people live, and that is where cell phones are. MAGIC has self-adjusting redundancy property: places with high concentration of people often need more monitoring, and that is where the most gateways (cell phones) are. Mobility of gateways allows data to be transferred even during network disruptions, because the gateway can temporarily store and retain sensor data (buffering). Finally, the MAGIC approach offers a smooth transition from today's existing technology and network infrastructures (cellular networks and the Internet) to the most futuristic scenario (10-20 years from now) in which the PCU will have integrated connection and connectionless services.

To make MAGIC a reality, a number of open challenges need to be addressed. In the proposed projects, the following areas of research will be addressed (see Figure 2).

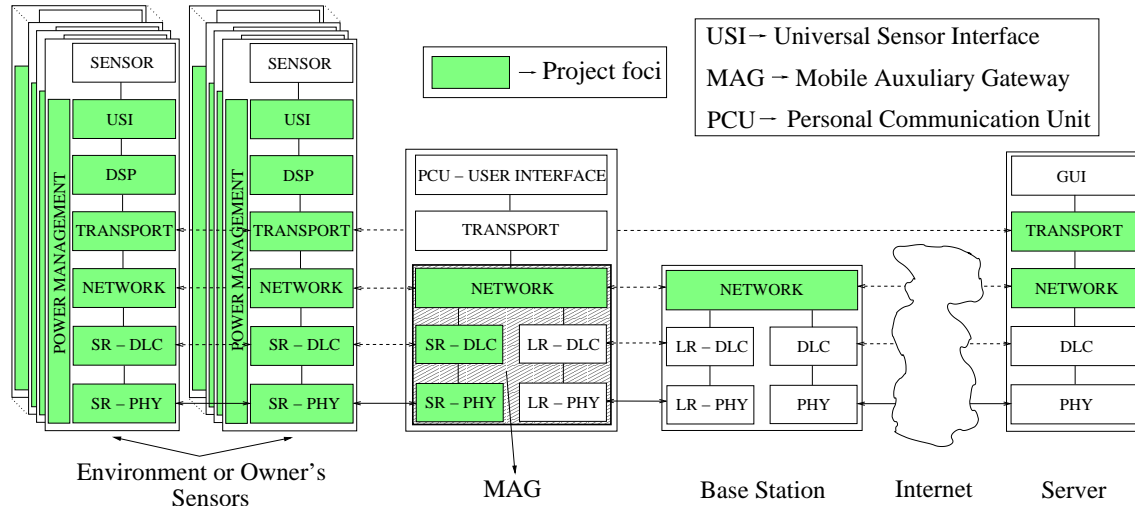


Figure 2: MAGIC project layers: grey blocks indicate project foci

- **Research Area 1:** Network Protocols and Architectures. To fully benefit from the potential advantages of the MAGIC platform, it is necessary to identify efficient, low-energy protocols, routing and signaling solutions. Solutions that make use of the energy-rich phone and alleviate consumption at the energy-constrained sensor will have to be identified, while guaranteeing QoS of sensor data. Capacity and profitability of the MAGIC platform will need to be considered, and evaluated.
- **Research Area 2:** Wireless Communications. The challenges involving efficiency, energy, and capacity as outlined above in Research Area 1 clearly involve the physical layer and the air interface. Unless the links are well designed, it is not possible to have an efficient network. In this part of our research, we will develop

advanced coding and power control algorithms that are tuned to the requirements of sensor networks, and the MAGIC platform in particular.

- **Research Area 3:** Digital Signal Processing (DSP). DSP provides the required interface between the sensor (Research Area 4) and wireless sub-system (Research Area 2) on the sensor platform. The questions of how the sensor system should operate when various quantities need to be sampled, during self-testing and fault detection of the system, and extraction of necessary and accurate information from the measured data, need to be addressed. Minimizing the amount of data to be transported will help optimizing the power required for communication. We will focus our work on the intelligence that the processor and digital signal processing techniques bring to the individual sensor system to optimize its cost, reliability, power consumption, and performance.
- **Research Area 4:** Microelectronics. Universal Sensor Interface (USI). The ubiquitous use of sensors capable of detecting a wide range of physical, chemical, and biological quantities requires a quick and flexible interfacing of a specific sensor and the communication system. A large number of new sensors resulting from research on micromachining and nanotechnologies will become available in the near future. The generated signals will be voltage, current or variation of an electrical variable (resistance, capacitance, frequency). The band will be typically in the low frequency range; however, some sensors will generate high bandwidth (many MHz) signals. The amplitude of signals is, for integrated sensors, very low. Therefore, in order to achieve a suitable dynamic range, low noise circuits, including gain pre-amplifiers and filters are necessary. Finally, the communication system requires a digital format, thus demanding suitable analog-to-digital converters.

A field trial demonstrator on the UTD campus will capitalize on and integrate the findings of the 4 research areas, and will expose several UTD students, administrative, and staff personnel to the project (see Section 3.2.5).

Finally, we are aware that in the MAGIC architecture, as well as in any networking situation where someone's data is being handled by nodes he/she does not own, security is an issue. We will make security, in terms of coding and other prudent design choices, part of the MAGIC architecture. However, research on network security does not constitute a central thrust of this research proposal.

## 2 Previous Work

To the PIs' best knowledge, no previous publication has addressed or studied the proposed MAGIC based vision. However, a number of papers are available on related subjects. Such published results will form the stepping stones for the research activities of the proposed project. This section provides a short survey of previously published results and state of the art in the research fields that have an impact on the proposed research.

