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A Technology Review of Smart Sensors With Wireless Networks for Applications in Hazardous Work Environments

Department of Health and Human Services
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health

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By John J. Sammarco, Ph.D., P.E., Robert Paddock, Edward F. Fries,
and Vijia K. Karra, Ph.D.

DEPARTMENT OF HEALTH AND HUMAN SERVICES
Centers for Disease Control and Prevention
National Institute for Occupational Safety and Health
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April 2007

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TABLES

UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

A	ampere
bps	bits per second
cm	centimeter
cm^3	cubic centimeter
fps	frames per second
ft	foot
ft^2	square foot
g	acceleration of gravity
GHz	gigahertz
Hz	hertz
in	inch
lb	pound
kbps	thousand bits per second
Kbyte	kilobyte
kHz	kilohertz
km	kilometer
km/h	kilometers per hour
lb	pound
m	meter
mA	milliamp
MB	megabyte
Mbps	million bits per second
MHz	megahertz
mm	millimeter
mm^3	cubic millimeter
mph	miles per hour
ms	millisecond
mW	milliwatt
nA	nanoamp
oz	ounce
sec	second
V	volt
V ac	volt, alternating current
V dc	volt, direct current
µA	microamp

GLOSSARY

Accelerometer: A sensor that measures acceleration. Acceleration can be due to gravity or changing motion. Acceleration is measured in units of Earth's gravity (g) or meters per second squared.

Bluetooth: A technical industry standard that facilitates communication between wireless devices such as mobile phones, personal digital assistants (PDAs), and handheld computers, and wireless enabled laptop or desktop computers and peripherals.

Internet Protocol (IP): The method by which data are sent from one computer to another on the Internet. Each IP-based device has at least one IP address that uniquely identifies it from all other devices.

Internet Protocol Security (IPSec): A security protocol that provides for confidentiality and authentication.

Local area network (LAN): A computer network that spans a relatively small area. Most LANs are confined to a single building or group of buildings. However, one LAN can be connected to other LANs over any distance via telephone lines and radio waves. A system of LANs connected in this way is called a wide area network (WAN).

Machine-to-machine (M2M): Data communications between machines that generally refer to telemetry that is accomplished using networks and wireless networks.

Micro-electro-mechanical systems (MEMS): The integration of mechanical elements, sensors, actuators, and electronics on a common silicon substrate through microfabrication technology. While the electronics are fabricated using integrated circuit process sequences (e.g., CMOS, Bipolar, or BiCMOS processes), the micromechanical components are fabricated using compatible "micromachining" processes that selectively etch away parts of the silicon wafer or add new structural layers to form the mechanical and electromechanical devices [MEMS and Nanotechnology Clearinghouse 2007].

MIMO (multi-in, multi-out): An advanced technology that uses multiple smart antennas to increase range and speeds. The smart antennas constantly survey the environment for physical barriers and interference and adjust the wireless signal to compensate for these performance inhibitors.

Network IP camera: A stand-alone camera with a built-in Web server allowing users to view live, full-motion video over a computer network or the Internet. The camera also contains a CPU and embedded operating system (OS).

Radio frequency identification (RFID): A transponder technology for the contactless recognition of objects. The technology uses an RFID tag—a small computer chip with a miniature antenna. When the chip receives the radio signal from a reading device, it automatically transmits the stored data wirelessly.

Sensor: A device or system that responds to a physical, chemical, electrical, or optical quality to produce an output that is a measure of that quality.

Sensor mote: A small, wireless hardware platform that enables sensors to be wireless. Typically, motes are battery-powered.

Sensor node: A fundamental element (node) of a sensor network that consists of a sensor mote and sensors. A node typically consists of on-board sensors, memory, wireless connectivity, processing power, and a power source.

Smart sensor: A sensor with built-in intelligence, whether apparent to the user or not. The intelligence is partially or fully integrated on a single chip. Smart sensors provide added functionality beyond the primary function of producing an output representing a sensed quantity.

Transducer: A device converting energy from one domain into another and calibrated to minimize the errors in the conversion process.

Ultrawide band (UWB): A radio modulation technique based on transmitting very-short-duration pulses, often on the order of nanoseconds or less, whereby the occupied bandwidth goes to very large values. “Ultrawide band” may also refer to anything with a very large bandwidth.

USB (universal serial bus): A standard interface commonly used to connect peripheral devices to computers.

Wireless fidelity (WiFi): A set of standards for wireless local area networks (WLAN) currently based on the IEEE 802.11 specifications. Also known as WiFi, Wi-fi, Wifi, wifi.

Wireless personal area network (WPAN): A wireless network that serves only the individual wireless user. This type of wireless network usually relates to the Bluetooth technology, a personal network.

ZigBee: A proprietary set of high-level communication protocols designed to use small, low-power digital radios based on the IEEE 802.15.4 standard for wireless personal area networking.

A TECHNOLOGY REVIEW OF SMART SENSORS WITH WIRELESS NETWORKS FOR APPLICATIONS IN HAZARDOUS WORK ENVIRONMENTS

By John J. Sammarco, Ph.D., P.E.,[1] Robert Paddock,[2] Edward F. Fries,[3] and Vijia K. Karra, Ph.D.[4]

ABSTRACT

Workers in hazardous environments such as mining are constantly exposed to the health and safety hazards of dynamic and unpredictable conditions. One approach to enable them to manage these hazards is to provide them with situational awareness: real-time data (environmental, physiological, and physical location data) obtained from wireless, wearable, smart sensor technologies deployed at the work area. The scope of this approach is limited to managing the hazards of the immediate work area for prevention purposes; it does not include technologies needed after a disaster. Three critical technologies emerge and converge to support this technical approach: smart-wearable sensors, wireless sensor networks, and low-power embedded computing. The major focus of this report is on smart sensors and wireless sensor networks. Wireless networks form the infrastructure to support the realization of situational awareness; therefore, there is a significant focus on wireless networks. Lastly, the “Future Research” section pulls together the three critical technologies by proposing applications that are relevant to mining. The applications are injured miner (person-down) detection; a wireless, wearable remote viewer; and an ultrawide band smart environment that enables localization and tracking of humans and resources. The smart environment could provide location data, physiological data, and communications (video, photos, graphical images, audio, and text messages).

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INTRODUCTION

Workers in hazardous environments such as mining are continually exposed to dynamic and unpredictable hazardous conditions. For instance, slipping and tripping hazards are created by mine conditions such as water, mud, uneven floors, and mine floor obstacles. Moving machinery in the confined mine environment creates pinning and striking hazards. These environments also have limited visibility due to line-of-sight restrictions, poor lighting, airborne dust, and smoke. Workers must be able to constantly monitor their hazardous environments in real time so they can be aware of impending and existing dangers.

This report details the current state of the art in smart sensors and wireless sensor network technology and some potential applications for situational awareness in harsh, dynamic environments such as mining. The objective is to enable miners to safely manage the hazards produced by an ever-changing, unpredictable, dangerous work environment by providing them with real-time environmental and physiological data obtained from wireless, wearable, smart sensor technologies. Miners will be able to better manage hazards because smart-wearable sensors could provide the key information needed for early warning of potential and existing hazards. Thus, these technologies could be useful for preventing injuries and disasters. This report does not address in specific detail the topics of intrinsic safety, tracking and locating trapped miners, or communication with trapped miners.

Numerous technologies and references are presented to help create awareness and common understanding of the pros, cons, and application requirements of these technologies. Specifically, a glossary of terms is presented at the beginning of the report, followed by sections on sensors, wireless networking, and wireless sensor networks. Lastly, the “Future Research” section pulls together the technical information by proposing applications that are relevant to mining and that could also potentially cross over to other workers such as firefighters, emergency rescue workers, and other first responders. The applications for future research are injured miner (person-down) detection; a wireless, wearable remote viewer; and ultrawide band localization and tracking of humans and resources.

TECHNICAL APPROACH

As stated earlier, the objective is to enable situational awareness of potential and current health and safety hazards produced by an ever-changing, unpredictable, dangerous work environment. Workers must first be aware of these hazards if they are to safely manage them. Safety must be from a system viewpoint. Safety cannot be assured if efforts are focused on parts of the system because safety is an emergent property of the entire system. Safety emerges once all the parts and interfaces of the system have been identified and integrated.

One of the first steps to safety is defining the system. The system model used in the technical approach is shown in Figure 1, where a system is the collection of a human, machine, and the environment interconnected to perform a desired function. In the context of this report, the system provides a worker with the functionality of situational awareness. The system functionality is depicted by an information-processing model (Figure 2). The key parts of this model are: sensing through the use of sensors that measure key attributes of the machine, environment, and human; information processing (monitoring, collecting, and displaying) through the use of embedded computers; and decision-making and action as done by humans.

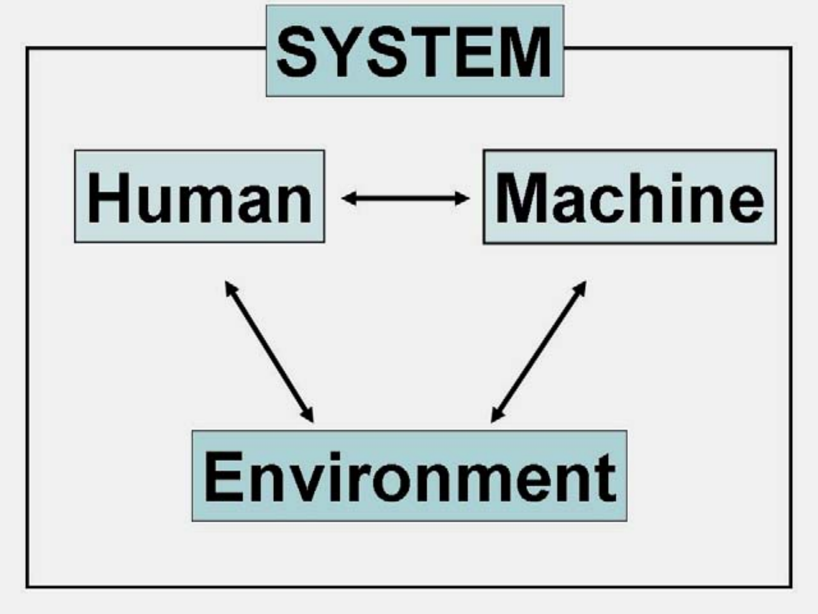


Figure 1.—The system model.

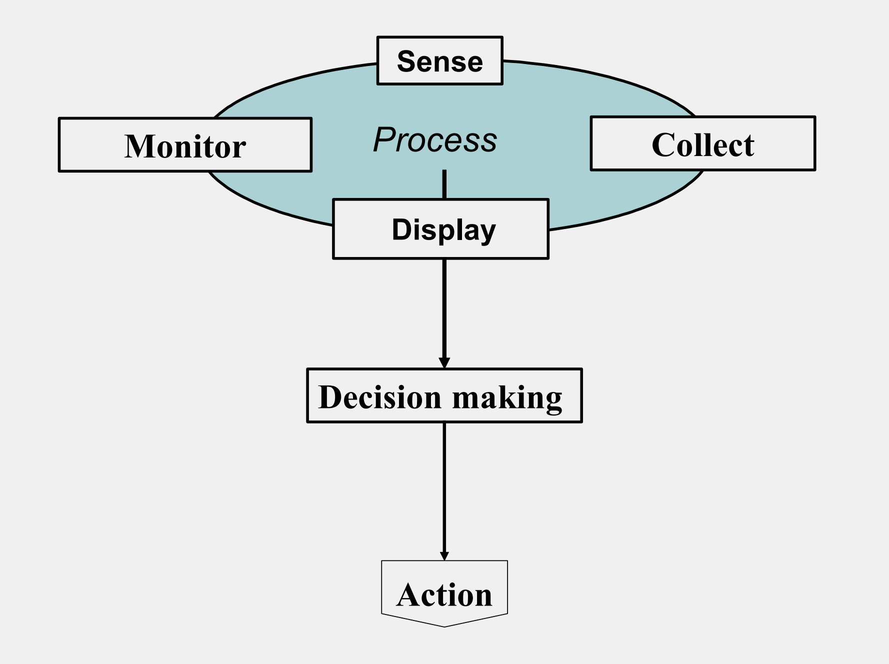


Figure 2.—An information-processing model for sensor-based situational awareness.

Three critical technologies emerge and converge to support this information-processing model. They are wireless networks for sensors, low-power embedded computing, and smart sensors. Computer and smart sensor technologies have advanced rapidly; they are relatively mature technologies. Wireless networks for sensors are still emerging. Robust wireless networks are the key part of an infrastructure to support the realization of wireless smart sensor networks that provide users with situational awareness of their environment. Therefore, this report has placed the greatest focus on wireless networks for sensors. The second major focus is on smart sensors that range in size from a "spec" to a matchbox. Lastly, the "Future Research" section ties together all three technologies by proposing multiple applications that could improve the health and safety of workers in hazardous, dynamic environments.

SENSORS

A sensor is a device or system that responds to a physical, chemical, electrical, or optical quality to produce an output that is a measure of that quality. A simple sensor has two parts: a sensing element and a transducer that converts the sensed quality to a representative signal.

Sensor technology plays a key role in situational awareness. Sensors are needed to measure the critical parameters of the environment, machines, and the human. In this report, sensors are grouped into five classifications:

- Chemical
- Electric, magnetic, electromagnetic wave
- Heat, temperature
- Physical (mechanical displacement)
- Optical

Sensors, regardless of the classification, are characterized by the specification of various parameters. The parameters of importance largely depend on the application. These parameters include:

- Sensitivity
- Stability
- Accuracy
- Hysteresis
- Drift
- Cost, size, weight
- Range (span)
- Resolution
- Linearity
- Environmental (temperature, shock, vibration, etc.)

SMART SENSORS

A sensor with built-in intelligence, whether apparent to the user or not, can be referred to as a “smart” sensor. The intelligence is partially or fully integrated on a single chip. Smart sensors provide added functionality beyond the primary function of producing an output representing a sensed quantity.

