Wireless Sensor Networks: Challenges and Opportunities

Neiyer Correal and Neal Patwari
Florida Communications Research Labs
Motorola Labs
8000 West Sunrise Blvd, Rm 2141
Plantation, FL 33322
[N.Correal, N.Patwari]@Motorola.com

Abstract

Advancements in sensing, microelectronics and wireless communications technologies are paving the way for the development of a new breed of integrated wireless sensing devices. The relatively simple devices that we envision are akin to the sensory receptors of the nervous system in that they are capable of detecting changes in the environment due to stimuli. As are their biological counterparts, these "RF neurons" or neuRFon^{TM} devices are endowed with the ability to associate, producing efficient sensory networks. These pervasive wireless sensor networks may potentially have an unprecedented impact on the way we interact with our surroundings, by providing a sensory fabric, linking cyberspace to our surrounding environment. Many issues must be addressed in order to bring this unconventional communication centric vision to mainstream. This paper presents an overview of research trends and challenges in the design and implementation of large-scale wireless embedded networks.

1 Introduction

The information gathering capabilities of distributed sensor networks are poised to revolutionize the way the information infrastructure interacts with our physical environment. Projecting IC cost curves into the future leads us to conclude that wireless sensing systems on a chip will soon become so low-cost that that wireless capabilities will be built into everything, from your home garden to stuffed animals to library books.

If wireless sensors are to become pervasive in businesses and homes, researchers must provide more than inexpensive ICs. Due to the large densities of nodes, networks must be zero-configuration, and zero-maintenance. In addition, the very long life required for autonomous operation dictates that these devices must be extremely energy efficient for their energy sources to last for the full life of the product to which they are attached.

In the majority of applications, locating sensors is also critical. An alarm from a sensor may be meaningless unless the source is identified and located. If devices are to be dropped into place or moved periodically users should not be required to input each device ID and its coordinates, nor should the user interface identify devices by number. In fact, a device's location can become its ID [1]. Location of a device will be relative to its neighbors, which it will cooperatively calculate based on peer-to-peer range measurements. Furthermore, sensor data fusion and processing algorithms will reduce and make decisions based on the relative location of input data.

This paper is organized as follows. In Section 2, we provide a broad overview of research issues in wireless sensor networks, Section 3 presents current prototyping efforts and Section 4 describes location techniques for wireless sensor networks.

2 Technology Areas

This section provides an overview of design issues regarding the development of a highly energy efficient system architecture for embedded wireless sensor networks; beginning with device technology and progressing to the application layer. Figure 1 shows a conceptual system architecture. While this figure provides a profile with clearly drawn boundaries, as is customary in modular system development, to achieve the ultimate energy efficient architecture one must optimize across all layers of the stack.

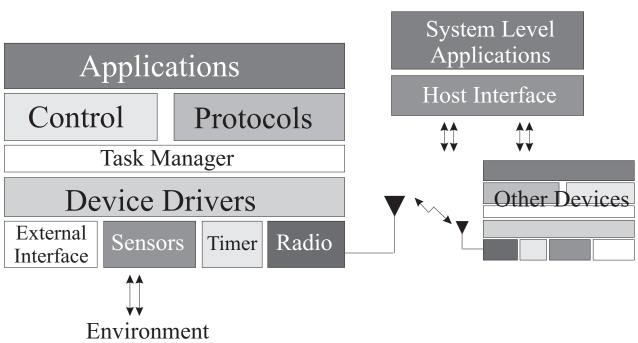

Figure 1. Layered architecture of wireless sensors.

2.1 Device Technology

A cornerstone for the implementation of distributed wireless sensor networks is the development of extremely low cost micro-powered devices suitable for pervasive wireless networking. Programs such as WINS [2], AMPS [3], PicoRadio [4] and SmartDust [5] are addressing the challenge of developing low-power devices integrated on a chip. Low power analog and digital electronics, Microelectromechanical System (MEMS) fabrication and integration and energy scavenging are some of the key enablers [6]. MEMS technologies will allow IC integration of sensors, oscillators, and filters, while at the same time reducing the power consumption of the device [7]. Envisioned power consumptions on the order of 100 μW open the door to unconventional approaches such as energy harvesting [8] for powering the devices and micro-powered RF wake-up circuitry for improved responsiveness at low-duty cycle operation.

2.2 Software

Embedded software provides the intelligence required to deal with the complex tasks of autonomous and networked operation. While today there is a trend in migrating complex functions from hardware to software, power efficiency and die size favor the use of power aware hardware over software running on a low power microprocessor core. Therefore, careful consideration must be given to how to properly partition the implementation into its software and hardware elements.