Yet another powerful motivator for the concept of mobile gateways (MAGs) is provided by the the work of Grossglauser and Tse [1]. In an award-winning, highly mathematical paper, they prove that in a fading wireless channel, mobility of nodes increases the capacity of ad-hoc wireless networks.

A few attempts have been made at projects that bear some resemblance with our ideas. We briefly mention these past projects.

The Pollen project [2] exploits people's movement from device to device in the same location or from one location to another to transfer data. In this study, human mobility is used for distribution and collection of information among network nodes in the same way bees collect some pollen on their body while moving from flower to flower in search of nectar. Using PDAs, or other mobile devices, information (such as reviews, recipes, problem reports, messages, schedules) can be associated with physical objects in the environment and made easily available to others. An organizational memory, called the hive, is then used to provide centralized storage of collected data and as a mean of controlling the distribution of messages. A simulator is used to obtain preliminary results concerning the message delivery delay. The implemented prototypes rely on the iButtons technology [3]<sup>2</sup>.

<sup>2</sup>iButton technology allows transfer of information through physical contact or infrared communication.

The Manatee project[4] studies an information delivering mechanism based on moving individuals (human, animals, robots) equipped with Bluetooth [5] smart tags. The Bluetooth smart tags are used to retrieve data from otherwise unreachable static nodes that are spread across the monitored area. This study focuses its attention on data dissemination. Information is exchanged between static nodes and mobile smart tags when they are within transmission range of each other. The smart-tags contain a limited amount of memory and are capable of exchanging data via radio communication. The implementation relies on BlueTags [6] development kits, i.e., alpha-version of Bluetooth-based smart tags, with an operational range of approximately 20 meters.

Previous research and development on cellular telephony based sensors, simply use cell phones as transmission devices, for data transport without the hassles of wiring the sensors. For example in [7, 8] the cellular phone is used offshore, where wiring is nearly impossible. In [9] GSM phones are used to quicken the response time of ambulances, and improve the medical care availability during emergencies.

A number of projects, demonstrators and test-beds focused on more conventional sensor networks, where the information collected by the sensors is conveyed to the user(s) through one or more fixed gateways.

The Locust Swarm project [10] uses solar powered devices positioned in buildings to obtain and store information regarding the sensor location using a wireless infrared link. Mainwaring et. al [11] presents an implementation of a remotely accessible sensor network used for real-world habitat monitoring.

In the field of conventional sensor network, a number of problems have been studied [12, 13]:

- design of different kind of interfaces for sensors [14, 15, 16, 17, 18, 19, 20, 21, 22, 23, 24, 25, 26, 27],
- energy aware operation, as sensors have limited battery lifetime [28, 29, 30, 31, 32, 33]
- ad hoc deployment [34, 35],
- dynamically changing environmental conditions, requiring the system to reconfigure [36, 37], and
- unattended operation, i.e., automatic configuration and reconfiguration [38, 39].

One of the major dilemmas in sensor networks is that the seemingly optimal way of solving a problem results in algorithms and protocols whose communication and signaling requirements have an associated energy cost that exceeds the associated benefit [12]. One of the major research efforts in sensor networking deals with protocols and algorithms that maximize the sensor battery lifetime. With multi-hop routing [13], sensors transmit the information toward the gateway, i.e., the MAG, through a number of shorter hops involving some intermediate sensors that act as forwarding nodes, rather than sending the information directly to the gateway<sup>3</sup>. This strategy allows to reduce the energy required for the transmission.

Additionally, due to the increased availability of low cost digital signal processing (DSP) processors, a number of research studies focused on strategies involving collaborative signal processing, both coherent and non-coherent [31, 36]. Intelligent sensors and their use in wireless networks for variety of applications have been discussed in many studies available in the literature. Intelligent sensor system includes single or multiple sensing elements, power unit, digital processor, and wireless communication capability [40]. PicoRadio or PicoNode sensors are aimed at ultra low power (<100 microwatts), small size (< 1cm<sup>3</sup>), and minimum unit cost (< 1US\$) for mostly in-door environmental applications with few meter communication distance [41]. Such constraints may be relaxed and vary in different applications such as medical [42], military [43], industrial, biological, pollution, and hazardous environments [44, 45]. The demand for on-the-sensor DSP capability has been growing continuously for all sensor applications whether the sensor network is fixed or distributed, in indoor or outdoor environments [40, 41, 44, 43, 42, 46, 45]. Application of DSP in the sensor system for MAGIC project offers technical challenges that are complementary to the works that have been reported so far. Programmable digital signal processors can be used to run and optimizing network performance in relation to the data transmission and network requirements.

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<sup>3</sup>The position of the sensors is typically close to the ground, making the propagation loss proportional to  $r^{-4}$  rather than  $r^{-2}$ .



Distributed power control algorithms that have been developed in [47, 48, 49, 50] for cellular networks attempt to counteract signal fading and to maximize the spatial reuse of the frequency spectrum. In particular, given a set of link quality requirements for the mobile terminals, these power control algorithms attempt to provide each terminal an acceptable connection if there is any possible way to do so. However, since multi-hop sensor radio networks and cellular radio networks have significant structural differences, the use of distributed power control algorithms in sensor networks is not clear.

In summary, a number of technical advances are now available in the fields of wireless networking and communications, DSP, and microelectronics. These advances and related results will be re-evaluated in the proposed project and applied to create the foundations for the MAGIC based vision to yield broader sensor capabilities.