Typically, a smart sensor contains a physical transducer, a network interface, a processor, and a memory core that can all be fabricated on a single die [Kovacs 1998; Frank 2000]. The physical transducer can be made very small because silicon micromachining technology that is used to make integrated circuits is now being used to create micro-electro-mechanical systems (MEMS) that can be an integral part of a smart sensor.

It is anticipated that the cost and functionality of smart sensors will progress at rates similar to those experienced by other integrated circuits, such as microprocessors and memory, because smart sensors use much of the same technology [Frank 2000]. Smart sensor growth should also increase now that a smart sensor standard is in place.

SMART SENSOR STANDARD

The smart sensor standard, Institute of Electrical and Electronics Engineers (IEEE) 1451.2–1997, was developed to define a flexible, standard interface that would enable any smart sensor from any manufacturer to connect to a multinode network of smart sensors [IEEE 1998]. The standard defines a standard transducer interface module (STIM) that includes the sensor interface, signal conditioning and conversion, calibration, linearization, and network communication. In essence, IEEE 1451.2–1997 enables plug and play functionality for smart sensors that connect to smart sensor networks.

BODY SENSORS

Wearable body sensor systems are available to continuously measure and monitor the physiological conditions of workers in real time. BodyMedia has produced a wearable body sensor system (Figure 3) that acquires, analyzes, transmits, and stores physiological data such as energy expenditure, duration of physical activity, number of steps, distanced traveled, sleep/wake states, movement, heat flux, skin temperature, and galvanic skin response.

The system is used mainly as a health and safety research tool. For instance, PPG Industries used the BodyMedia system to monitor the activity level and energy expenditure trends of their shift workers. The data obtained were used to reduce job-related fatigue and improve the ergonomic design of equipment. Fatigue is a significant health and safety hazard for shift workers in general, but it is of special concern for miners who must keep alert to recognize moving machinery hazards, trip/slip hazards, and potential falls of ground from the roof, ribs, and back areas.

The BodyMedia system has applications beyond that of a research tool. For instance, the system can monitor workers and alert them of potentially dangerous physiologic conditions from overexertion. This same application crosscuts to first responders such as firefighters who, while wearing protective equipment, expend large amounts of energy for sustained periods in hazardous atmospheres of heat and smoke. The BodyMedia system can also be used in person-down applications. The physiological data can be used to indicate that a person has become incapacitated because of an accident or a health condition. The system would then wirelessly alert other workers or rescue personnel of the worker’s condition.

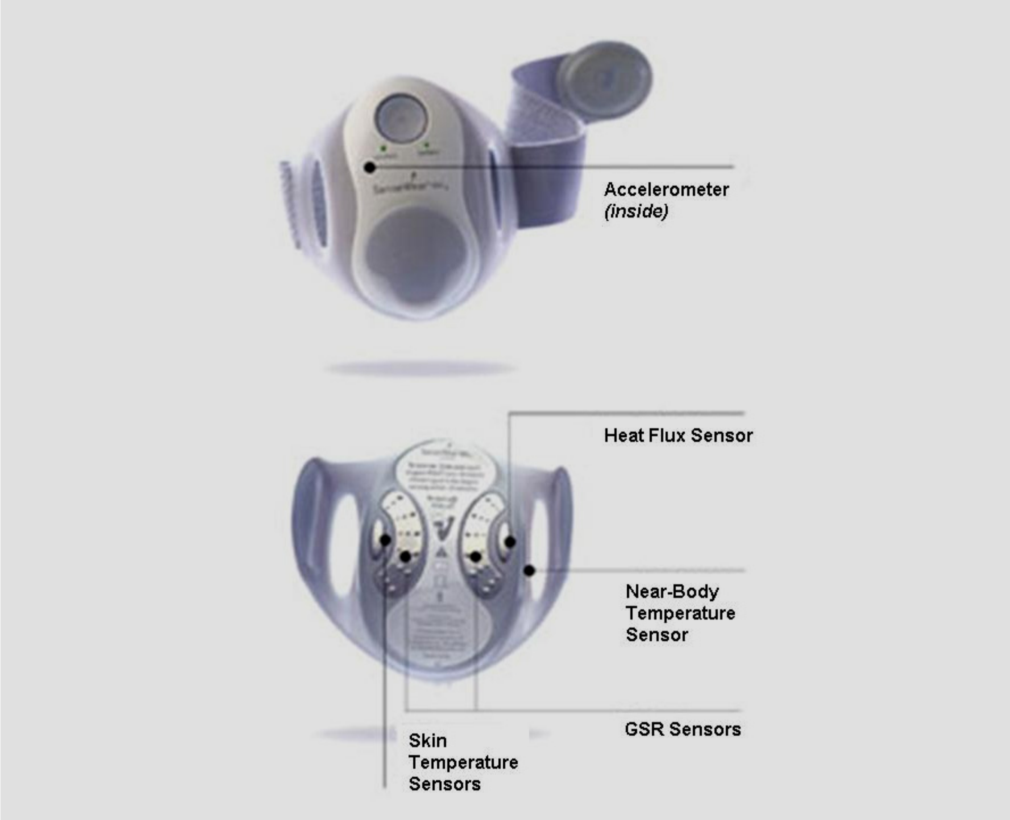


Figure 3.—Sensors incorporated into the SenseWear® PRO$_2$ armband. ***(Image courtesy of BodyMedia.)***

BODYMEDIA SYSTEM DESCRIPTION

The major features include the following:

- Can be worn up to 14 days continuously without changing the battery
- Stores up to 14 days of continuous physiological data
- Allows users to time-stamp specific events
- Compatible with BodyMedia InnerView™ software
- Eliminates the need to apply cumbersome sensors to research subjects

The heart of the system is the SenseWear® PRO$_2$ armband that is worn on the back of the upper right arm. The battery-powered device contains a dedicated sensor ensemble that is useful for the direct and indirect measurement of physiological data. The sensors for direct measurements (Figure 3) are listed below:

- Accelerometer (two-axis)
- Heat flux
- Galvanic skin response
- Skin surface temperature
- Near-body temperature

The sensor data can be used for indirect measurements. This is possible via the use of virtual sensors, sensor fusion, digital signal processing, and Kalman filtering. Derived measurements include:

- Total calories burned
- Duration of physical activity
- Number of steps
- Resting energy expenditure
- Active energy expenditure

SENSOR NODES AND SMART ENVIRONMENTS

Sensor nodes are critical elements of a smart environment to protect the health and safety of miners during operation and in emergency situations. Figure 4 depicts a smart mine environment that can provide interactivity and situational awareness of the mine environment, machinery, and people. Sensor nodes are used in this smart mine environment to provide communication and to acquire data about mining machine postion, mine roof and rib conditions, crosscut traffic, the location and status of miners, and the mine atmosphere such that the data can be used to alert miners of health and safety hazards during operation. For instance, the smart environment would automatically provide an alert that a miner has been struck by falling roof even though the miner is incapacitated. This application is detailed later in this report. The functionality of this smart environment could be expanded to help miners find the best escape route or find other miners in emergency situations, especially when smoke obscures visibility.

Limited or even zero visibility environments are also common to firefighters. A smart building environment could provide health and safety functions similar to that of a smart mine environment. Firefighters could find escape routes even under zero visibiltiy, or they could locate fallen firefighters who are unable to communicate their condition or location.

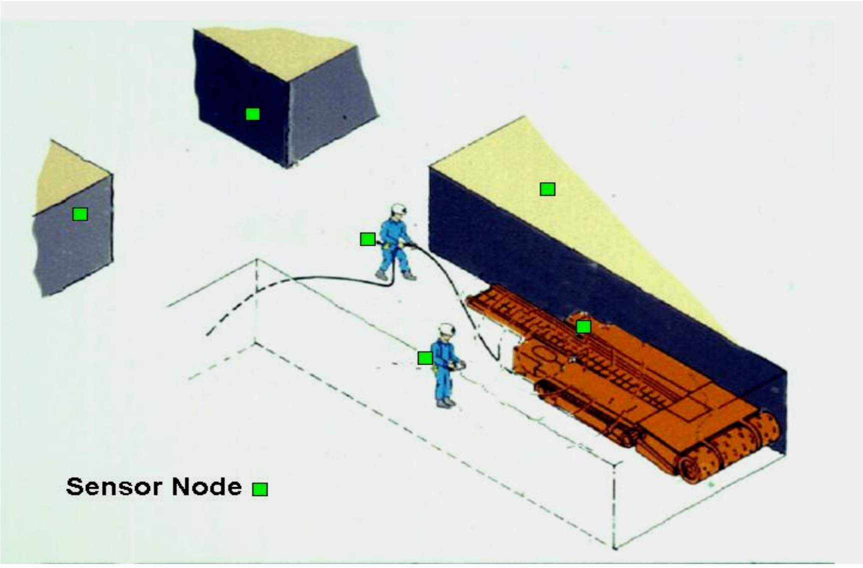


Figure 4.—A mesh network of wireless sensor nodes can be used to create a smart mine environment to protect the health and safety of miners during operation and in emergency situations.

A sensor node consists of a mote and sensors, as shown in Figure 5. Nodes typically have on-board processing power, on-board memory, wireless connectivity, sensors, and a small battery power source. A mote is a small, wireless hardware platform that enables sensors to be wireless. Motes can be highly specialized or general purpose; they can be of low bandwidth to support the transfer of limited data or high bandwidth to support the transfer of streaming video, graphics, and audio.

The MICAz (Figure 6) is a commercially available, high-bandwidth sensor mote from Crossbow Technology, Inc. It enables the creation of low-powered, wireless sensor networks that can collect data on physical and environmental properties such as temperature, acceleration, and vibration. The mote is small and battery-operated for use in wearable sensor applications. The power requirements are very low, making the motes a good choice for use in hazardous environments. The MICAz mote with its associated software also complies with the ZigBee protocol standard.

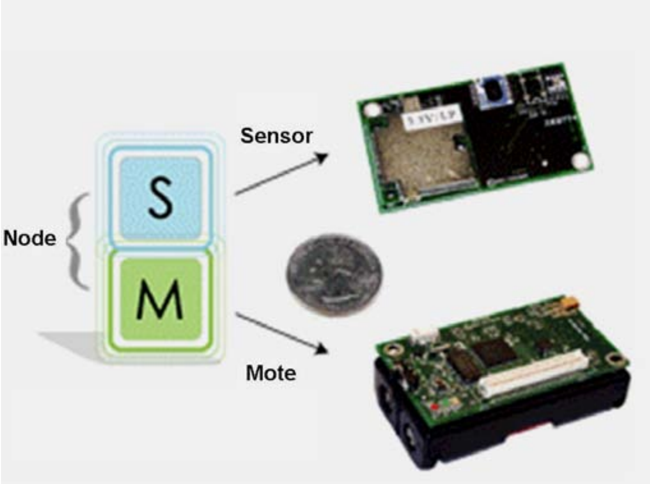
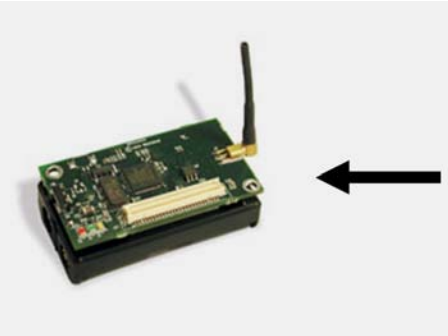


Figure 5.—A sensor node is composed of a sensor(s) and a mote. ***(Image copyrighted by Crossbow Technology, Inc., and reprinted with permission.)***



Name and size	MICAz, 1–10 cm^3
Applications	High bandwidth sensing such as image transfer, audio, and vibration
Radio data rate	<500 kbps
MIPS	<50
Flash	<10 MB
RAM	<128 kB
Energy usage (typ.)	3 V × 60 mA
Sleep energy (typ.)	3 V × 100 µA
Duty cycle (typ.)	5%–10%

Figure 6.—The MICAz mote specification. ***(Image copyrighted by Crossbow Technology, Inc., and reprinted with permission.)***

Sensor motes are rapidly developing in terms of size and cost reduction, and increasing functionality. For instance, the next-generation MICAz mote will be offered in a much smaller physical package. Figure 7 depicts this new mote, which is about the size of a postage stamp, yet it has the same functionality as the MICAz mote and lower power requirements. Smaller motes such as the "Spec" shown in Figure 8, also called smart dust, are available now; however, these motes are extremely limited in terms of functionality and bandwidth. The Spec can be used as an advanced, low-cost, radio frequency identification (RFID) tag. The small size enables these motes to be embedded virtually anywhere; the low cost makes them a disposable item that can be left behind. Size and cost reductions will drive its widespread usage. Some of the key features include the following:

- Lifetime longer than 3 years
- Size smaller than 1 mm^3
- Price less than 15 cents

Sensors are the other part of a sensor node. They too are rapidly developing in terms of size, cost, and functionality. For instance, a MEMS dual-axis acceleration sensor, shown in Figure 9, is featured in a "person-down" application described later in this report.