Due to its inherent flexibility it is a practical approach to use power aware software to manage and control the activities of the hardware subsystems. An example of a real-time kernel tailored for wireless sensor network applications is presented in [9]. Energy efficient operation is achieved using an event based model that has the CPU in the sleep mode for most of the time and becoming active to process valid events. Another source for reduced power consumption is the use of algorithmic optimizations and the development of energy scalable node software [10] .

2.3 Physical Layer

One of the crucial considerations in designing the physical (PHY) layer is the RF band of operation. Given the large number of devices involved, it is preferable to operate in a licence exempt frequency band.

However, operation in a licence free band brings up a variety of design constraints.

In the US, the FCC part 15 sets up restrictions for intentional radiators [11]. Interestingly, in some bands the restrictions go beyond power densities to encompass type of data and intended use. For example, in the 260 - 470 MHz band, FCC 15.231 does not allow periodic data transmissions unless the sensor is polled at a duty cycle of less than one second per hour. Operation in the 902-928 MHz, 2400-2483 MHz, 5725-5875 MHz, and 24-24.25 GHz bands is permitted at low EIRP (below 1 mW) by FCC 15.249. Higher powers (up to 1 W) can be transmitted using spread-spectrum in the lower three bands as specified in FCC 15.247. Yet, due to energy and complexity constraints use of higher transmit powers is unlikely.

When operating under 15.249 simple modulation techniques with low complexity implementation are possible. However, wide band implementations have the advantage of being more easily integrated on chip, because they do not require high-Q filters that consume space on the IC. The resulting reduction in analog IC area must be balanced with the increase in power consumption and complexity of the digital part of the IC as the modulation bandwidth is increased.

Modulation techniques inherently robust to interference are often preferred in these bands, as the advantages of spreading gain within the already crowded ISM bands often justifies the additional complexity. For example, when operating in the global 2.4 GHz band in low power mode, for which there are no spreading or data rate constraints, devices must be able to tolerate the interference from, among others, microwave ovens, 802.11b and Bluetooth devices.

Given the nature of the interference in the ISM band and the short packets used, it is expected that error correction coding will not be very useful for overcoming the data corruption caused by high power interferers. Instead, very simple error control coding is expected to operate in conjunction with automatic request of retransmission strategies. With low data rate requirements, getting small packets through the channel fast can have advantages in terms of power efficiency and reduced probability of collisions.

There are many tradeoffs between achieving robust operation and minimizing the complexity at RF and baseband. To achieve an ultra low cost solution radio designers advocate the relaxation of filter requirements in the transceiver as well as easing the constraints on timing and frequency references. On the other hand, slow roll-off filters have lower interference rejection capabilities, and time and frequency offsets degrade performance.

Taking notice of the distinctive characteristics of low cost, low data rate, power efficient wireless communications, requirements that are presently not addressed by current standards such as IEEE 802.11, the 804.15 task group 4 has been charged with defining the PHY and multiple access control (MAC) specifications for low data rate inexpensive solutions [12]. Ideally, the results of the standardization efforts will fall within the requirements of wireless sensor networks.

2.4 Medium Access Control

While significant efficiency can be achieved by reducing the power drain caused by individual components, maximization of system lifetime can only be achieved through careful optimization across all layers of the system [13]. An approach conducive to power conservation is to maintain devices in a doze mode for most of the time and make them active when communication is required. With this approach time spent in deep sleep mode dominates power consumption. To allow nodes to operate at low duty cycles, predefined traffic schedules can be broadcast, nodes can serve as data relays, or nodes can schedule rendezvous for other pairs of devices.

Energy efficiency and latency are, however, two conflicting requirements in wireless sensor networks. Low-duty cycle operation has ramifications that impact the design of channel allocation schemes and the associated MAC protocols [14] [15]. While a sparse wake-up schedule provides power savings, it may result in excessive latency, which can be unacceptable in certain applications, such as emergency notification.

Another important consideration in the design of low power MAC protocols deals with the energy spent during the ramp-up time of the transceiver hardware. Switching between transmit and receive modes has energy penalties due to the energy consumed in the transition [8]. It is therefore advantageous when possible to reserve multiple contiguous slots for streamed communication.

Maximization of the conflict free operation time can also lead to significant power savings, as the resolution process during contention periods and retransmissions consume valuable energy resources.