### 3 Proposed Research

This section consists of two parts. The first part describes some initial results obtained by the PIs' research teams. The second part describes the tasks, deliverables and management of the project.

#### 3.1 Preliminary Results

The preliminary results presented in this section illustrate the nature of the problems that will be addressed in this project.

The PIs team has introduced and studied the concept of Differentiated Reliability (Sec. 5) (DiR) in the context of wired (optical) circuit switched networks [51, 52, 53, 54, 55, 56]. According to the DiR concept, each connection, or circuit, in the layer under consideration, is guaranteed a minimum reliability degree, or equivalently a maximum failure probability, that satisfies the application requirement. Connections can be characterized by an absolute reliability degree that is not a function of the above network characteristics. This property is of fundamental importance to create network solutions whose reliability degree is solely determined by the application requirements, and not by the network extant topology and technology.

Within the DiR project extensive results have been obtained that numerically demonstrate and quantify the tradeoffs between increased reliability and required network resources.

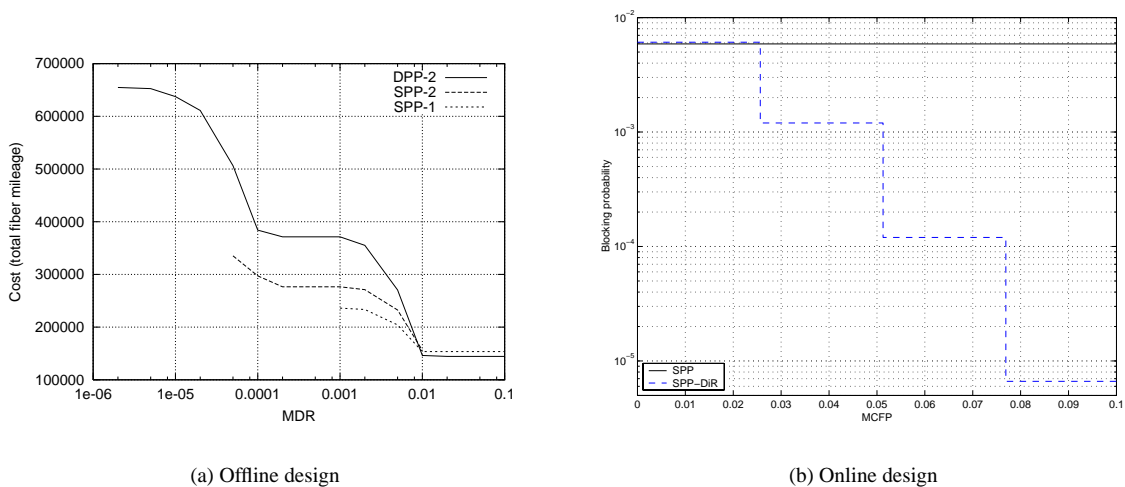


Figure 3: DiR in wired networks

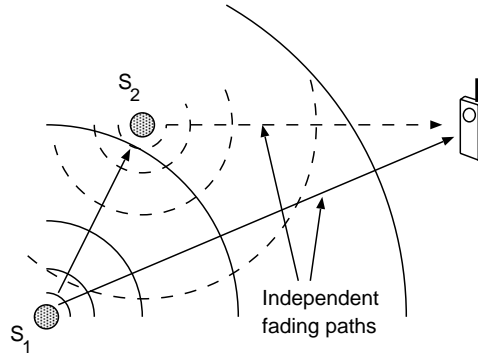


Figure 4: Sensor cooperation

Figure 3(a) shows results obtained using the DiR concept applied to the network offline (static) design problem. The problem is applied to a multi-channel network where reliability is achieved by means of an enhanced version of the shared path protection technique to take into account potential multiple concurrent network element failures. The plot reports the cost of provisioning a Wavelength Division Multiplexing (WDM) network with a general topology when the reliability requirement of each connection is varied. Different strategies are reported. SPP-1 is the conventional shared path protection, SPP-2 is the enhanced version of the shared path protection, and DPP-2 is an enhanced version of the dedicated path protection. The curves quantify the amount of resources needed to satisfy increasingly stringent reliability degrees (from right to left).

Figure 3(b) shows results obtained using the DiR concept applied to the network online (dynamic) analysis problem [56]. The problem is applied to a WDM network where reliability is achieved by means of an enhanced version of the shared path protection technique. The approach consists in applying routing algorithms that can translate the connection reliability requirement into a resource requirement and consequently assign the required resources to the connection. The plots reports two different strategies. SPP is the conventional shared path protection, SPP-DiR is the enhanced version of shared path protection that takes into account different degrees of reliability. The plots report the blocking probability experienced by connections that are dynamically set up and torn down, versus increasingly stringent reliability degrees (from right to left).

Although the proposed MAGIC concept is based on a packet switching network architecture, it is possible to draw an interesting parallel that demonstrates the applicability of the DiR concept to the proposed MAGIC network architecture. In MAGIC, the DiR concept cannot any longer be applied to circuits, it must be applied to data packets generated by sensors. In this context the DiR concept can be seen as the probability that a packet reaches a MAG. The need for higher degrees of reliability leads to concepts such as gossiping techniques [13, 57] rather than protection techniques. However, if we consider that one of the most important resources in a sensor network is energy, gossiping techniques are very similar to providing diversely routed paths to a connection in terms of resource cost, as the energy required by the end-to-end transmission between the sensor and the MAG is proportional to the number of hops, i.e., the amount of bandwidth resources used in a wired circuit switched network. It has to be noted that in the MAGIC network a number of additional dimensions are possible to provide various degrees of differentiation, such as the possibility of buffering data packets at both the sensor node or at the MAG, the possibility of cooperative coding, statistical characterization of the MAG presence within a sensor transmission range, etc.