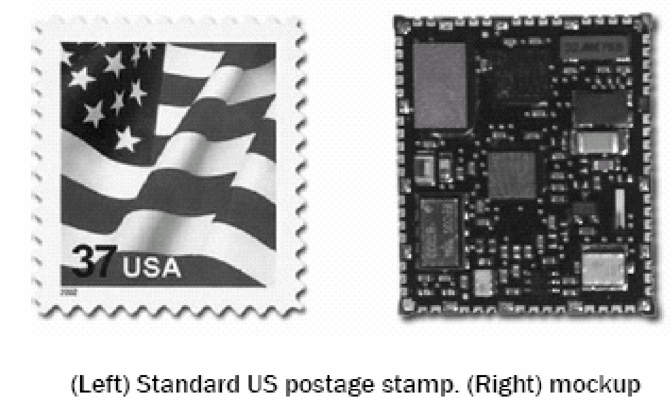


Figure 7.—The next-generation mote from Crossbow Technology, Inc. ***(Image copyrighted by Crossbow Technology, Inc., and reprinted with permission.)***

Name and size	“Spec”, mm^3
Applications	Specialized, single-purpose sensor, or advanced RFID tag
Radio data rate	<50 kbps
MIPS	<5
Flash	<0.1 MB
RAM	<4 kB
Energy usage (typ.)	1.8 V × 10 to 18 mA
Sleep energy (typ.)	1.8 V × 1 μA
Duty cycle (typ.)	0.1%–0.5%

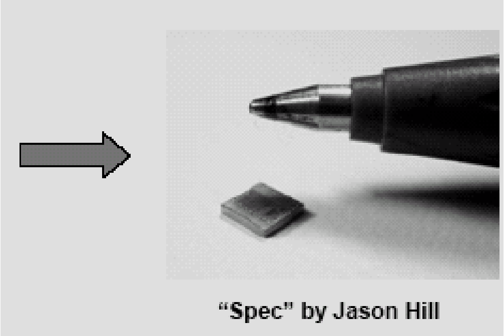


Figure 8.—Highly specialized motes such as the "Spec" can be used as an advanced RFID tag. The small size makes wearable sensor nodes practical. ***(Image copyrighted by Crossbow Technology, Inc., and reprinted with permission.)***

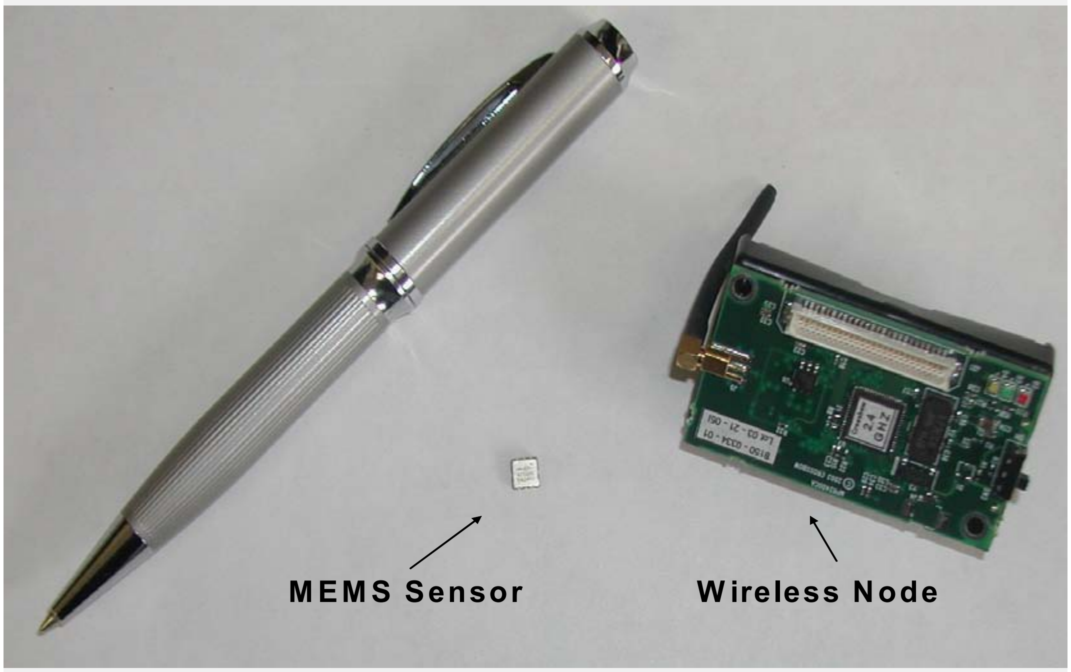


Figure 9.—MEMS sensors can be extremely small. This sensor measures acceleration.

COMMERCIAL SENSOR NODES AND NETWORKS

Commercial wireless sensor nodes and networks are becoming available and will also continue as an area for research [Culler et al. 2004]. Sensor nodes can be purchased as part of complete wireless sensing systems that contain tools for development and prototyping. Crossbow Technology, Inc., offers an extensive line of wireless sensing systems, kits, nodes, and motes. Other systems include:

- Ambient Systems µNode
- Intel iMote
- Microstrain X-link
- Caiser from Cambridge Silicon Radio
- Ember motes
- Lynx Technologies motes

HUMAN INTERFACES

Wearable wireless sensor ensembles can be used to provide a wealth of continuous, real-time data that can be used to communicate the health and safety of people, the location and identification of people and critical assets, and the state of the environment. All the data acquired and processed by wearable wireless sensor ensembles can be useless unless the data can be quickly and richly conveyed to people without encumbering those people to obtain and view the data. Therefore, the human interface is a vital part of the system.

WEARABLE DIGITAL DISPLAYS

Wearable digital displays can provide the equivalent of a desktop monitor or a personal digital assistant (PDA) screen, yet they are small, lightweight devices that can be worn. For instance, the M920–CF video display by Icuiti Corp. weighs only 3.5 oz, yet it provides a video display equivalent to a 1-in color monitor.

Wearable digital displays are also known as head-mounted displays, helmet-mounted displays, and personal monitors. These displays are grouped into three categories:

- See-around displays – Provide visual information without obstructing the user’s view of the surroundings or task at hand.
- See-through displays – Superimpose images onto the user’s panoramic view. Applications include entertainment, military operations, and maintenance support.
- Immersive displays – Typically used for training and entertainment applications, such as for simulators and virtual reality.

The see-around displays are the most practical for people working in hazardous environments. These displays allow hands-free operation and they do not obstruct the user’s view; thus, see-around displays are the primary focus here.

DISPLAY TECHNOLOGY

Kopin Corp. is a leading developer and manufacturer of ultrasmall, high-density imaging devices for consumer, industrial, and defense systems. The Kopin CyberDisplay (Figure 10) is a rugged, robust display that is well suited for harsh, demanding environments such as those found in mining and first-responder applications. This is the microdisplay standardized for the U.S. military.

The color and monochrome CyberDisplays use nanotechnology to make active-matrix liquid crystal displays (AMLCDs). This technology helps enable the highest resolution and performance available today for AMLCDs. The CyberDisplay is incorporated in numerous commercially available wearable display products.

Figure 10.—The Kopin CyberDisplay. ***(Image courtesy of Kopin Corp.)***

COMMERCIALLY AVAILABLE WEARABLE DISPLAYS

There are many commercially available wearable display products available today; however, those from MicroOptical Corp. and Icuiti Corp. seem well suited to harsh environment applications because they are used for harsh and rugged military applications as opposed to other displays used for home entertainment and commercial products such as cameras, cell phones, and video recorders.

MicroOptical Corp.

MicroOptical Corp. offers two categories of wearable displays: VGA viewers (Figure 11) and video viewers [MicroOptical 2007]. Both viewers can be mounted directly to existing eyewear such as prescription glasses or safety glasses. The viewers can be mounted for left-eye or right-eye viewing.

The SV–6 PC is a VGA viewer. The key specifications are as follows:

- Display:
  - VGA LCD panel
  - 640 × 480 resolution in true color
  - Field of view: 16º horizontal, 20º diagonal
  - Image appears as if projected at a distance of up to 15 ft
  - Independent focus of 2–15 ft
- Weight: 2.5 oz
- Display interfaces:
  - Compact Flash Type II
  - PCMCIA via optional adapter
  - Windows® Pocket PC® 2000–2003
- Video input formats:
  - VGA, SVGA, XVGA
  - 18-bit color

Figure 11.—The SV–6 PC viewer mounted to safety glasses. ***(Image courtesy of MicroOptical Corp.)***

Icuiti Corp.

Icuiti Corp. also offers a VGA display, the Icuiti M920–CF, and a digital video display, the Icuiti M920–VIDEO. Both displays are see-around displays that can be worn with protective equipment such as safety glasses and hardhats (Figure 12). Both interface to a wide variety of devices such as pocket PCs, laptop PCs, portable media players, and video cameras (Figure 13). Currently, the displays use a single-wire connection. Future plans by Icuiti are to provide a wireless model.

The key specifications of the Icuiti M920–CF are as follows:

- Display:
  - VGA LCD panel (920,000 pixels)
  - 640 × 480 resolution in true color
  - 26° field of view
  - Image appears as if projected at a distance of 11 ft
  - Independent focus
- Weight: 3.5 oz
- Display interfaces:
  - Compact Flash Type II
  - PCMCIA Via optional adapter
  - Windows® Pocket PC® 2000–2003
- Video input formats:
  - VGA
  - 16-bit color

Figure 12.—The M920–CF does not obstruct the user's frontal or peripheral line of sight.

Figure 13.—The Icuiti M920–CF interfaces to pocket PCs.

WIRELESS INFRASTRUCTURE

This section gives an overview of wireless technologies and wireless sensor networks. Wireless devices are constructed with three major sections: (1) data acquisition, (2) data transportation, and (3) data presentation. Data acquisition is the acquiring of data of interest. The data may be physiological data, such as a person's heart rate, or data on the environment, such as gas level concentrations. Data transportation is moving data items of interest from a source device, such as a gas sensor, to a destination device, such as a display or database. Data presentation is the displaying or annunciation of the acquired data in some usable form.

The focus in this section is on data transportation. The underlying networking topologies are addressed, as well as the tradeoffs of each wireless technology with respect to physical size, data rate, and power consumption. Also addressed are a brief introduction to RFID and the problems of location awareness, i.e., the ability to know the location of an object in three-dimensional (3–D) space.

INTRODUCTION

Emerging wireless networking technologies are opening up opportunities for new systems, achieving significant cost savings in equipment design and maintenance, as well as significant reductions in time-lost incidents due to injuries, in mining operations.

When a machine operator uses a wired control pendant, he or she must be constantly aware of the tangle and tripping hazards presented by the wires. Full concentration is not focused on the task at hand. By removing the wires from the proximity of operators, the tripping and tangle hazards are removed, allowing the operator to fully concentrate on the task at hand, thereby increasing productivity. Also, data transmitters worn by the operators can act as personal "shield" devices that automatically shut down equipment when the operator enters an unsafe location, such as a pinch or pinning area. Emerging ultrawide band (UWB) technology now allows for personal/asset tracking applications that were impossible to implement less than 2 years ago.

Significant reductions in maintenance downtime can be achieved by replacing the notoriously weak links of cables and connectors with wireless devices. Once the connectors are removed from equipment, it becomes easier to seal, leading to less downtime.

Device costs may be significantly reduced by removing displays from equipment that are often hard to read and in dangerous locations. The displays are replaced by a single display device, such as a PDA-style device, carried by the operator. Virtual displays allow for easy-to-use operator interfaces, while keeping the device node cost low. This is because each device no longer has to include the cost of the physical display and related packaging issues. The PDA-like device becomes an easy-to-update diagnostic/control device, while simultaneously removing the need to continually update the wireless device nodes throughout the mine.

A network of wireless sensors can gather environmental data during mine operations to demonstrate compliance and real-time status information, as well as during and after mine reclamation processes.

In the ideal world, it would be possible to transmit an infinite amount of data in zero amount of time while consuming no energy to accomplish the task. In the real world, there are tradeoffs that must be made among data rates, energy consumption, physical size, security, and costs of units. These tradeoffs have resulted in a number of different, usually incompatible, network systems that optimize certain attributes at the expense of the others.

Conceptually, networks are constructed of physical and logical layers, typically seven. Most commonly used is the Open Systems Interconnection Seven-layer Reference Model [Wetteroth 2002]. Layer 1 of the reference model deals with the physical real world, with physical hardware such as wires, radio hardware, or optical systems. The remaining layers implement a protocol stack. A protocol stack is two or more layers of software and hardware that build upon each other to form a system that manages the data flow of a communication channel according to the rules of a particular protocol.

A number of different protocol stacks have been created to solve different problem domains. Some stacks have been optimized for lower power/low data rates; others have been optimized for high data rates with no consideration to energy consumption. Later in this report, a number of wireless protocol stacks will be summarized and their application to wireless sensor networks in a mining environment described.

NETWORK COMPOSITION

Networks are composed of a number of devices called nodes. The nodes are arranged in various configurations, such as master/slave networks, mesh networks, peer-to-peer networks, star networks, or ring networks.

There are two general types of networks or combination of the two types: peer-to-peer networks and master/slave networks. In a peer-to-peer network, all nodes are equal in terms of priorities; they will negotiate with each other to determine which gets control of the network at any given moment. In the master/slave topology, the master node directs all network activity. It directs which slave may access the network at any given time.

In a star network (Figure 14), the slave nodes are connected solely to a fixed master node that directs slave node communication. The master will relay messages between the slave nodes as required. Star networks are the easiest to set up and manage; however, they have a single-point failure problem in that if the master node goes down, the entire network goes down.

In a ring network (Figure 15), the master is not a fixed node. Each node becomes a master by passing a “token.” The node that has the token is the master until it relinquishes the token to the next node in the ring. In a single-direction ring topology, a break in two sections of the network disables the network. In a bidirectional ring topology, the token may flow in both directions, clockwise or counterclockwise. This gives redundancy to the network even if both connections are down between two adjacent nodes because one node can loopback the clockwise traffic toward the counterclockwise connection and the other node can loopback the other way around. Therefore, the logical ring remains intact and the network remains functional. However, the network speed may be reduced as the time it takes the token to transverse all of the nodes increases. For instance, it would take one “hop” to go from node 1 to 2 in an intact bidirectional ring topology; however, multiple hops are needed if there is a break between nodes 1 and 2. While the number of nodes remains fixed, the number of hops changes with damage to the ring, thus decreasing performance.

A new standard of networking is beginning to emerge for wireless sensor networks known as mesh network (also called multihop networks) (Figure 16). It is so named because it appears as a mesh fishing net when lines are drawn between each node to the neighboring nodes. Unlike a conventional network, a mesh network does not have a central computer that orchestrates communication with the nodes. Each node acts as a router for the neighboring nodes. The concept would be like having a cell phone network with no towers. As long as there are cell phones between the phone placing the call and the destination phone, each phone along the way passes on the phone call data.