2.5 Networking

Due to the large numbers of devices involved, autonomous operation is another feature that becomes necessary. In order to achieve network connectivity, a mechanism is necessary for nodes to efficiently identify their neighbors and form a network without the aid of an infrastructure [16]. Adding to the complexity is the dynamic nature of sensor networks. In these networks, the topology of the network changes due to node additions and node departures due to energy depletion. Topology is an active area of research in wireless sensor networks. In flat networks, devices are equals. In hierarchical networks, devices have classes, and their routing behavior varies based on their level in the hierarchy. Typically, a cluster head or master node controls a group of nodes. This makes routing simple for the controlled nodes, however, frequent changes in the cluster head can tie up nodes in cluster head selection instead of packet relaying [17]. In contrast, flat networks are more robust to device failures and mobility, but require nodes to keep information on their neighbors or do frequent route-discovery.

There is even debate in the hopping nature of sensor networks. Single hop networks, in which messages go from sensor to information sink directly, have the difficulty that devices far from the information sink require more energy to report data. However, in multihop networks, in which packets hop from device to device to get to the information sink, devices near to the information sink will experience the heaviest burden of packet forwarding. In [18], a hybrid topology ensures that sensor data sources both near and far away from the information sink are all utilized evenly. Multihop networks can reduce the overall energy required to transmit a message, as long as the energy dissipation in the receive mode is low [18]. Algorithms that take advantage of the channel to adaptively change transmit powers and routes can significantly reduce the energy requirements of a multi-hop system [19]. However it has been shown analytically in [20] that the throughput of multihop networks will decrease with increasing number of nodes. This tradeoff between energy and capacity will determine the nature of a particular system.

Due to the Ad Hoc nature of sensor networks, many lessons can be learned form the growing knowledge base of Mobile Ad hoc NETworks (MANET). MANET routing protocols can be broadly categorized as table-driven or demand driven. Table-driven routing protocols attempt to provide an up-to-date view of network connectivity at all times. This is achieved using routing tables and propagating routing information updates through the network. With demand driven protocols, on the other hand, routes are discovered on-demand, thus the energy and bandwidth required by route maintenance traffic is minimized [17]. However, the key difference is that MANET networks are optimized for Quality of Service (QOS), while sensor networks must be optimized for low energy dissipation.

Another possibility would be to use an approach similar to the one used in Bluetooth, where up to eight devices can be inter-networked into a piconet. Several piconets can be linked together to form an Ad Hoc scatternet. To form a scatternet a Bluetooth device assumes a dual role as a master of one piconet and slave of another. This device then acts as a bridge between piconets. While this approach is suitable for loosely linking a few clusters, it does not provide the flexibility required for large scale connectivity in pervasive sensor networks.

An alternative to casting sensor networks routing in the same framework of Ad Hoc networking is to exploit the parallel between information flow in wireless sensor networks and physical phenomena to derive a solution. Examples of this approach are gradient-based information diffusion [21] and pheromone trail routing [22]. All things considered, the design of efficient routing protocols for sensor networks remains an active area of research.

2.6 Transport

Given the relatively large packet error rates that can be encountered when operating in the ISM band, end-to-end reliable transport in wireless sensor networks requires transport and congestion control protocols tailored to the system requirements. Reliability of data transfers is expected to be provided at the upper layers of the protocol stack through acknowledgements and retransmissions rather than via complex error control coding at the physical layer.

Wireless sensors can also take advantage of system redundancy to provide robust performance and reduce transmit energy. Because very large numbers of sensing devices are deployed more densely than required, devices can reduce or combine information from multiple nodes based on their location to reduce and compress data transmission requirements [23].

2.7 Applications

Crucial to the success of the vision also lies in the development of compelling applications. Currently, a variety of research activities in government, academia and industry are underway, stemming from a variety of applications envisioned. DARPA envisions using distributed sensors deployed by the thousands in battlefields to detect the presence of enemy tanks. Scientific users hope to enable widespread environmental monitoring and collection of experimental data. Manufacturers could use the technology to sharply reduce the cost of wired sensors in factories [24], and warehouses could use location sensors to actively track inventory. Sensors in automobiles could react to traffic jams and pass messages to others warning them to take different routes. Consumers could benefit from devices that showed them where to find their keys, where they parked their car, where their camera is and if it needs film, and if they need to water their plants. The sheer numbers of cooperating devices envisioned and the specific requirements in terms of cost and energy efficiency require revolutionary solutions in areas ranging from microfabrication integration to energy efficient self-organizing networking.