In the area of cooperative coding for wireless communications, a highly efficient air interface, called *coded cooperation*, has been investigated that can be applied to the wireless sensor networks. The basic concept of coded cooperation is to allow sensors to cooperate in their uplink communication to achieve higher signal-to-noise ratios in the fading channels that are typical of many indoor and outdoor scenarios.

The basic idea is as follows: assume that we have two sensors in the vicinity of a mobile MAG. Referring to

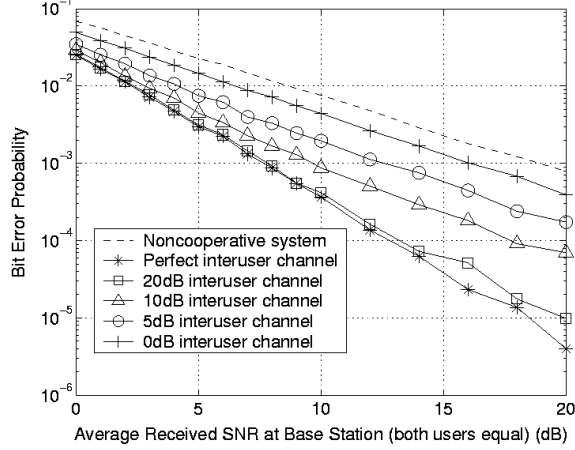


Figure 5: Bit-error rate simulations

Figure 4, assume that sensor  $S_1$  transmits data to the mobile. Because of the nature of the wireless channel, the second sensor ( $S_2$ ) also may receive the same data from  $S_1$  and retransmit it to the MAG. So far, this is only a conventional packet forwarding.

We propose to allow sensor  $S_2$  to act in the following manner: the channel codeword of the first sensor  $S_1$  is partitioned into two sections, possibly by puncturing. If the second sensor  $S_2$  receives and decodes the first partition, it will retransmit the *second* partition for the benefit of the MAG. This is known as coded cooperation, and it has been shown to provide 4-6dB gain in slow fading channels that are typical of the scenarios of interest in this proposal [58, 59].

In our experiments, we have maintained the overall bandwidth, transmit power, and bit-rate to be the same as a non-cooperative system. Under these conditions we have realized a 4-6 dB gain. Preliminary results from these simulations are shown in Figure 5.

Notice that there is no loss in rate, as we accomplish the gains by splitting codewords. This method is akin to hybrid ARQ (Automatic Repeat Request) protocol in that the transmitted data, even if incorrectly received, are never wasted. The interesting aspect is that the incremental redundancy in our case is provided by different sensors, thus leading to the key advantage of our method: that it generates a higher diversity order for the fading channel, as shown by our extensive BER analysis whose results are shown in the table below. In these results,  $d$  represents the minimum distance of the code,  $\gamma_i$  the average signal-to-noise ratio of each user (sensor), and  $P_d$  the probability of error.

Fading Condition	No Cooperation	Cooperation	
		Two Users	$K$ Users
Slow Rayleigh fading	$P_d \leq \frac{1}{2} \left( \frac{1}{1+d\bar{\gamma}} \right)$	$P_d \leq \frac{1}{2} \left( \frac{1}{1+d_1\bar{\gamma}_1} \right) \left( \frac{1}{1+d_2\bar{\gamma}_2} \right)$	$P_d \leq \frac{1}{2} \prod_{k=1}^K \left( \frac{1}{1+d_k\bar{\gamma}_k} \right)$
Fast Rayleigh fading	$P_d \leq \frac{1}{2} \left( \frac{1}{1+\bar{\gamma}} \right)^d$	$P_d \leq \frac{1}{2} \left( \frac{1}{1+\bar{\gamma}_1} \right)^{d_1} \left( \frac{1}{1+\bar{\gamma}_2} \right)^{d_2}$	$P_d \leq \frac{1}{2} \prod_{k=1}^K \left( \frac{1}{1+\bar{\gamma}_k} \right)^{d_k}$

On a different front, we have developed distributed stochastic power control algorithms for wireless networks. In the context of sensor networks, stochastic power control can be useful in order to (1) automatically regulate network topology to meet throughput and quality objectives using minimum transmitted power, (2) reduce power requirements of sensors and mobile gateways for lighter batteries or increased communication time and (3) ensure more efficient coexistence of different types of competing systems in an unlicensed environment. Our existing work in the area of stochastic and distributed power control has led to algorithms that do not require exact measurement of the signal-to-interference ratios (SIR) at the receiver, but only require the receiver to feed back a (possibly noisy) measurement of

received power. This relaxes the conditions on power control and is indeed very useful for sensor networks, where resources are scarce.

Besides the two problems discussed above, to efficiently implement the MAG platform proposed by the PIs, it is necessary to focus the research efforts on the following four fundamental research areas: network protocols and architectures, wireless communications, on-MAG DSP, and microelectronics and the Universal Sensor Interface (USI). More details and the research plan for each research area are discussed next.

## 3.2 Research Plan

This section describes in details the research areas that constitute the proposed project, and presents the research activities that will be undertaken to carry out the study.