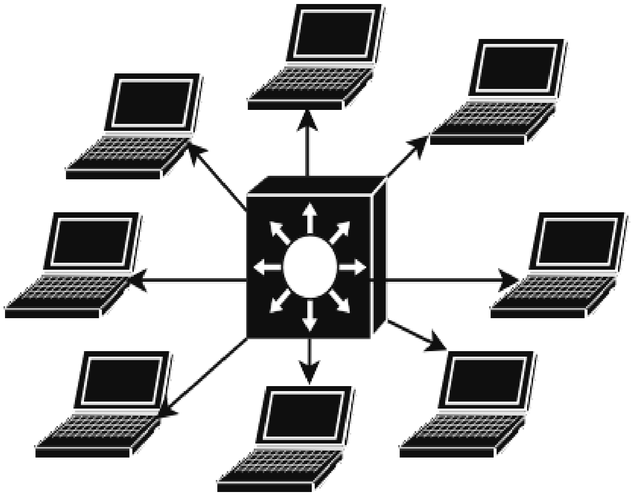


Figure 14.—Star network topology.

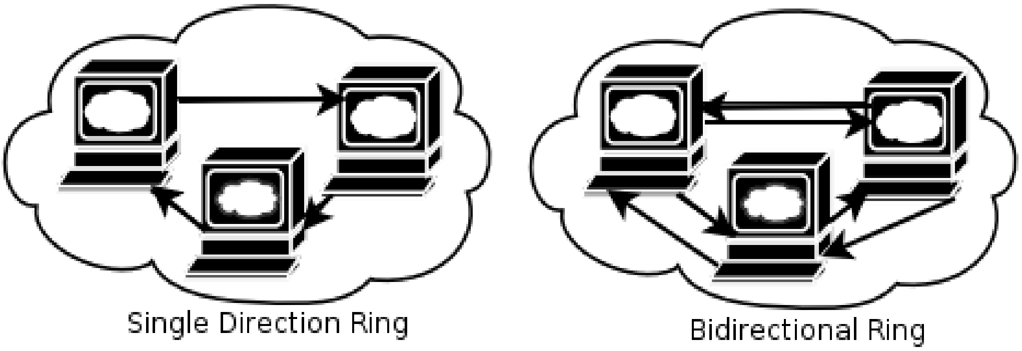


Figure 15.—Ring network topology.

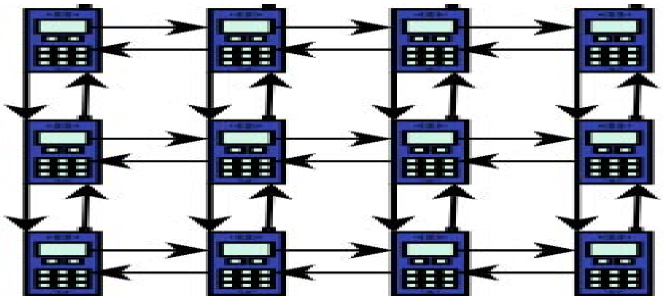


Figure 16.—Mesh network topology.

Mesh networking is particularly suited to machine-to-machine (M2M) and wireless networks, allowing for instant growth in an unpredictable, constantly changing environment such as a mine.

Typically, nodes are as small as the technologies will allow, but in Portsmouth, U.K., the city buses comprise the nodes of the network that allow passengers to check arrival times at the bus stop [Rupley 2004]. Mining vehicles acting as nodes can act as relay stations for smaller nodes, as well as report on their own position to a central control system. Data gathered from position reports may be analyzed to locate traffic bottlenecks, which, once removed, lead to increased production.

A mesh network has two subdivisions: full-mesh topology and partial-mesh topology. In the full-mesh topology, each node is connected directly to each of the others. In the partial-mesh topology, some nodes are connected to all the others, but some of the nodes are connected only to other nodes with which they exchange the most data.

It would be a waste of bandwidth for each node to talk to each of its adjacent nodes for every data transaction, so each node keeps some sort of routing table that tells it to which of its neighbors a packet with a particular address should be forwarded. Networks can be either fixed, where the number and connection of the individual nodes are generally static, or fixed in place. However, the connections and number of nodes can change if a node is switched off. An ad hoc network differs in that the routing will dynamically change or adapt as its nodes experience changes, such as being physically moved.

Mesh networks have the capability to provide:

- Effortless installation of a communications infrastructure
- Enhanced reliability via route redundancy
- Extended distance and communication speed
- Extensions of network coverage without increasing transmit power or receive sensitivity
- Increased speed
- Low power
- Resiliency, with no single point of failure
- Self-configuration, self-diagnostics, and self-healing

Interference and other factors that lead to the loss of data increase as distance increases. Mesh networks increase bandwidth and robustness of the network using multiple short hops. Also, little power is required to transmit signals over short distances, allowing for the overall network power to exceed the Federal Communications Commission (FCC) limitations on the maximum transmission power levels of a single transmitter. The analogy is the difference between a shout and a whisper.

Mesh networks can perform multihop firmware field upgrades either over the air or through other nodes within a logical mesh network. This is crucial in maintaining the firmware integrity of large networks. This upgrade feature is particularly useful in mining environments where the unit must remain sealed and may be in locations difficult to access. However, the ability to do over-the-air upgrades also opens the network up to potential compromise by viruses unless security issues are considered as part of the system safety design.

Currently, there are no standards governing mesh networks, which means you have to stick with one mesh vendor or construct bridges between the different mesh networks. The Internet Engineering Task Force (http://www.ietf.org) is evaluating two ad hoc mesh network standards: the Mobile Ad hoc Networking (MANet, http://www.ietf.org/html.charters/manet-charter.html) and Ad hoc On-demand Distance Vector published by the National Institute of Standards and Technology.

Of all topologies, mesh networks are the best suited to the mine environment due to the constantly changing mine environment.

MACHINE-TO-MACHINE (M2M)

SensorLogic has published the M2MXML protocol and put it in the public domain at: http://www.m2mxml.org. The purpose of the M2MXML project is to develop an open-standard Extensible Markup Language (XML) based protocol for machine-to-machine (M2M) communications. The primary design philosophy of M2MXML is simplicity. Other attempts to develop protocols for M2M communications have resulted in protocols that are difficult to understand and too verbose to be used in small devices with limited communications bandwidth.

One of the goals of M2MXML is to establish an open standard that can be adopted by device manufacturers and M2M application developers, thus allowing some interoperability that does not exist today.

By using M2M communication standards each manufacturer can concentrate on its core markets while interoperating with other manufacturers. When wireless connection standards are used, even issues of different styles of connectors and cabling are removed.

NETWORK DATA MOVEMENT

Regardless of the protocol stack or network topology, there are two styles of data movement in networking: datagrams and virtual circuits.

Datagrams contain all source and destination information in their message packet and are conceptually similar to mailing a letter at the post office. The envelope contains the desired address and the return address, making the data packets larger. Each node in the network only needs to know how to route the envelope to the next node along the way. No knowledge of previous nodes is retained or needed, but effort is expended at each node to get the envelope to its destination. Datagram networks are robust in one sense because nodes could be shut down or fail after the envelope has been passed to the next node with no consequence to the delivery of the envelope. However, datagram networks are unreliable in the sense that there is no guarantee that the envelop will be delivered.

Virtual circuits are conceptually similar to making a phone call. It takes a bit of effort to initiate the call via establishing the best route through the network, but virtually no effort to maintain the call, leading to a significant energy savings. Once the connection between the caller and the destination is established, that route is maintained until the connection is terminated or the equipment fails.

At the physical layer, there are two broad classifications of data networks: (1) those that use wire, or fiber optics, to move data from point to point, and (2) those that do not use wire, but instead use wireless media such as light or radio waves.

LIGHT-BASED NETWORKS

Light-based systems may use visible light or invisible infrared light. Point-to-point light-based wireless technology is commonly found on computers, PDAs, and cell phones. The Infrared Data Association (IrDA) defines specifications for infrared wireless communications typically used for distances of less than 2 m (6.6 ft). However, light-based systems may be used over significant distances and for many-to-many point transfers.

Networks based on diffuse infrared light saturate a confined space rather than requiring directional orientation, as do IrDA-based systems. Diffuse networks are used in areas where security is paramount because, unlike radio waves, the light waves do not penetrate walls. Diffuse networks can work in dusty environments as each dust particle acts as a diffuser, but the overall distance range will be somewhat reduced.

Light-based systems will always use an error-checking or correction system because of the prevalence of infrared sources in the environment. For example, a spider building a web on the front of an infrared motion sensor would look like a 6-ft-tall person walking past the sensor 10 ft away.

RADIO-BASED NETWORKS

Radio transmissions occupy a particular frequency or range of frequencies (Figure 17). The style of transmission, such as AM or FM, will occupy a certain width of frequencies centered around (on) a particular frequency. The occupied frequency width around the center frequency is known as bandwidth. A typical analog voice signal sent using frequency modulation (FM) will occupy up to 30 kHz. As frequencies are a limited resource, means for sharing the frequencies simultaneously by different devices and users have been developed. In radio-based networks, Spread spectrum and UWB are the most common of the frequency-sharing methods.

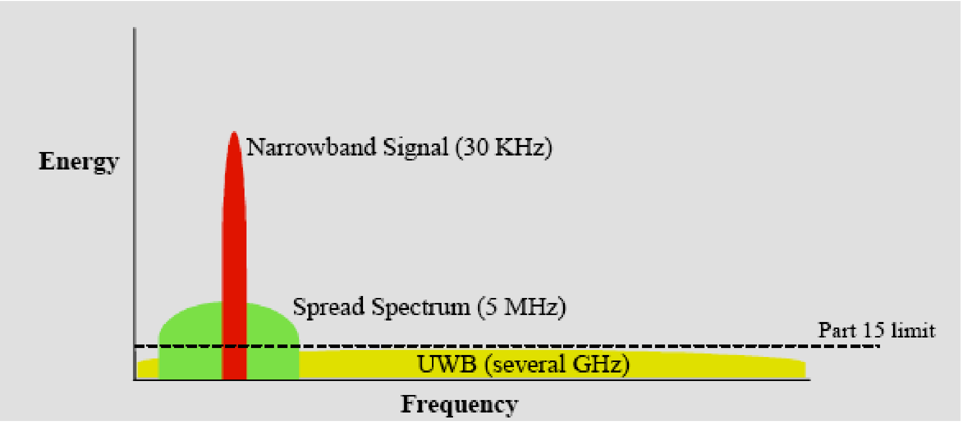


Figure 17.—Radio energy concentration. ***(Image courtesy of Loop Start Consulting Group, Leesburg, VA.)***

SPREAD SPECTRUM

In continuing with the FM voice transmission example, when using spread spectrum techniques the 30-kHz voice signal will have the radio energy of 30 kHz divided up into a bandwidth of 5 MHz. (Spread spectrum signals may use more or less than 5 MHz depending on the FCC frequency allocations.) The overall energy of the radio transmission remains the same, but the radio energy at any given frequency within the 5-MHz bandwidth is now approximately 1,000 times smaller. The signal is so small, in fact, that it appears as radio background noise to non-spread-spectrum receivers. Special processing is required by the receiver to separate the signal of interest from the background noise and to reconstruct the 30-kHz signal.

ULTRAWIDE BAND (UWB)

A new form of radio signal is just now emerging from the research labs into real-world products known as ultrawide band (UWB) signaling. It is similar in concept to spread spectrum except that instead of being spread across a few million frequencies (5 million in our spread spectrum example), the signal of interest is now spread across billions of frequencies at power levels so low they are hard to comprehend.

UWB has unique properties due to the extremely short and fast pulses used to comprise the UWB signal. It does not use a radio carrier as all conventional radio frequency devices would. Short pulses allow for accurately pinpointing the location of people and objects. This cannot be done using longer signal wavelengths. UWB radar signals are also being used in x-ray vision-like applications, so that even behind-the-wall movements of terrorist suspects may be seen. Applications to mining are numerous. Examples include locating trapped miners after a hazardous event and looking into the coal face to assess depth of coal/rock interface.

UWB signals are digitally based rather than analog-based as all radio technology has been in the past. UWB technologies are designed to cost significantly less than current radio technology. Current radio technologies rely on expensive selection filters and tuning processes to pass only the signals of interest. By the very nature of UWB, such expensive filters are not needed.

WHY USE SPREAD SPECTRUM OR UWB?

Through the use of spread spectrum or UWB techniques, the radio spectrum may be shared by simultaneous users and devices. If narrow band signals are used, there are a limited number of frequencies that can be used simultaneously before signals start to interfere with each other. Spread spectrum and UWB offer numerous advantages that are especially important for applications in hazardous environments. Major advantages of spread spectrum are: reduced crosstalk interference, very good data integrity with less static noise, less susceptibility to multipath fading, and very good coexistence with other systems such that it doesn't create severe interference with other systems. UWB advantages include: high data rates, low power (suitable for battery-powered applications), very good coexistence with other systems, relative immunity to multipath problems, and precise ranging or distance measurements that can be used for location identification.

WIRELESS SENSOR NETWORKS

A combination of factors (recent catastrophic natural disasters, terrorist activities, rapidly deteriorating infrastructure, and increasing costs for new construction) point to the need for a robust, low-cost, low-power, and high-performance autonomous wireless monitoring system for the health and safety of workers in mines, in buildings, on bridges, and on other civil structures. Wireless sensor networks enable the remote monitoring and management of critical devices while providing data to enable more informed decision-making, better control, and increased revenue opportunities.

In the past, wired networks made many ideas economically or physically impossible to consider. Wireless sensor networks are opening the door to a new world of opportunities in supply chain logistics, data collection, system monitoring, and control applications. Actuators, gauges, and sensors can now be monitored and controlled wirelessly, obviating the expensive installation and maintenance of copper or fiber-optic cables.

The basic goals of a wireless ad hoc sensor network generally depend on the application. However, the following tasks and examples are common to many networks:

1. *Determine the value of some parameter at a given location:* In an environmental network, one might want to know the temperature, atmospheric pressure, gas concentrations, and the relative humidity at a number of locations. This example shows that a given sensor node may be connected to different types of sensors, each with a different sampling rate and range of allowed values.
2. *Detect the occurrence of events of interest and estimate parameters of the detected event or events:* Has someone entered a restricted area or area with a high risk of injury (e.g., a pinch point), has a ground fault been detected, etc.?
3. *Classify a detected object:* Make decisions based on the quality of the coal or ore, i.e., its disposition while in motion.
4. *Track an object:* Direct a battery hauler to the next free dumping station, return it to the next machine ready to unload, etc.