3 Prototyping Activities

Prototypical devices featuring sufficient processing power to support a proof of concept have been developed as an integral part of Motorola's neuRFon^{TM} research initiative. Following a trend in rapid prototyping, devices are built using Commercial Off-The Shelf (COTS) technology. As illustrated in Figure 2 our hardware consists of a low-power microprocessor, a low-power radio transceiver, a packet controller, external memory, and a sensor suite.

Our approach is based on a modular design consisting of a collection of stackable custom boards. Careful attention was paid at all levels of the design to achieve energy efficient operation, a tenet also advocated by the designers of other experimental testbeds for wireless sensor networks [25] [26] [27] [28] [1].

While our testbed is currently being used to support experiments in self-organization, Ad Hoc networking and context-aware computing, in this paper we will focus on position location as it is our belief that it is a fundamental application enabler. The following section deals with position location technology.

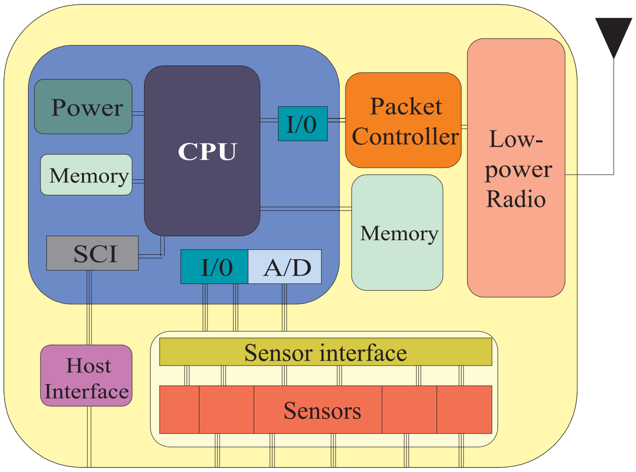

Figure 2. Functional diagram of a neuRFon^{TM} device.

4 Location Estimation

Knowing the location of the devices in an ad hoc network is very important. For ad-hoc networking, researchers have proposed using location information for routing purposes [29]. Location of individual sensors allows distributed data fusion algorithms to condense information based on position. Sensors that know their location can coordinate to perform localized sensor array processing tasks [30]. For military, police, or fireman radio networks, knowing the precise location of each person with a radio can be critical. In offices and in warehouses, object location and tracking solutions are finding a large market. Finally, for wireless sensor networks, knowledge of sensor location is critical. Actuators can respond locally to a stimulus if the location of the stimulus is known. In human-moderated systems user interfaces will have a map of the reported data. Because of the density of devices it is objectionable to require users in the set-up phase to enter the location of each device. To achieve true zero-configuration networks, automatic location determination becomes an essential capability.

The Global Positioning System (GPS) has been suggested as a means to obtain location information in ad-hoc networks [29] [1]. For outdoor applications in which device density is low, and cost is not a major concern, GPS is a viable option. However, adding GPS capability to each device in a dense network is expensive. Furthermore, achieving high accuracy from GPS requires use of differential techniques.

Local positioning systems (LPS) deploy a grid of RF base stations that communicate with devices and then triangulate to determine their locations based on received signal strength (RSS), time difference of arrival (TDOA), or time-of-arrival (TOA) technologies [31]. In LPS, devices communicate only with fixed base stations. When one device is to be located, a network of base stations calculates the position of the single device based on range measurements made in one or more device-to-base station links. Such an idea could be used in a large scale sensor network in combination with GPS. Since the cost of including GPS capability in every node would be too expensive, GPS could be included in just a fraction of devices [32]. Devices without GPS would range themselves to the devices with GPS functionality. However, as the fraction of GPS functionality decreases, the range of the devices must be larger, and the power drain at the GPS-functional device increases.

Another way to obtain relative location in a network is to use pair-wise range estimates made between all devices. In [33] and [34] range estimates are used to draw lines between pairs of devices. One difficulty using these geometric methods is that as more and more devices are added into the location map, the range errors can add onto each other. In [34], a residual weighting algorithm from [35] is used to remove TOA ranges that appear to be due to non-line-of-sight (NLOS) errors. All possible combinations of estimated ranges are tested to find a MSE solution. But in a peer-to-peer network, the possible combinations of pair-wise ranges will rise very rapidly with increasing numbers of devices. Another method uses a maximum likelihood method, using all measured pair-wise range estimates and a few known coordinates as inputs, to estimate the location of devices in a network [36]. This algorithm is implemented in the prototype presented in Section 3.