### 3.2.1 Research Area 1: Network Protocols and Architectures

This research area aims to study and define efficient network protocols and to optimally use the available network resources, including both the MAG (Mobile Auxiliary Gateway) and the sensor energy. The outcome of this research will not only facilitate a better understanding of the properties and performance of the MAG-based system, but also allow us to model it and predict its performance. A unique aspect of this study will be the integration of protocols that have been designed so far for two independent networks, i.e., the sensor and cellular networks. The interaction between the two networks occurs at the MAG.

The following tasks will be carried out.

- **Task 1.1: Routing protocols.** Network layer forwarding decisions are made in a distributed fashion, taking into account both energy management and the self-learning ability of the sensor nodes, i.e., sensor nodes can empirically obtain a statistical characterization of the presence of MAGs within their transmission range by recording past behaviors of MAGs. Daily routine of people carrying MAGs will help predict the availability of MAGs in an area, for improved transmission efficiency. In particular two cases will be considered:
  - Buffering capability is not available at sensor nodes, i.e. sensor nodes can only transmit the data packet toward a MAG if there is one within transmission range, or sensor nodes can forward one or more copies of the data packet to neighboring sensor nodes according to the *gossiping* paradigm in a multi-hop fashion.
  - Buffering capability is available at sensor nodes, i.e., in addition to the above possibilities, each sensor node has the possibility of storing a data packet and wait for a MAG to appear within transmission range<sup>4</sup>.
- **Task 1.2: QoS.** The concept of Differentiated Reliability (DiR) (see Section 3.1) will be tailored to fit the MAGIC network architecture and provide QoS for end-to-end delivery of the sensor data to the remote site. The end-to-end transmission requires up to four steps (see Figure 2): short range transmission from sensor to sensor (multi-hop), short range transmission from sensor to MAG (single hop), transmission from MAG to base station (BS), and transmission from BS to remote site for data analysis. This study will especially focus on the tradeoffs between the energy penalty arising from enhanced signaling and the desired performance gain in terms of QoS (e.g., end-to-end latency). In analyzing the differentiated reliability, catastrophic scenarios (e.g., loss of a BS) will be taken into account, to determine the overall robustness of the system.
- **Task 1.3: Network models and simulations.** Existing simulators will have to be modified to combine the behavior of both the sensor-MAG (short range) transmission and the MAG-BS (long range) transmission. Mobility models for the MAGs (people) and the sensors will have to be identified and used to provide meaningful performance results.

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<sup>4</sup>The sensor node itself might be mobile.

- **Task 1.4: Scalability of network design and management.** The scalability of the proposed network architecture will be investigated with particular attention to routing algorithm complexity and scalability, in terms of network geographical size, number of network nodes (sensors, MAGs and BSs), and required amount of signaling.
- **Task 1.5: Integration of wireless communications results.** Relevant findings resulting from the tasks described below concerning cooperative coding (Tasks 2.1, 2.2, and 2.3), power control (Task 2.4), and MAG DSP (Task 3.2), will be taken into account in the routing strategies to optimize the sensor lifetime and the capacity of the MAGIC architecture.
- **Task 1.6: Implementation of the identified routing protocols.** Selected promising protocols and routing solutions will be extensively simulated and emulated in the lab. After this phase, they will be implemented and tested to be part of the field trial demonstrator described in Section 3.2.5.

### 3.2.2 Research Area 2: Wireless Communications

The challenges in the area of wireless communications are to provide reliable links with low bit-error rate probabilities under low power constraints for the sensors, as well as power control in the face of interference. The research activity concerning wireless communications is divided into the following tasks:

- **Task 2.1: Cooperation vs. packet forwarding.** The cooperative coding mentioned previously is actually an alternative to a regular packet forwarding scenario. Together with the PI's team that specializes in networking, the scenarios (in terms of power availability and spatial distributions of sensors) where one method is superior to the other and vice versa will be investigated. The aim is to use dynamic mode switching between cooperation and packet forwarding to get the maximum gains available from each method. The main challenge in designing this adaptive strategy is that it must work in a distributed environment.
- **Task 2.2: Efficient codes for sensor cooperation.** Efficient cooperation codes under the constraint of severe power limitation in sensors will be analyzed and developed. The previous work in user cooperation has led to advances in terms of transmit power which is very useful because (1) each sensor's transmission will add to the background interference with other sensors, and (2) conserving the limited power of each sensor is essential. But another factor to consider is that each sensor needs to decode in order to participate in cooperation (the same is true for packet forwarding). This part of our research is devoted to developing cooperative codes under a *total power constraint*, i.e., decoding power as well as transmit power. Potentially gainful directions include: (1) simplified decoders, e.g. sequential decoders, (2) different codes and puncturing/concatenation strategies from an overall power point of view, and (3) adaptive mechanisms that switch between amplify-and-forward vs. decoding, to minimize the *average* power required.
- **Task 2.3: Multi-sensor cooperation.** The existing user cooperation research is mostly in the context of two transmitters. In sensor networks, we have a previously indeterminate number of sensors that are not necessarily controlled by a central authority. One task in our research is to develop multi-sensor cooperative air interface. That is, a sensor must transmit its data not knowing which (or for that matter, how many) sensors will seek to cooperate with it. Managing this task will require two thrusts of research. First, we will extend 2-sensor cooperation strategy to a multi-sensor strategy. We will attempt this extension via various strategies, including power-splitting and rate-splitting between the cooperating sensors. Second, we will address issues related to the link layer, so that the cooperating sensors do not interfere with each other.
- **Task 2.4: Distributed and stochastic power control.** This task is essentially one of resource management. Since the sensors (a) are power limited and (b) may interfere with each other, power control is a key issue. We aim to extend our existing results on power control and apply them to sensor networks. In particular, development of stochastic power control algorithms, that do not require perfect measurement of quantities such as STR, received power, or interference, but can simply feedback their noisy estimates, will be preferred. We will study

convergence properties of these power control algorithms under realistic conditions typical of sensor networks, and will devise simplified algorithms that are necessary for the spartan sensor-mobile environment.