Power

The key to an effective wireless sensor network is power. An iPod or cell phone can be recharged every night, but what about items that can never be recharged? Pacemakers, implantable physiological monitors, and mine environmental sensors in physically inaccessible or dangerous locations are examples of devices that must function for years without the power source ever being replaced.

In the application of wireless sensor networks, called a smart sensor network, the conservation of power is paramount. The average inactive (sleep) current consumption goal of each independent node is to be as low as possible. Current technologies place this in the 200-nA to 10-µA range. There are two different schools of thought on power consumption by network nodes. The first is that when a task needs to be executed, get the work done as fast as possible even if it means high peak currents into the hundreds of milliamps, so that the node can return to sleep as fast as possible. The opposing school of thought is that the average current consumption should be kept low, taking as long as needed to do the job at the slowest speed acceptable, as current consumption is proportional to speed. When the task is completed, return to sleep.

At the extreme low-power end of the energy consumption spectrum are some switches and sensors that require no power at all because they use piezoelectric generators as switch elements or gather energy by small changes in environmental pressure. The mechanical act of pressing the button generates enough power for the switch to power the wireless node transmitter long enough to transmit the state of the switch. Handheld remote controls with up to eight single pushbuttons or up to four rocker switches with medial positions can be constructed. Issues of batteries or power supply wires are completely eliminated. However, there are many safety issues to consider if these switches are used for emergency stop applications [Sammarco 2005].

Startup EnOcean GmbH (Oberhaching, Germany) has introduced a solar-powered wireless sensor module. The STM100 unit includes three analog and four digital sensor connections, but not the sensors themselves, and integrates them with a controlling microprocessor, an RF transceiver, and light energy capture and storage in a module measuring 20 mm by 40 mm by 10 mm. The two-stage solar cell reservoir system will operate in lighting levels as low as a typical hallway light. The energy storage is sufficient for the module to operate continuously for up to 5 days in complete darkness. These solar-powered wireless sensor modules would be applicable to surface mining applications or could be recharged with a simply flash of a caplamp light every few days.

Event-driven

To conserve energy, wireless sensors are event-driven, i.e., they sleep until some stimuli causes them to wake up and take action. The stimuli may be a periodic timer expiring, a change in a monitored environmental condition, or direct user interaction. An operating system is required to handle such events and coordinate network traffic.

Operating Systems

Considerable work has been done by the academic community to create an operating system that will run on small low-cost, low-power systems. Initially funded by the Defense Advanced Research Projects Agency (DARPA), an operating system specifically designed for wireless sensor networks was created at the University of California, Berkeley [Hill 2003]. The wireless sensor operating system known as TinyOS has become the premier operating system for sensor network research.

TinyOS is an open-source operating system designed for wireless embedded sensor networks. It features a component-based architecture that enables rapid innovation and implementation while minimizing code size as required by the severe memory constraints inherent in sensor networks. TinyOS's component library includes network protocols, distributed services, sensor drivers, and data acquisition tools, all of which can be used as is or be further refined for a custom application. TinyOS's event-driven execution model enables fine-grained power management, yet allows the scheduling flexibility made necessary by the unpredictable nature of wireless communication and physical world interfaces.

TinyOS has been ported to over a dozen platforms and numerous sensor boards. A large community uses it in simulation to develop and test various algorithms and protocols. More than 500 research groups and companies are using TinyOS on the Berkeley/Crossbow motes. Numerous groups are actively contributing code to the site "http://sourceforge.net/projects/tinyos" and are working together to establish standard interoperable network services built from a base of direct experience and honed through competitive analysis in an open environment.

TinyOS programs are compiled with a C language-like compiler called "nesC." TinyOS and nesC are now supported on the Gentoo Linux (http://www.gentoo.org) development platform.

An alternative to TinyOS is SOS (https://projects.nesl.ucla.edu/public/sos-2x) from the Networked and Embedded Systems Laboratory at the University of California, Los Angeles (UCLA). SOS is a dynamic operating system for sensor networks that relies on conventional C compilers for code creation, removing one step from the learning curve for those new to wireless sensor networks. SOS uses a common kernel that implements messaging, dynamic memory, module loading and unloading, and other services. SOS uses dynamically loaded software modules to create a system supporting dynamic addition, modification, and removal of network services.

Off-the-shelf Hardware

The hardware platform consists of processor/radio boards commonly referred to as "motes." A mote runs the TinyOS to provide low-level event and task management. Crossbow Technology, Inc., is the major supplier of off-the-shelf motes running TinyOS. Crossbow offers XMesh, a self-forming, micropower, networking stack. Cogent Computer Systems, Inc., is the major supplier of off-the-shelf motes running SOS based on the XYZ Sensor Node wireless sensing platform developed at Embedded Networks and Applications Laboratory, Yale University (http://www.eng.yale.edu/enalab).

Protocols

Pros and cons for each protocol relative to mining applications are summarized below, along with a basic overview of data transfer rate(s), distance, and frequency range(s). Distances listed are those for an unobstructed line-of-sight path.

Bluetooth

Pros: Bluetooth is the oldest of the wireless-based protocols discussed in this report. As such, it is found in millions of cell phones and PDAs. The primary application of a Bluetooth-enabled device is in virtual displays. Nodes, referred to as "headless," contain no display of their own, but transfer data to an external viewer to present the node data.

Cons: As the oldest wireless method discussed here, Bluetooth is the most attacked. Numerous security breaches have been documented [Biever 2005; Bluetooth 2005]. Also, it consumes more energy than newer protocols, limiting its usefulness in sensor nodes.

Data rate: Up to 723.1 kbps. Bluetooth Enhanced Data Rate – 2.1 Mbps.

Range: 10 m (33 ft).

Frequencies: The protocol operates in the license-free ISM band at 2.45 GHz. In order to avoid interfering with other protocols that use the 2.45-GHz band, the Bluetooth protocol divides the band into 79 channels (each 1 MHz wide) and changes channels up to 1,600 times per second.

Comments: Bluetooth devices can have groups of up to eight devices (one master and seven slaves). They are called piconets.

Digital-enhanced Cordless Telecommunications (DECT)

DECT was developed mainly for use by European cordless phones, but is now starting to be used as a general data transmission method.

Pros: Wide acceptance in Europe. Nodes are designed to operate while in motion up to 20 km/h (12 mph).

Cons: Limited support in the United States. This may change, as the FCC approved the use of DECT in the 1,920–1,930 MHz band in the spring of 2005. Currently no known support for sensor systems.

Data rate: 552 kbps and 1.15 Mbps.

Range: 100 m (328 ft).

Frequencies: 1.80–1.93 GHz.

EnOcean

Pros: Ultralow power, scavenges minute amounts of energy from the environment. Gas sensors for several gases are already on the market. Already in use for environmental monitoring systems in car parking garages. Used for lighting control in building automation.

Cons: Limited public availability of technical details.

Data rate: Unknown.

Range: Unknown.

Frequencies: Unknown, presumed to be ISM spread spectrum-based.

Comments: MSR-Electronic supplies EnOcean-compatible wireless sensor technology monitors for gases such as CO, CO_2, NO_x, NH_3, EX, and O_2.

Ensation

Pros: For use in headphones and hearing protection devices in high-noise mine environments.

Cons: Ensation was formally announced while this report was in preparation. No devices that use it are on the market yet. Long-term support and market penetration is therefore unknown.

Data rate: 150–500 kbps.

Range: Indoor distances of 30 m (98 ft) at a transmit power level of 10 mW.

Frequencies: 863–865 MHz for Europe and 902–928 MHz for the United States.

Comments: Ensation's main usage is point-to-multipoint low-latency audio, such as a single transmitter communicating with multiple headphones. The protocol may be useful for control pendants due to the low-latency data transfer. Latency is the time between an action, such as a button press, and a result, such as the startup of a haulage motor. Latency time is less than 20 ms.

IEEE P1902.1™ Standard for Long Wavelength Wireless Network Protocol (RuBee™)

Pros: RuBee networks and tags are distinguished from most RFID tags in that they are unaffected by liquids and can be used underwater and underground. Being magnetic-based rather than radio-based allows them to operate in and near areas of high metal content.

Cons: Limited public availability of technical details, as the P1902.1™ standardizations process has just began.

Data rate: 300–9,600 bps.

Range: 3–15 m (10–50 ft).

Frequencies: Below 450 kHz.

Comments: RuBee tags maintain performance around steel, which removes a key obstacle for low-cost deployment of RFID in industrial item-level tracking environments.

Millennial Net, Inc.

Pros: Ultralow power will run for years on a 3-V coin-sized battery.

Cons: Limited public availability of technical details.

Data rate: Unknown.

Range: Unknown.

Frequencies: 916 MHz, 2.45 GHz.

Comments: Millennial Net devices can operate with an extremely low rate of power consumption on the energy of a 3-V coin-sized battery for years at a time as part of a scalable, self-organizing wireless sensor networking system. Millennial Net supplies the *Wireless Sensor Networking Source Book* [Rhee and Liu 2005], which is a must-read for anyone considering a wireless sensor network system.

A unique feature of Millennial Net is Persistent Dynamic Routing. This provides a mechanism for the network to ensure reliable data transmission without dropping data packets. Combined with the technique of dynamic route discovery, which discovers the best route for packet delivery on the fly, Persistent Dynamic Routing enables a level of scalability and power efficiency that other networking systems have not yet achieved. Standard reference kits are available.

Near-field Communication (NFC)

Pros: Intended for short distances, such as for transferring configuration information or as a connector replacement. Used in many new cell phones and electronic cards. NFC uses very low power. NFC devices can serve as connector replacements and as replacements to IrDA infrared devices.

Cons: Limited public availability of technical details, must become a member of the NFC Forum to obtain them. However, off-the-shelf modules are available from Philips Semiconductors.

Data rate: Up to 424 kbps.

Range: 20 cm (8 in).

Frequencies: 13.56 MHz.

Comments: A radio wave is a combination of an electric wave and a magnetic wave. When these waves leave the antenna, they are offset by 90°. By the time the electric and magnetic waves have traveled about a half-wavelength from the transmitting antenna, the phase offset has decreased to almost zero. NFC technology operates by using magnetic field induction.

NFC is already standardized according to globally accepted standardization bodies, such as the International Organization for Standardization (ISO 18092), Ecma International (ECMA–340) and the European Telecommunications Standards Institute (ETSI TS 102 190). NFC is compatible with Philips' MIFARE® (ISO 14443 A) and Sony Corp.'s FeliCa™ smart card protocols.

NFC may be used to configure and initiate other wireless network connections, such as Bluetooth, via transferring the hard-to-set-up Bluetooth address. NFC may also be used in address training modes where a particular receiver has to be told to listen to a particular transmitter, in situations where multiple transmitters may be in operation in close proximity to each other at the coal face, completely removing the need for teach/learn connectors.

There are many similarities between NFC and RFID, as they both operate very much in the contactless connections arena and share the same frequency spectrum.

RFID-Radar™

Pros: Achieves millimeter precision for monitoring movement. RFID-radar has the ability to measure the radio path length, which is the signal distance from the transponder to a reader. RFID readers can handle up to 800 transponders in a zone at a time with speeds up to 300 km/h (186 mph), while the radar will give accurate location information for up to 50 transponders in a zone at a time at low speeds. Due to low spectrum utilization, multiple readers and radars can operate in close proximity with minimal interaction.

Cons: Antenna system(s) being used are currently a work in progress. A large-scale, high-volume manufacturer is currently being sought.

Data rate: Currently limited to preprogrammed serial numbers of the tags.

Range: Up to 40 m (131 ft). Manufacturer's tests indicated that a target of 0.2-m (8-in) accuracy would be achievable out to 100 m (328 ft).

Frequencies: 860–960 MHz.

Comments: Besides identifying RFID transponders in its zone, the RFID-radar system is able to measure the range and direction of those transponders from the reader antennas. The system operates at UHF frequencies in the bands allocated for RFID using electric coupled propagation properties to transfer energy from the reader to the transponder and from the transponder back to the reader. The RFID-radar measures the path length for signals traveling from the transponder to the reader to determine range. By comparing signals arriving at two identical receivers with closely spaced antennas, the reader is able to determine the angle of arrival of the signals from the transponder and thus the direction of that transponder from the reader. A third receiver channel can be added to give 3–D coverage rather than two-dimensional (2–D) coverage.

Wi-Fi / WiFi / Wireless Fidelity

Wi-Fi is a wireless networking technology based on the IEEE 802.11b/802.11g standards. IEEE's 802.11g standard defines the way in which wireless gear communicates at up to 54 Mbps while remaining backward-compatible with 11 Mbps 802.11b.

Pros: Found virtually everywhere, such as laptop computers.

Cons: Power-hungry. Not suited for long-term battery-powered usage. Not designed for low data transfer applications such as sensors.

Data rate: 802.11b has a maximum raw data rate of 11 Mbps, but network overhead limits the maximum usable data rate to less than 7 Mbps. 802.11g has a data rate up to 54 Mbps.

Range: Line-of-sight distances up to about 100 m (328 ft).

Frequencies: 16 channels in the 2.4-GHz ISM band, 10 channels in the 915-MHz ISM band, and 1 channel in the 868-MHz band.

Wireless Personal Area Network (WPAN) / 802.15.4

The IEEE 802.15 TG4 was chartered to investigate a low data rate solution with multimonth to multiyear battery life and very low complexity. 802.15.4 is not usually used directly; however, it forms the lower layers of other protocols such as ZigBee.

Pros: Designed from the start to be low-power, with sensor applications in mind. Many subfeatures such as network time synchronization (all nodes in the network show the same time). Time synchronization is important in data logging and location features.

Cons: Overwhelming amount of publicly available technical details. The 802.15.4 protocol document is 679 pages long. Such complexity requires reliance on semiconductor suppliers to implement the protocol in hardware correctly.

Data rate: 20 kbps, 40 kbps, 250 kbps.

Range: Dependent on system design. Up to 10-m (33-ft) radius.

Frequencies: Dependent on system design.

Comments: Incorporates a variety of features to ensure reliable operation. These include a quality assessment, receiver energy detection, and clear channel assessment. Data transfers have a maximum payload of 104 bytes, with 16-bit or 64-bit address.