4.1 Range Estimation

In an ad-hoc wireless sensor network, there will likely be no fixed infrastructure available to synchronize devices. Since range estimates must be made with asynchronous devices, TOA ranging uses two-way delay methods [37] [38]. In two-way TOA, the range estimate will be degraded by the multipath and noise in the channel and the inaccuracies of device reference clocks. The errors due to multipath can be reduced by using very wide bandwidths or radar-like technologies such as ultra-wideband (UWB). However, the range estimate is limited by clock inaccuracies, which can be brought down by using expensive low parts-per-million (PPM) and low phase noise oscillators. For dense networks of low cost, low power wireless devices, it would be advantageous if RSS could be used to make range measurements. RSS can be implemented in simple devices. Although traditionally seen as a crude distance estimator, RSS is less inaccurate at short ranges. The application and device density will determine the ranging technology, but for applications in which inter-device distances are smaller than the desired location accuracy, RSS will be a viable ranging technology. For other applications in which accuracy is an overwhelming priority, UWB techniques may prove essential.

5 Conclusions

Technological advances are making ultra low-power, low-cost wireless devices on a chip feasible. In order to achieve a vision of pervasive wireless sensor networking researchers must address many technological challenges. This paper provides an overview of key research areas in academia, government, and industry, with a slant toward position location. It is our position that position location is a key application enabler. Research into accurate location techniques, free of infrastructure, will translate into greater ease of installation and usefulness of sensor data. Paramount to the success of the wireless sensor network concept is achieving unprecedented end-to-end energy efficiency across all layers of the system architecture. Integral to achieving this goal is the development of experimental testbeds, as they are invaluable to the exploration of the the design space and the minimization of technical risks. As implementations reduce in size and energy consumption, prototypes will demonstrate compelling applications and point in new directions for further applications. While many challenges lie ahead, there are great opportunities for those who share the vision to bring this concept to fruition.

References

[1] M.G. Corr and C.M. Okino. Networking reconfigurable smart sensors. In *SPIE International Symposium on Enabling Technologies for Law Enforcement and Security*, volume 4232, Nov. 2000.

[2] UCLA. Wireless Integrated Network of Sensors (WINS). http:\\www.janet.ucla.edu\WINS\.

[3] MIT. MicroAMPS (μAMPS). http:\\www-mtl.mit.edu\research\icsystems\uamps\.

[4] Berkeley. PicoRadio. http:\\bwrc.eecs.berkeley.edu\Research\Pico_Radio\Default.htm.

[5] Berkeley. SmartDust. http:\\www-bsac.eecs.berkeley.edu\~pister\SmartDust\.

[6] G. Asada, M. Dong, T.S. Lin, F. Newberg, G. Pottie, W.J. Kaiser, and H.O. Marcy. Wireless integrated network sensors: Low power systems on a chip. In *Proceedings of the 1998 European Solid State Circuits Conference*, 1998.

[7] C. T.-C. Nguyen. Micromechanical components for miniaturized low-power communications. In *1999 IEEE MTT-S International Microwave Symposium RF MEMS Workshop*, pages 48–77, June 1999.

[8] A. Chandrakasan and et. al. Design considerations for distributed microsensor systems. In *Proceedings of the 1999 IEEE Custom Integrated Circuits Conf.*, pages 279–286, May 1999.

[9] Berkeley. TinyOS. http:\\www.cs.berkeley.edu\~jhill\papers\tos.pdf.

[10] A. Sinha, A. Wang, and A. Chandrasakan. Algorithmic transforms for efficient energy scalable computation. In *Proceedings of the International Symposium on Low Power Electronics and Design*, pages 31–36, July 2000.

[11] Federal Communications Commission. *Code of Federal Regulations, Title 47*. Government Printing Office, Oct. 2000.

[12] IEEE. 802.15 $WPAN^{TM}$ Task Group 4. http:\\www.ieee802.org\15\pub\TG4.html.

[13] J. M. Rabaey, M. Josie Ammer, Julio L. Jr da Silva, Danny Patel, and Shad Roundy. PicoRadio supports ad hoc ultra-low power wireless networking. *IEEE Computer Magazine*, 33(7):42–48, July 2000.

[14] H. Woesner, J. Ebert M. Schlager, and A. Wolisz. Power saving mechanisms in emerging standards for wireless LANs: The MAC level perspective. *IEEE Personal Communications Magazine*, 5(3):40–48, June 1998.