### 3.2.3 Research Area 3: Digital Signal Processing

The research objective is to study, develop, and apply advanced DSP methods (software and hardware components) that will optimize the cost, power, and performance of the sensor system. Efficient DSP algorithms will be sought to implement the following tasks.

- **Task 3.1: Data Processing.** Processing of the measured data locally to generate minimal amount of information that must be transmitted. For example; data sampling, feature extraction, classification, and decision making are carried out by DSP algorithms on the sensor system to avoid overloading of the transmission channel. The data is then prepared for transmission to appropriate destination at appropriate time.
- **Task 3.2: System control.** System control and supervisory operation including testing, calibration, diagnostic and fault detection, and status (maintenance) update of the sensor system.
- **Task 3.3: Power management.** Power management schemes including the power and battery status, scheduling of the system operation, power-down (sleep-mode) of appropriate system components, and wake-up operations.
- **Task 3.4: Emergency management.** Handling of the high priority or emergency operations of the sensor system.
- **Task 3.5: DSP implementation.** Digital circuitry, or programmable processor that would be most suitable for use in the sensor system, or in the demo unit, to implement the DSP tasks will also be studied and identified. Performance of the developed DSP algorithms will be tested and analyzed by simulation and implementation on the demo system.

### 3.2.4 Research Area 4: Microelectronics

The activity of this research area will lead to the design of a Universal Sensor Interface (USI) capable to meet interface requirements (up to the digital representation) of any type of sensor. The interface will be modular and expandable. Therefore, it will enable, for instance, interfacing hundreds of sensors on a single chip. Analog switch matrices with 16 inputs each will direct each input to a proper processing chain, possibly made by pre-amplifier, filter, and data converter. It is estimated that 8 low-noise pre-amplifiers, 4 digitally programmable filters and 2 data converters will serve each switch matrix. The research activity is divided in the following tasks:

- **Task 4.1: USI-1: Study and classification of sensor signals.** This task will study a wide range of sensors and applications to determine a set of specifications for basic components of the USI.
- **Task 4.2: USI-2: Design of basic blocks.** This task will concentrate on the design, simulation and integration of the foreseen low-noise amplifiers, programmable filter and data converters. The data converters will move from conventional Nyquist-rate and over-sampled implementations to be specialized for sensor needs. For example, sigma-delta capable to detect resistive and capacitive variations will be designed. Also, the project will study frequency-to-digital converters with different ranges of operation.
- **Task 4.3: USI-3: USI Prototyping and testing.** The blocks designed in the USI-2 task, after integration and experimental verifications, will be assembled in a single integrated circuit. The prototype of the USI will be used for interfacing different kinds of sensors in the foreseen field trial demonstrator.
- **Task 4.4: Power consumption optimization.** The limited energy available either on the mobile MAG or in remote sensors require a power aware policy. This involves studying the more effective short-range communication methods and the best use of frequency bands available. The project will complement the activities in another

recently funded NSF project (GAP4S, starting September 2002) for ad-hoc and very-short range (less than 10 m) communications. The frequencies considered are: 2.4 GHz, 910 MHz, 433 MHz, and 315 MHz. The early-stage activities in that project, while not ready for formal presentation, have already begun to contribute to our understanding of the trade-offs between the reduced antenna efficiency (equal or smaller than 1 sq inch) and the minor power required by low modulation frequency.

### 3.2.5 Field Trial Demonstrator of the MAG Concept

The PIs, in conjunction with a number of companies, plan to further demonstrate the advantages and possible drawbacks of the proposed MAG concept by means of a field trial experiment. Additional support will be provided by the interested companies for this last task (see attached letters of support).

The field trial demonstrator will capitalize on and incorporate some of the findings from all of the above research areas. During the first year, a wireless networks will be built based on existing Bluetooth and WLAN (Wireless Local Area Networking) technologies. The characteristics of the sensors would be incorporated through software simulation using notebook computers. The simulated behavior of the sensors and the effectiveness of the wireless networks will be evaluated. Initially, attempts will be made to create a self-sufficient independent and fully functional wireless network without any industrial participation. This network will have hardware and software to monitor and analyze the performance of the simulated sensors using the existing Short Message Service (SMS)/Multi-Media Services (MMS) technology with Bluetooth and WLAN technology. Figure 6 depicts the possible setup of the test configuration after one year into the project.