Support exists for critical latency devices, such as joysticks. There is an automatic network establishment by the coordinator and a full handshake protocol for transfer reliability. Power management ensures low power consumption.

Wireless USB (Atmel Corp., Cypress Semiconductor Corp.)

Pros: All modern computers contain human interface device drivers, so that no custom software is required to be written when used with laptop or desktop computers.

Cons: None known.

Data rate: 62.5 kbps.

Range: 10 m (32 ft) for the short-range version, 50 m (164 ft) for long-range version.

Frequencies: 2.45 GHz.

Comments: WirelessUSB N:1 is based on a wireless star topology consisting of multiple nodes connected to a central aggregator or hub. The hub ties directly to the controller through either a serial connection or an existing wired control system. Wireless nodes use the WirelessUSB N:1 multipoint-to-point protocol to receive and send data to the hub. Wireless USB has received several industry awards for outstanding interference avoidance, high-node density (up to 65,000 nodes), and long-range wireless capabilities, all of which contribute to a cost-effective, simple, yet highly reliable wireless sensor environment.

WirelessUSB N:1 is optimized for low power. The hardware is fully off until an event occurs. Because a wireless USB sensor node can be asleep for a majority of the time, the radio is transmitting and/or receiving less than 0.1% of the time. Thus, the average current consumption is very low (in microamps). A wireless USB sensor node can achieve 5+ years of battery life using typical batteries. Further details may be obtained at: http://www.atmel.com, and http://www.cypress.com.

Wireless USB (USB Forum)

Pros: A pro cannot be established at this time, as this technology was released while this report was in preparation. Wireless USB is expected to be widely used within a few years.

Cons: Overwhelming amount of publicly available technical details of the protocol, but lacking details in frequency range and distance. The Wireless USB Forum protocol document is 303 pages long. Such complexity requires reliance on semiconductor suppliers to implement the protocol in hardware correctly. Further details may be obtained at: http://www.usb.org/wusb.

Worldwide Interoperability for Microwave Access (WiMax)

802.16 [Eklund et al. 2006] provides up to 50 km (31 miles) of linear service area range and allows users connectivity without a direct line of sight to a base station. Note that this should not be taken to mean that users 50 km (31 miles) away without line of sight will have connectivity. The technology also provides shared data rates up to 70 Mbps.

Not relevant to data collection devices such as sensors; however, may be useful for linking mine campuses.

ZigBee

ZigBee is a wireless networking technology based on the newly defined IEEE 802.15.4 Low-rate Wireless Personal Area Network (WPAN) standard. ZigBee adds the upper protocol layers of the ISO stack where the logical network, security, and application software reside.

Pros: ZigBee provides static and dynamic, star, cluster tree, and mesh networking structures to create large-area scalable networks with single point-of-failure avoidance. Many manufacturers are about to bring ZigBee-based products and semiconductors to the market.

Cons: There is limited availability of off-the-shelf devices at this time.

Data rate: 20 kbps in the 868-MHz band, 40 kbps per channel in the 915-MHz band, 250 kbps per channel in the 2.4-GHz band.

Range: 10–75 m (33–246 ft).

Frequencies: Operation in the unlicensed 868-MHz, 915-MHz, and 2.4-GHz bands.

Comments: ZigBee shows the most long-term promise to a ubiquitous mine-wide deployment of sensors on equipment and worn by personnel.

ZigBee has an optional method for time synchronization, which is important in mine-wide data logging and location applications. In addition, it is recognized that some messages need to be given a high priority. To achieve this, a guaranteed time slot mechanism has been incorporated into the specification. This enables these high-priority messages to be sent across the network as swiftly as possible. This has applications such as automatic and emergency shutdowns.

Z-Wave™

Pros: Z-Wave™ generally costs less and has a smaller code size footprint than ZigBee. Z-Wave™-enabled end-user products are now available from commercial retailers, while ZigBee-enabled end-user products were not available at the time this report was in preparation.

Cons: Limited public availability of technical details. Not as many features as ZigBee.

Data rate: Unknown at this time.

Range: Unknown at this time.

Frequencies: 868/915-MHz bands.

Comments: Z-Wave™ is a wireless RF-based communications technology designed for residential and light commercial control and for status reading applications such as meter reading, lighting and appliance control, HVAC, access control, intruder and fire detection, etc. Z-Wave™ is the de facto standard for wireless home controls using mesh networking. Further details may be obtained at: http://www.zen-sys.com.

RADIO FREQUENCY IDENTIFICATION (RFID)

Radio frequency identification (RFID) is an emerging subset of wireless technology. RFID devices are known as tags, as they “tag” an object or person with a small device containing a large binary number, typically 48 bits or 2.8×10^{14} different numbers. A few styles of tags allow a small amount of information to be written to the tag.

Figure 18 shows a common “pet implant.” This is a very common form of RFID in use today by consumers.

Some RFID systems are designed to handle reading multiple tags clustered into a small space, such as a shopping cart, or a number of personnel standing near a piece of equipment. A potential mining application would be an “automatic” emergency stop system that would protect miners from machine striking or pinning accidents. An emergency stop system could be constructed to shut down a machine if an RFID tag worn by a miner came in view of a tag reader (Figure 19).

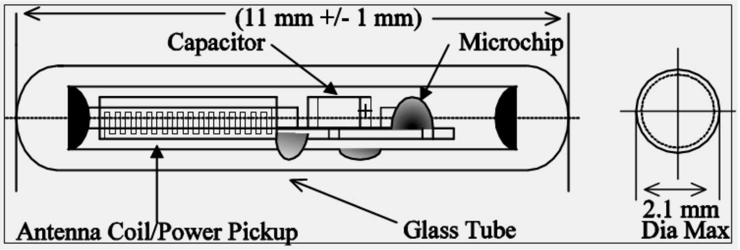


Figure 18.—RFID tags can be very small. An implantable pet tag is shown.

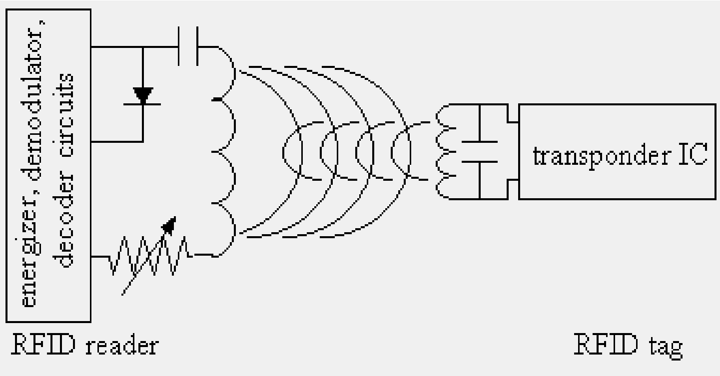


Figure 19.—An emergency stop system concept that uses an RFID. (*Image courtesy of Intersoft Corp).*

Due to the small size of tags, they rarely contain their own power source. Rather, they receive their power from a magnetic field supplied by a device known as a reader, as it reads the binary number from the tag. A tag that contains its own power source, such as a battery, is known as an active tag. Tags that do not contain their own power source are known as passive tags. The magnetic power system used by passive tags may not work well in areas containing a lot of metal.

The typical operating frequency of RFID systems are 125 kHz, 13.56 MHz for older legacy systems, and the 400-MHz / 2.4-GHz / 5-GHz regions for newer systems.

RFID has been used for the tagging of coal [Lauf 2001]. In other applications of RFID, there is a movement to replace the ubiquitous UPC bar codes with RFID tags.

Opponents to RFID tags fear that there maybe a loss of privacy associated with widespread RFID usage. One possible scenario is that you buy an item of clothing, such as a shirt or dress, and pay with your credit card. There is now a link between a piece of personal identification, your credit card number, and the RFID tag used for inventory management. If the RFID tag is not disabled at the point of sale, it is hypothetically possible that the next time you enter the store wearing the item of clothing, you could be targeted with ads specifically directed at you.

BLOCKER TAGS

A special class of RFID tags has been created known as blocker tags. An individual tag is identified out of a cluster of tags by a process known as singulation. Singulation is where the tag reader breaks down each of the individual tag addresses, trying to identify a unique tag. In the shopping scenario, this would be multiple people passing through the entrance of the store simultaneously. Blocker tags interfere with the singulation process by generating all possible RFID identification numbers, which confuses the tag reader. Blocker tag technology can be countered by using "tags talk first" (TTF), as they do not rely on the singulation process.

LOCATION AWARENESS

Location awareness is the ability to know the location of an object or person in 3–D space and in real time. Contrary to what one might expect, the wider the area that an object or person needs to be tracked within, the easier the tracking can be done. It is tracking of objects or personnel within an area of a few meters that is the most difficult. However, emerging UWB techniques are enabling asset and personnel tracking at ranges of 600 ft to a resolution of 10 in.

By using a global positioning satellite system, it is comparatively easy to locate objects on a global scale. The Automatic Position Reporting System (APRS) (http://www.aprs.org) is one such example. APRS, in conjunction with "findU" (http://www.findu.com), is a live, real-time example of location awareness on a global scale. From findU, a properly tagged object, such as a vehicle, is shown with a satellite image and a local street map. APRS is a real-time tactical digital communications protocol for exchanging information among a large number of stations covering a large area. APRS integrates maps and other data displays to organize and display data by using a one-to-many protocol to update the network in real time.

A more regional location problem is that of locating a cell phone user dialing "911" emergency services. On June 12, 1996, the FCC adopted a Report and Order known as Enhanced 911, or E911, which will eventually require all cell phone operators to provide identification of the wireless caller's phone number and physical location.

One challenge is that of locating a person or object inside of a building or underground mine, where GPS and systems requiring outside signals do not function.

There are eight fundamental ways to do base location awareness, which may be used alone or in conjunction with each other. The carrier of the information may be a radio wave, light wave, sound wave (ultrasonic), or magnetic wave (near-field inductive coupling). All systems require more than one point of reference.

- **Angle of arrival (AOA):** Uses multiple antennas at a reference point to determine the incident angle of an arriving signal.
- **Time difference of arrival (TDOA):** Uses the time it takes for a signal to travel as an indirect method of calculating distance. Precisely synchronized time between units and/or reference points is required.
- **Time of arrival (TOA):** Similar to the TDOA technique, this technology differs only in that it uses the absolute time of arrival at reference points rather than the difference between two stations.

- **Enhanced observed time difference (E–OTD):** E–OTD is an enhancement of TDOA, where the receiving unit, e.g., a cell phone, returns information back to the reference points for location calculations.
- **Signal strength:** The received signal strength is measured from a transmitter sending a known level of power. This is the oldest method used in classic direction-finding techniques. Multiple points of reference are still needed. A single measurement of signal strength is helpful for determining distance from the transmitter.
- **Multipath fingerprint (MF):** Waves of various types will have received a signal directly from a transmitter and receive indirect signals reflected off of objects in the environment. Multipath is a problem when the direct wave and the reflected waves cancel each other out so that no signal is received at the receiver. MF takes advantage of what is normally considered to be a problem. It requires knowledge of the environment; if the environment changes, new fingerprints have to be created.
- **Smart antennas or smart optics:** Antennas are rotated mechanically or electronically to locate the strongest signal.
- **Near-field electromagnetic ranging (NFER):** The physics behind NFER technology is relatively easy to grasp. Radio signals are electromagnetic waves. A radio wave is a combination of an electric wave and a magnetic wave. When these waves leave the antenna, they are offset by 90°. By the time the electric and magnetic waves have traveled about a half-wavelength from the transmitting antenna, the phase offset has decreased to almost zero. By measuring the angle between the electric wave and the magnetic wave, distance may be calculated.

An unstructured environment is one that has not, or cannot, be prepared in advance, such as a train wreck or a mine collapse. Structured environments can unexpectedly become unstructured due to outside influences such as earthquakes or explosions.

The major problem in location awareness that has not yet been solved is knowledge of the vertical z-axis, or height. It is easy to locate a player in contact with the basketball court, but extremely difficult to determine the player location in 3–D while making a jump shot in real time. A practical problem would be to locate an injured person lying on the floor in a high-rise building. It can be hard to distinguish a tall person standing on the second floor from an injured person lying on the third floor.

FUTURE RESEARCH

INJURED MINER (PERSON-DOWN) DETECTION

Miners, as well as firefighters and first responders, work in dynamic, hazardous environments. Miners can become incapacitated from falls of ground (i.e., roof, rib, and back falls); from slips, trips, or falls; or from being struck or pinned by moving machinery. In all of these mishaps, a miner will be subjected to bodily impact hazards that can be detected by using accelerometers to measure the force of impact. Alternately, the lack of bodily movement can be measured using the accelerometers; this lack of movement indicates that the miner has been incapacitated (“person down”). Commercial systems with person-down functions are available for firefighters. For instance, the TPASS–3 EVACUATE™ system uses a solid-state accelerometer for “lack of motion sensing.” An alarm signal indicating a person-down situation is sent to a central command base if body motion is not detected after 18–23 sec.

A wearable accelerometer would play a key role in a person-down system designed to alert other miners that a mishap has occurred. Such a person-down system for mining could save valuable time so that medical attention could be more quickly administered. This is especially important for situations where a worker is alone. This is common in mining because miners walk down entries to retrieve tools or materials or to inspect or repair a piece of equipment. A person-down system could also be very useful for situations when the miner is not alone. Mines are often characterized as dark, dusty, and noisy environments, so it is quite conceivable that a miner could be injured without the immediate knowledge of other miners in the vicinity. For instance, a remotely controlled continuous miner could strike a worker positioned in one of the machine’s blind spots. This mishap could go unnoticed because of noise and the absence of a line of sight to the worker; thus, the extent of injury could become more severe as the machine advances. Also, precious time would be lost until the injured worker was seen.

The wearable person-down system (Figure 20) is composed of just a few simple components. Thus, the system is small enough to be wearable and cost-effective to be used by every miner. Each component is described below.