[15] G. Girling, J. Kam Wa, P. Osborn, and R. Stefanova. The design and implementation of a low power ad hoc protocol stack. In *IEEE Wireless Communications and Networking Conference, 2000*, volume 3, pages 1521–1529, Sept. 2000.

[16] K. Sohrabi, J. Gao, V. Ailawadhi, and G.J. Pottie. Protocols for self-organization of a wireless sensor network. *IEEE Personal Communications Magazine*, 7(5):16–27, Oct 2000.

[17] E. Royer and C.-K. Toh. A review of current routing protocols for ad hoc mobile wireless networks. *IEEE Personal Communications Magazine*, 6(2):46–55, April 1999.

[18] W.R. Heinzelman, A. Chandrakasan, and H. Balakrishnan. Energy-efficient communication protocol for wireless microsensor networks. In *IEEE Hawaii International Conference on System Sciences*, Jan 2000.

[19] R. Ramanathan and R. Rosales-Hain. Topology control of multihop wireless networks using transmit power adjustment. In *IEEE INFOCOM*, volume 2, pages 404–413, March 2000.

[20] P. Gupta and P.R. Kumar. The capacity of wireless networks. *IEEE Trans. on Information Theory*, 46(2):388–404, March 2000.

[21] C. Intanagonwiwat, R. Govindan, and D. Estrin. Directed diffusion: A scalable and robust communications paradigm for sensor networks. In *International Conf. on Mobile Computing and Networking (MobiCOM 2000)*, 2000.

[22] MIT. Amorphous Computing web page. http:\\www.swiss.ai.mit.edu\projects\amorphous\Network\.

[23] D. Hall. *Mathematical Techniques in Multisensor Data Fusion*. Artech House, 1992.

[24] G.O. Allgood, W.W. Manges, and S.F. Smith. It's time for sensors to go wireless. *Sensors Magazine*, May 1999.

[25] H. Marcy, J. Agre, L. Clare, and N. Romanov. Development platform for self organizing wireless sensor networks. In *SPIE Proceedings*, volume 3713, pages 257–268, July 1999.

[26] Berkeley. PicoRadio Testbed. http:\\bwrc.eecs.berkeley.edu\Research\Pico_Radio\Test_Bed\.

[27] K. A. Delin and S. P. Jackson. Sensor web for in situ exploration of gaseous biosignatures. In *IEEE Aerospace Conference*, volume 7, pages 465–472, March 2000.

[28] A. Mason, N. Yazdi, K. Najafi, and K.D. Wise. A low-power wireless microinstrumentation system for environmental monitoring. In *Proceedings of the International Conference on Solid-State Sensors and Actuators*, volume 1, pages 107–110, June 1995.

[29] Y.-B. Ko and N.H. Vaidya. Location-aided routing (LAR) for mobile ad-hoc networks. In *ACM / IEEE MOBICOM '98*, Oct. 1998.

[30] D. Estrin, R. Govindan, and J. Heidemann. Scalable coordination in sensor networks. Technical report, USC/Information Sciences Institute, USC Technical Report 99-692, 1999.

[31] J. Werb and C. Lanzl. Designing a positioning system for finding things and people indoors. *IEEE Spectrum*, 35(9):71–78, Sept. 1998.

[32] G. J. Pottie. Wireless sensor networks. In *IEEE Info. Theory Workshop 1998*, pages 42–48, June 1998.

[33] Jan Beutel. Geolocation in a picoradio environment. Master's thesis, UC Berkeley, 2000.

[34] S. Capkun, M. Hamdi, and J. P. Hubaux. GPS-free positioning in mobile ad-hoc networks. In *IEEE HICSS-34*, Jan. 2001.

[35] P.-C. Chen. A non-line-of-sight error mitigation algorithm in location estimation. In *IEEE WCNC*, pages 316–320, Sept. 1999.

[36] N. Patwari, Y. Wang, and R.J. O'Dea. Location in wireless networks. In *IEEE Vehicular Technology Conference 2001*, May 2001.

[37] R. Fleming and C. Kushner. Low-power, miniature, distributed position location and communication devices using ultra-wideband, nonsinusoidal communication technology. Technical report, Aetherwire Inc., ARPA Contract J-FBI-94-058, July 1995.

[38] D. McCrady, L. Doyle, H. Forstrom, T. Dempsy, and M. Martorana. Mobile ranging with low accuracy clocks. *IEEE Trans. on Microwave Theory and Techniques*, 48(6):951–957, June 2000.