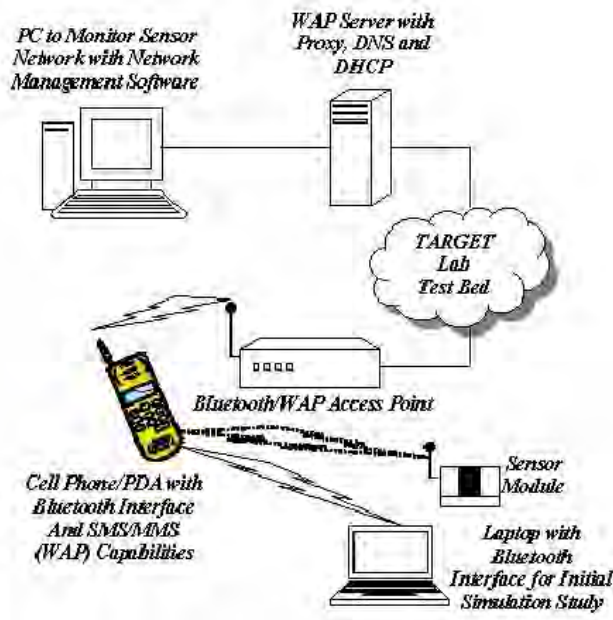


Figure 6: MAGIC field trial demonstrator

The gateway functionality of the MAG, e.g., cell-phones and PDAs will be achieved by modifying the programs associated with the SMS/MMS functionality to integrate seamlessly with Bluetooth or multi-hop low powered wireless LAN sensors.

The actual sensors themselves will be designed on the basis of very low power consumption. The processing power of the sensor will include either the interface for Bluetooth or functionality for a multi-hop WLAN.

After the first year, experiments will be carried out with active industrial participation employing actual base stations

supporting SMS/MMS. After the second year, studies will be carried out with 4 fabricated sensors and the MAG devices realized by modifying existing wireless devices. The sensors will detect some substance in the air (simulating bio-hazard materials) and send alarms when a threshold is reached. The alarms will then be monitored using the graphics display of the network management software which maps all the sensors on the screen.

The demonstrator will accomplish the following tasks:

- study the characteristics of the SMS/MMS technology using Wireless Application Protocol (WAP) to act as sensor network gateway,
- determine the suitability of Bluetooth as a network interface for the sensors,
- study the feasibility of WLAN as a network interface for the sensors<sup>5</sup>,
- analyze on the field the tradeoffs between multi-hop and single hop connectivity of the sensors before reaching the MAG,
- analyze the effectiveness of the monitoring system and determine drawbacks and limitations,
- implement and test on the demonstrator novel ideas developed by the PI's team.

It is expected that by using a field trial, it will be possible to find possible deficiencies of the demonstrators developed in the laboratory, and find appropriate solutions that will circumvent them. In addition, collected traffic patterns originated by the sensors will be made publicly available and will help the community to identify adequate modeling and simulation techniques for sensor networks.

The field trials will be carried out with the co-operation of about 100 users — each carrying a MAG — including undergraduate and graduate students, administrative personnel and staff, and police officers at the University of Texas at Dallas (UTD). The users will be chosen to represent different schools, different ethnicities and minorities, homogeneous gender, and possibly including handicapped and persons with disabilities. In this way, it will be possible to see, via collected statistics, how the different mobility, habits, and daily schedules affect the performance of the system. At times, the cell-phones of a sub-group will be de-activated (MAG feature) to learn the behavior and the respective contribution. Candidate students will be interviewed to identify services to offer over the field demonstrator as discussed in Section 4.

### 3.3 Project Coordination

Due to its large size, this project requires rigorous and active coordination. The PI of the project, with the help of a Post-Doctoral Fellow (2 m/y) will make sure that work progresses in the various areas according to a coordinated plan. Deadlines will be driven by the field trial demonstrator, whose complexity is growing year by year.

A project *Advisory Board* will be created, whose tasks include: establishing and adjusting directions of the research activities, facilitating the transfer of significant results to standard bodies, monitoring the status and the results of the project every 6 months (internal workshop with presentation of results), coordinating the contributions from the industry to the field trials, identifying means to widely disseminate results to both academia and industry, and fostering technology transfer, standardization, and practical implementation of the most promising results. The Advisory Board will consist of experts from interested companies (such as the companies that provided attached letters of support), NSF representative(s), as well as administrative and technical representation from the UT-Dallas.

Internally, the team of PIs and senior personnel involved in the project will meet regularly (monthly at the beginning of the project, bimonthly during the rest of the project) to discuss results and propose synergies across the various research areas.

Documents, such as technical reports, papers, results, presentations, description of the demonstrator progress, minutes of the meetings, and reports from the Advisory Board, will be made available on a web site. All collaborators of

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<sup>5</sup>The University of Texas at Dallas campus in Richardson offers IEEE 802.11b connectivity.



the project, and the members of the Advisory Board will have access to this information. In addition, a public web area will contain results that are ready for dissemination to the general public.

## **4 Expected Impact, Dissemination Plan, and Education Repercussion**

The MAGIC project has all the attributes and qualities to become highly successful. It is expected that it will be able to drive the evolution of sensor networks in a unified, ubiquitous infrastructure, similarly to what it is happening in wired networks today with the Internet success. In the event that the MAGIC project will be only partially successful, the obtained results will still have a significant impact on custom solutions and for monitoring limited areas, e.g., stadiums, campuses, malls. In any case, the results and the teamwork resulting from the MAGIC project will allow:

- to reach better understanding of sensor networks, communicating via MAGs,
- to collect traffic statistics from the field trial and make them publicly available to contribute to modeling efforts of such network traffic patterns,
- to interact with various companies spanning across numerous disciplines, such as microelectronics, wireless networks, network protocols and services, public services (see attached letters of support from some of the local companies interested in the project),
- to create new engineering courses, presenting the results and the experience gained from MAGIC, and to offer special senior design project courses to undergraduate students. These courses will be made available at the University of Texas at Dallas (UTD) and subsequently at other universities. At UTD they will be included in the Telecommunication Engineering (TE) program, the first ABET accredited TE program in the nation,
- to present and to discuss the results at various workshops and conferences, including the current ComSoc effort on the evolving telecom discipline.