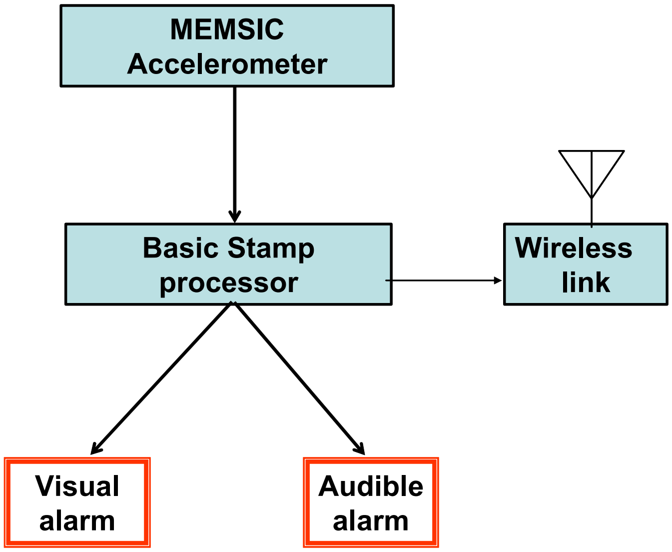


Figure 20.—Basic block diagram of a person-down system.

Sensor

The sensor (Figure 21) is the MEMSIC model MXD2020GL accelerometer. The major features of this sensor include:

- Dual-axis accelerometer fabricated on a monolithic CMOS IC
- No moving parts
- Less than 2 milli-g resolution
- No sensitivity or zero g bias hysteresis
- 50,000-g shock survival rating
- 35-Hz bandwidth expandable to >100 Hz
- Low-height (2-mm) surface mount package
- Continuous self-test for failures
- Low cost (about $5.00)

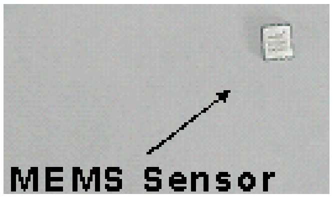


Figure 21.—A wearable accelerometer (MEMSIC model MXD2020GL).

Microcontroller

The BASIC Stamp microcontroller (Table 1 and Figure 22) is a computer on a chip optimized for monitoring and controlling specific systems or devices such as switches, timers, motors, sensors, relays, and valves. It is self-sufficient and has a processor, RAM and EPROM memory, clock, and interface (via 16 input/output (I/O) pins). The microcontroller software is PBASIC. This programming language is very similar to BASIC. The PBASIC language is relatively simple and has only 42 commands.

Table 1.—The key specifications of the BASIC Stamp microcontroller (adapted from Parallax [2006])

Processor speed	20 MHz
Program execution speed	~4,000 instructions per second
RAM	32 bytes (6 I/O, 26 variable)
EEPROM	2 Kbytes, ~500 instructions
Input/output (I/O)	16 + 2 dedicated serial
Voltage requirements	5–15 V dc
Current draw at 5 V	3 mA run / 50 μA sleep
Physical size	1.2 in × 0.6 in × 0.4 in
Cost	~$49 single; $39 each for 1,000

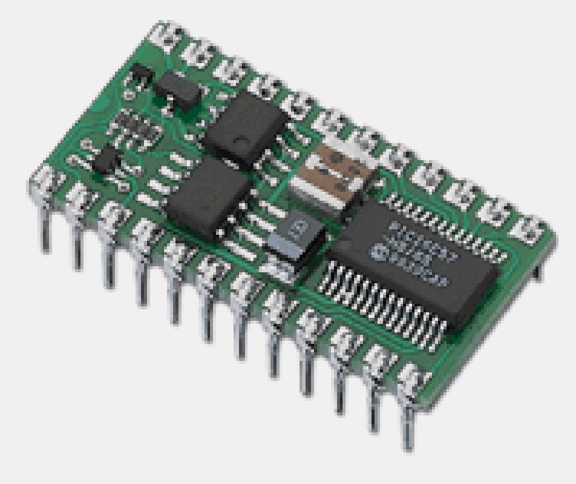


Figure 22.—The BASIC Stamp microcontroller. ***(Image courtesy of Parallax, Inc.)***

System Operation

The basic operation of a wearable person-down system centers on two hazardous states: the lack of motion and excessive bodily impact [MEMSIC 2007]. If one of these situations occurs, other miners are wirelessly alerted by using an ad hoc wireless mesh sensor network based on the ZigBee standard.

This MEMS sensor is sampled by the BASIC Stamp microcontroller. Data are periodically sampled and compared to the previous sample. The microcontroller provides the logic to ascertain if one of the hazardous states is present. The sensitivity and sampling frequency is software-programmable such that jitter and false signals are rejected. If a hazardous state is detected, the microcontroller activates a visual and audible alarm locally and wirelessly to other miners.

The logic to detect a high-impact hazardous state is based on the ability of humans to sustain impacts without incurring a concussion injury. This is dependent on the average acceleration and the duration of the acceleration as defined by the Wayne State University concussion tolerance curve (Figure 23). The area above the curve defines impact hazards that can cause injury, while the area below the curve is defined as safe. A person can be subjected to a high average acceleration, yet not incur a concussion if the exposure time is very small. Therefore, the microcontroller logic is programmed to activate the alarm when the impact exceeds the safe area of average acceleration and time duration.

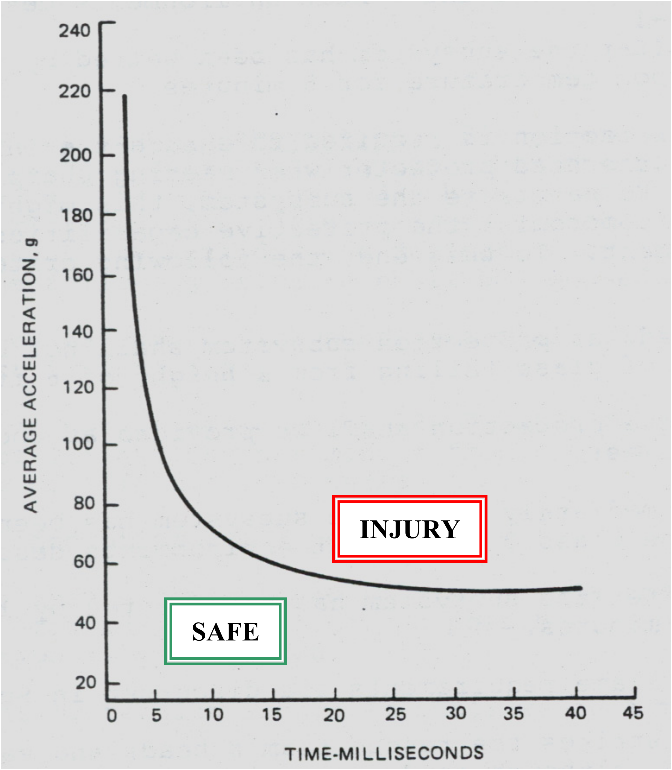


Figure 23.—Wayne State University cerebral concussion tolerance curve. (Adapted from SAE [1980]).

WEARABLE WIRELESS REMOTE VIEWER

The objective of this application is to mitigate striking and pinning injuries associated with remote-controlled mining machinery. There are two basic hazardous conditions: (1) workers are injured or killed because they are in a blind spot with respect to the machine operator; and (2) machine operators are injured or killed because they followed the unsafe work practice of placing themselves in unsafe areas to better see the task at hand.

The use of remote-controlled mining machinery subjects miners to injuries from the striking and pinning hazards of moving machinery. The Mine Safety and Health Administration reported that there were 167 remote-control incidents in mining during 1988–2004; of these, there were 24 fatalities [Dransite and Huntley 2004]. The most hazardous job function for remote control was tramming to a new location (76 incidents). Poor work practices were listed as the main cause because the operators placed themselves in dangerous areas near the machine. Operators often place themselves in dangerous areas because these areas afford the best vantage points to operate the machine (Figure 24).

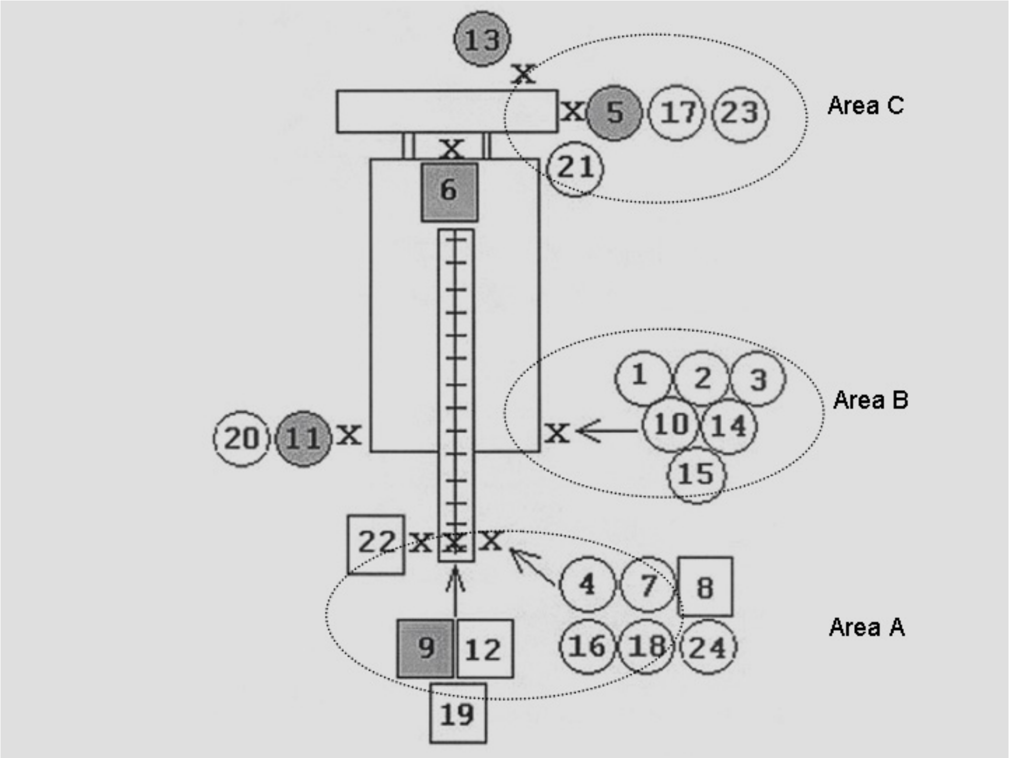


Figure 24.—The locations of 24 remote-control mining fatalities during 1988–2004. Circles represent the operator, squares represent other workers, and gray background indicates accidents during maintenance. The locations are categorized into three areas: A, the tail area; B, the cab area; and C, the cutter head area. (Adapted from Dransite and Huntley [2004].)

This application employs wearable display technology and wireless sensor technologies to enable operators to see blind spots and to see well enough to tram to new locations without positioning themselves in dangerous areas near the machine (Figure 25). Until recently, the technologies to display video (CRT monitors) were large and bulky, were visually and physically restrictive, and required significant power such that they were not intrinsically safe. Wearable display technology overcomes these limitations. This innovative technology uses a small, single eyepiece that weighs just 2 oz, yet it appears as if you're looking at a 17-in monitor from 3 ft away. The display doesn't restrict the user's field of vision; thus, the wearer can maintain awareness of his or her surroundings. The display is not physically restrictive because it is worn by the user, thus giving the flexibility to use the system without sitting in the operator's cab.

A second major benefit of wearable display technology can be achieved by combining it with remote control. This can afford the operator with all the visual information needed to control the machine and to see the machine's blind spots without having to sit in the machine's cab, which can reduce striking and pinning hazards.

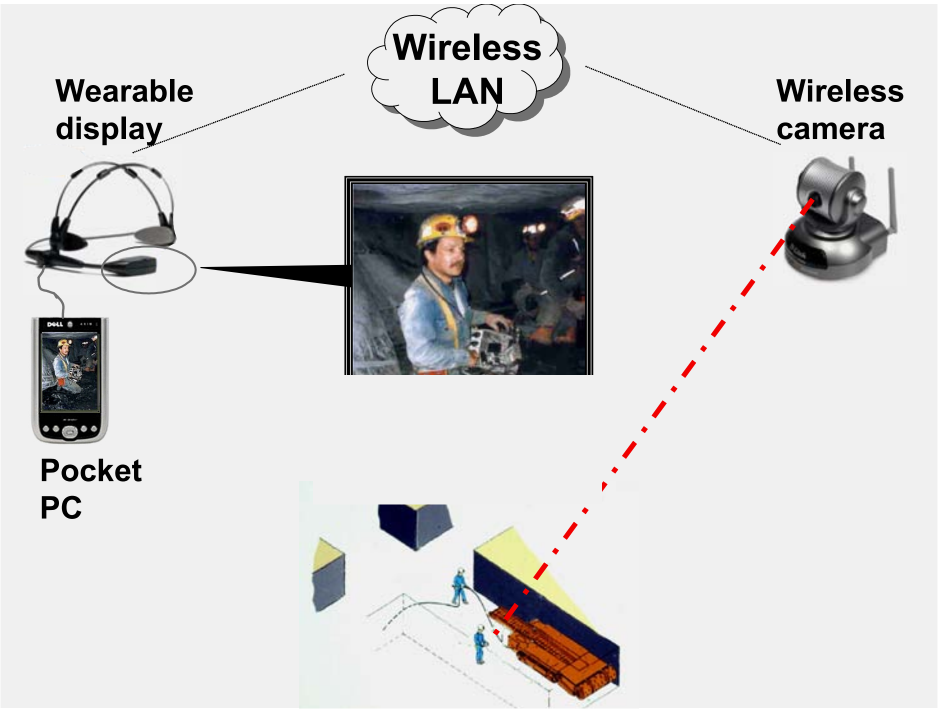


Figure 25.—This system enables a person to remotely view people or objects in blind spots.

Wireless Camera

The video camera is a wireless, networked IP camera that directly connects to a network or the Internet without the need of cabling. It enables users to remotely view live, full-motion video over a computer network or the Internet. It supports multiple users and can be viewed using any Web browser. Therefore, for the mining environment, the IP camera gives unmatched flexibility in terms of mobility, mounting locations, and the number of cameras and users.