Besides conventional conference and journal publications of results, the PIs will give the broader visibility of the project by announcing the field trial in newspapers and TV channels, presenting seminars at IEEE chapters across the globe, showing “small” demonstrators, with the supports of the participating companies, at exhibits.

The MAGIC project will strongly influence the education activities at UTD. Several students will be invited to take part in the MAGIC project and will be given a PCU-MAG of the field trial. Candidates will be selected from various programs at UTD — e.g., management, mathematics, biology, art and literature — after attending a tutorial on the project. Candidates to participate in the field trial demonstrator — approximately one hundred persons will be given a PCU-MAG — will be chosen to represent different schools, different ethnicities and minorities, homogeneous gender, and possibly including persons with disabilities. In this way, it might be possible to see how the different habits, daily schedules, affect the performance of the system using the collected statistics.

Once selected, the candidates will be invited to write a proposal about how the MAGIC platform can be used in their own field of education. At the end of their participation, they will have to write an essay on their experience with the PCU-MAG and results obtained in their respective majors using the MAGIC platform.

Other future project proposals are expected to be generated that will capitalize on the MAGIC effort. Colleagues at UTD and at other (international) universities have already expressed their interest in the use of the field trial to improve their research activities.

## **5 Previous NSF Work**

Two of the PIs in this project have currently-funded NSF projects that have made significant progress to date. In this section, we briefly review the results of this previous NSF support.

Professor Aria Nosratinia is the Principal Investigator of the NSF CAREER grant CCR-9985171 entitled “Processing of Images and Video for Emerging Communication Media.” The grant award was from January 1, 2000 and expires on January 1, 2004. The total value of the grant for the four year period is \$199,998.

This NSF project had three inter-related components. The first component was related to the PI’s previous research in motion estimation and post-processing for reduction of quantization error [60, 61, 62]. This research resulted in what is at this point, to our knowledge, the best-performing image post-processor in the MSE sense reported in the literature. A public domain software for this algorithm was developed with the NSF support. This software has been extensively downloaded from <http://www.utdallas.edu/~aria/mcl/>.

The second research component pursued issues related to rate allocation for joint source-channel coding, and later extended into the area of iterative (turbo) decoding of joint source channel codes [63, 64, 65, 66, 67, 68, 69]. This extended theory has resulted in interesting and useful results, including new algorithms for list turbo decoding of variable length source-channel codes.

The final component of the research funded by the CAREER grant was to explore new directions related to the topic of the grant, transmission of visual signals over wireless and packet switched networks. This exploratory thrust has been extremely fruitful, leading to a theory and a new class of algorithms for coded cooperation in wireless networks. This coded cooperation allows simple, single-antenna mobiles to share antennas and thus achieve uplink diversity without loss of rate, power, or bandwidth. We believe this method can have a significant impact on multimedia wireless communications. [58, 59].

The following is a list of conference papers, journal articles, and theses supported in whole or in part by the NSF grant CCR-9985171: [58, 64, 65, 66, 70, 69, 59, 71, 68, 67, 72, 73, 74, 75, 76] [60, 61, 63, 62, 77],[78, 79]. Several students have been supported in part by this grant. N. Hegde and V. Thilak who have graduated, and A. Hedayat, T. Hunter, M. Janani, B. Hong, and S. Sanayei whose doctoral programs are currently underway in Professor Nosratinia’s group.

Professor Andrea Fumagalli is the Principal Investigator of an NSF project entitled Differentiated Reliability (DiR) in Multi-Layer Optical Networks, started on 01/01/01. With this project, the concept of differentiated Reliability, or DiR for short, is introduced in high speed optical networks. The most relevant publications resulting from the award are [80, 81, 82, 83, 84, 85, 86, 87, 88, 89, 90, 91, 92, 93, 94]. The project is briefly described next. Current networks typically offer two degrees of service reliability: full (100%) protection (e.g., in presence of a single fault in the network) and no (0%) protection. This reflects the historical duality that has its roots in the once divided telephone and data environments, in which the circuit oriented service required protection, i.e., provisioning readily available spare resources to replace working resources in case of fault, while the datagram-oriented service relied upon restoration, i.e., on dynamic search for and reallocation of affected resources via such actions as routing table updates. The current trend, however, is gradually driving the design of networks towards a unified solution that will support, together with the traditional voice and data services, a variety of novel multimedia applications. The problem of designing cost effective multi-layer network architectures that are capable of providing various reliability degrees (as opposed to 0% and 100% only), as required by the applications, is addressed in this NSF project. The concept of Differentiated Reliability (DiR) is for the first time formally introduced and applied to provide multiple reliability degrees (classes) in the same layer using a common protection mechanism, e.g., path switching. According to the DiR concept, each connection in the layer under consideration is assigned a minimum reliability degree, defined as the probability that the connection is available at any given time. The overall reliability degree chosen for a given connection is determined by the application requirements. In a multi-layer network, the lower layer can thus provide the above layers with the desired reliability degree, transparently from the actual network topology, constraints, device technology, etc. The cost of the connection depends on the chosen reliability degree, with a variety of options offered by DiR. The NSF DiR grant was leveraged by the PI to launch an international collaboration with the Brazilian CPqD and produce a network demonstrator, called the OMEGA test-bed. The OMEGA test-bed consists of 5 nodes, interconnected to form an arbitrary mesh, that run DiR protocols to ensure the desired degree of reliability [85].

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