An IP camera differs from a Web camera (WebCam), which needs to connect to a host computer that supports only one user at a time. The IP camera has a built-in CPU, embedded operating system, and Web server. Both the IP camera and WebCam are digital and differ from traditional analog video cameras that use a single analog video signal sent through a dedicated coaxial cable. Each analog camera needs a dedicated coaxial cable. The digital cameras digitize the images, and the video stream data are sent over the network. Therefore, multiple cameras can be used by multiple users at the same time.

The IP camera used in this application is the DCS–5300G from D-Link [2006]. It has pan, tilt, and zoom functions that can be remotely controlled from the Web interface or from the included remote control. The camera pans up to 270° horizontally and vertically tilts up to 90°. The complete camera specifications are listed in Table 2.

Table 2.—Detailed specifications of the DCS–5300G IP camera (adapted from D-Link [2006])

Camera specification	1/4-in color CCD sensor
	Electronic shutter: 1/60–1/15,000 sec
	Fixed focus glass lens, F2.0, 1 lux
Ports	10/100 Mbps Fast Ethernet
	Audio/video output
	External microphone input
	External I/O
Connectivity	Wireless 802.11g
	10/100 Mbps Fast Ethernet
Audio	Built-in omnidirectional microphone
Video resolution	Up to 30 fps at 160×120
	Up to 30 fps at 320×240
	Up to 10 fps at 640×480
Pan, tilt, and zoom control	Auto pan and auto patrol mode with preconfigured stops
	Pan: range 270°
	Tilt: range 90°
	4× digital zoom
Networking protocols	TCP/IP, HTTP, SMTP, FTP, Telnet, NTP, DNS, and DHCP
General I/O	1 opto-isolated sensor input (max. 12 V dc 50 mA)
	1 relay output (max. 24 V dc 1 A, 125 V ac 0.5 A)
Operating system	Microsoft Windows® XP, 2000, Me
Power input	External power supply; 12 V dc 1.5 A
Dimensions	4.0 in long × 4.1 in wide × 4.4 in high
Weight	12.2 oz (0.76 lb)

IP Camera Viewer Software

Viewer software is needed to display video on a pocket PC. ViewCommander-Mobile software enables you to remotely view the live streaming video output from multiple IP cameras on a pocket PC. The software includes the following major features:

- Connect to up to 16 video cameras or 16 video servers (with each server supporting up to 32 cameras, totaling 512 cameras)
- View video from Motion JPEG (M–JPEG) video streams
- Take snapshots and save to local device
- Pan/tilt/zoom controls
- Digital zoom: digitally zoom in on objects

The ViewCommander-Mobile software also configures the pocket PC buttons for pan/tilt/zoom controls, as shown in Figure 26. The controls are as follows:

- Zoom Fully Out: Use this button to zoom the camera to its widest field of view.
- Zoom Fully In: Use this button to zoom the camera to its maximum zoom level.
- Zoom Step Out: Use this button to zoom out one step.
- Zoom Step In: Use this button to zoom in one step.
- Up, Down, Left, and Right: Use this button to move the camera in the desired direction.

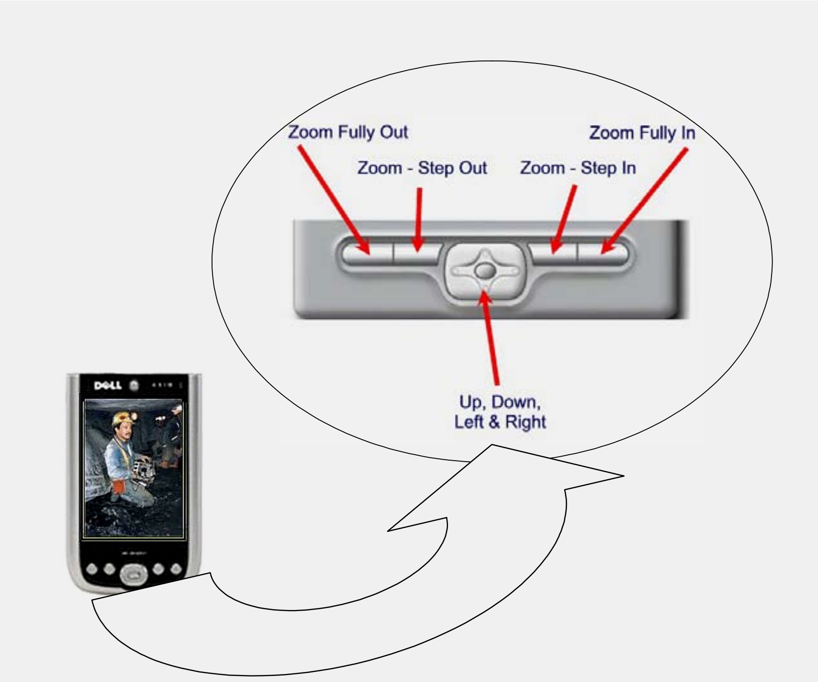


Figure 26.—The pocket PC buttons are used for controlling the IP camera.

Wearable Display

The wearable display is the model M920–CF by Icuiti Corp. A technical description is provided in the earlier "Icuiti Corp." section.

Wireless Router

The Netgear WPN824 RangeMax wireless router (Figure 27) is a key device for setting up the wireless network of this application. This router is well suited for the mine environment given its sleek physical design, excellent range, and strong resistance to interference, yet it is relatively inexpensive (about $130). The RangeMax does not have external antennas that can be damaged in the dynamic, hazardous mine environment. Instead, seven internal antennas are mounted inside the top cover. These antennas are part of the multi-in, multi-out (MIMO) technology employed by the RangeMax to increase the wireless range and speeds. The unit's seven antennas help the router counteract the negative impact of interference by dynamically reconfiguring themselves to changing conditions. For instance, if the signal of one of the transceiving antennas becomes weak, the unit automatically searches for a better signal from the other antennas. This dynamic reconfiguration of antennas is especially important given the dynamic mine environment of mobile machinery, changing physical geometries of the mine face and entries, and the presence of high-voltage electrical sources that can cause interference. The MIMO technology will also be useful to optimize the antennas given other wireless challenges such as large metallic machines, signal occlusions, and multipath effects.

The key specifications for the RangeMax are as follows:

- Connectivity: Wired or wireless
- Data transfer rate: Up to 108 Mbps
- Data protocols: Ethernet, IEEE 802.11b, 802.11g, and 802.11 Super G
- Transport protocol: Internet Protocol Security (IPSec)
- Weight: 1.1 lb
- Features: Firewall protection, DoS attack prevention, Smart MIMO technology, Intrusion Detection System (IDS)
- Bandwidth: 2.4 GHz
- Compatibility: PC, Mac

Figure 27.—The Netgear WPN824 RangeMax wireless router.

UWB SMART ENVIRONMENT

This application uses UWB to help create a smart environment that enables localization and tracking of first responders and resources. The smart environment provides location data, physiological data, and communications (video, photos, graphical images, audio, and text messages).

UWB technology has many advantages for a smart environment. It uses extremely short and fast pulses. This reduces multipath cancellation problems encountered from signal reflections off of walls, ceilings, and large objects. These short waves can also penetrate walls. Other advantages include the following:

- Time-of-flight properties that can be used for precision distance and positioning measurements
- Relative immunity to multipath problems
- Extremely high data rates
- Well suited for mobile wireless applications
- UWB transceivers can be made very small with MEMS technology

Commercial UWB Systems

Commercial UWB systems are emerging for indoor location and tracking of people and assets in smart environments [Fontana et al. 2003]. For instance, Ubisence offers a system and the associated development tools. Multispectral Solutions, Inc. (MSSI), offers multiple systems and associated development tools. MSSI's Sapphire UWB Precision Asset Location System™ (PAL™) has been approved to meet UL1604 safety standards for operation in hazardous locations. Some research has been conducted for first responder applications. The PAL650™ is another system by MSSI. The specifications follow:

- Typical indoor range: 300 ft
- Measurement accuracy: ±1 ft
- Transmission power: FCC §15.517
- Operating frequency: 6.2 GHz
- Coverage area: Up to 90,000 ft^2

Commercial UWB systems for indoor location and tracking of people and assets are intended for applications within a building. The efficacy of commercial UWB systems for underground mining applications has not been rigorously established.

Related Research

The Center for Advanced Integrated Radio Navigation (CAIRN) at Worcester Polytechnic Institute is conducting research to integrate communication and navigation system technologies in order to create systems for infrastructure-based and ad hoc-based networks [CAIRN 2007]. A location system for first responders is an active area of research for CAIRN.

Commonwealth Scientific and Industrial Research Organisation (CSIRO) Exploration and Mining in Australia has taken the lead in wireless technologies for localization of mobile equipment operating in an underground coal mining environment [Ralston et al. 2005]. CSIRO research involves the use of IEEE 802.11b Wireless Ethernet and uses the signal strength received from several wireless access points for the real-time localization.

A local positioning system (LPS) for outdoor applications such as construction, agriculture, and marine safety has been developed by the National Institute for Occupational Safety and Health [Lee et al. 2005]. In essence, the LPS is a smart environment for health and safety assessment of tasks conducted by multiple workers. The system is able to track the locations of multiple workers via a global positioning system and through integrated position data and assessment data obtained from real-time monitoring systems. Field testing of the LPS was conducted in order to evaluate noise levels for a highway paving project. The LPS enabled researchers to successfully measure, log, map, and analyze worker exposure to noise in order to pinpoint the primary source of noise.

CONCLUDING REMARKS

This report presents an overview of the technologies that could be used to supply miners and first responders with real-time situational data (environmental, physiological, and physical location data) needed for early warnings of health and safety hazards. Secondly, the same situational data can be useful to assist injured miners. This report does not address in specific detail the topics of intrinsic safety, tracking and locating trapped miners, or communication with trapped miners.

Three critical technologies emerge and converge to support this technical approach: wireless networks, low-power embedded computing, and smart microsensors. Computer and MEMS technologies have rapidly advanced; they are relatively mature technologies. Numerous inexpensive, commercial, off-the-shelf MEMS sensors, sensor motes and nodes, and embedded microcontrollers exist. However, wireless technologies are rapidly changing. While this report was being prepared, one new “standard” emerged—the Wireless USB from the USB Forum, which was in conflict with the de facto standard of the day, Wireless USB from Atmel Corp. and Cypress Semiconductor Corp., and two wireless methodologies merged.

This report does not address the realities of using the technologies to construct devices that are practical and certifiable for use in coal mines. It is unlikely that one could simply go out and purchase off-the-shelf technology and directly install it in an underground mine. The scope of this report was to highlight the technology that is available upon which products could be developed not only for coal mining, but also for other hazardous environments.

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APPENDIX A.—LIST OF USEFUL WEB SITES

1. Designing wireless interfaces for patient monitoring equipment. [http://rfdesign.com/mag/504rfdf4b.pdf].

2. Medical usability: how to kill patients through bad design. [http://www.useit.com/alertbox/20050411.html].

3. Virtual Network Computing (VNC) software makes it possible to view and fully interact with one computer from any other computer or mobile device. [http://www.realvnc.com].

4. The Open Systems Interconnection Seven-layer Reference Model. [http://www.answers.com/topic/osi-model].

5. Introduction to Mesh Network routing issues. [ftp://ieee:wireless@ftp.802wirelessworld.com/15/03/15-03-0393-00-0030-mesh-network-outline.doc].

6. Building a Wireless World With Mesh Networking Technology. [http://www.intel.com/technology/magazine/communications/nc11032.pdf].

7. RFC 3561 – Ad hoc On-demand Distance Vector (AODV). [http://www.faqs.org/rfcs/rfc3561.html].

8. Simulation Model for the AODV MANET Routing Protocol. [http://www.antd.nist.gov/wctg/manet/prd_aodvfiles.html].

9. Wireless Ad Hoc Networks homepage. [http://www.antd.nist.gov/wahn_home.shtml].

10. Distributed Detection for Smart Sensor Networks. [http://w3.antd.nist.gov/wctg/smartsensors/sensornetworks.html].

11. RFC 3684 – Topology Dissemination Based on Reverse-path Forwarding (TBRPF). [http://www.faqs.org/rfcs/rfc3684.html].

12. Ronja: Reasonable Optical Near Joint Access, optical point-to-point data link. [http://ronja.twibright.com].

13. An Introduction to Optical Wireless. [http://www.eng.ox.ac.uk/optcomm/research/Intro/optical%20wireless%20introduction.htm].

14. UWB Archive: Ultra Wideband (UWB) Frequently Asked Questions (FAQ). [http://www.multispectral.com].

15. Propagated Reference Design Provides Portable Ultra-wideband (UWB) Personnel Tracking System. [http://www.eetimes.com/showArticle.jhtml?articleID=20300709].

16. Run for your life: Ultra low-power systems designed for the long haul. [http://www.edn.com/article/CA601827.html?industryid=2817&text=].

17. The DARPA-sponsored SensIT program. [http://www.sainc.com/sensit].

18. IEEE Begins Wireless, Long-wavelength Standard for Healthcare, Retail and Livestock Visibility Networks. [http://standards.ieee.org/announcements/pr_p19021Rubee.html].

19. Near-field Electromagnetic Ranging (NFER). [http://www.q-track.com].

20. Near-field Communication (NFC) Forum. [http://www.nfc-forum.org].

21. Near field or far field? How do we define the far field of an antenna system, and what criteria define the boundary between it and the near field? The answer depends on your perspective and your design's tolerances. [http://www.edn.com/article/CA150828.html].

22. Trolley Scan (Pty.) Ltd., RFID-Radar™. [http://www.rfid-radar.com].

23. IEEE 802.15 WPAN™ Task Group 4 (TG4). [http://ieee802.org/15/pub/TG4.html].

24. IEEE 802.16 LAN/MAN Broadband Wireless LANS standards. [http://standards.ieee.org/getieee802/802.16.html].

25. Electronic ID, Inc. [http://www.electronicidinc.com].

26. Wal-Mart Suppliers Discuss RFID. [http://www.rfidjournal.com/article/articleview/956/1/1].

27. RFID Blocker Tags. [http://www.ddj.com/dept/architect/184405806].

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