Paper Number: 036157
An ASAE Meeting Presentation
Not a peer reviewed paper

Wireless Data Transmission of Networked Sensors in Grain Storage

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Written for presentation at the
2003 ASAE Annual International Meeting
Sponsored by ASAE
Riviera Hotel and Convention Center
Las Vegas, Nevada, USA
27- 30 July 2003

Abstract. *Current grain-temperature monitoring systems employ sensors that are hard-wired into a structure. Thermocouples are typically used and are integrated into a supporting cable which is suspended between the ceiling and floor of a structure. Multiplexed signal conditioning is performed outside the structure with the data transmitted to a display and storage device. Wireless sensors were studied as an alternative to these systems. The main issue addressed in this study was the data transmission distance through grain that can be achieved by a low-power radio frequency (RF) device designed to operate in the unlicensed FCC spectrum. Results showed that sensors transmitting at 915 MHz and 1 mW power were able to communicate reliably over a 2-m distance, although this was close to their transmission limit. Measured signal attenuation displayed typical small-scale fading patterns, i.e. sub-wavelength changes in position caused high variability in signal strength. A 2-m range would allow reasonable spatial resolution for monitoring grain conditions, such as temperature, although sensors would have to be networked in order for data to be sent to an external gateway. Theory on RF attenuation in grain gave an approximation of experimental transmission signal loss but did not provide the accuracy desired to determine RF range. It was, however, helpful in selecting the most appropriate frequency range to achieve the greatest transmission distance.*

Keywords. grain, storage, temperature, radio frequency

Introduction

Monitoring grain temperature during storage provides a good management tool for quality control. Temperature is useful for determining aeration needs to control excess moisture which causes microbial growth, sprouting and germination. It is also useful to determine optimal aeration times to control insect population growth or to achieve insect mortality.

Temperature-monitoring systems for grain storage can be constructed using different hardware implementations. Thermocouples are the most common method for temperature measurement. Thermocouple wiring systems consist of multiple sensors integrated into a structural cable that is suspended in the grain storage from ceiling to floor. The cable provides support for the sensor wiring, which is exposed to severe forces during the filling and unloading of grain in storage. Thermocouple junctions are spread at distances of 1.5 to 3 m along the support cable and wiring is routed to a common point where the signals are multiplexed and conditioned. Signals may be digitized for more reliable transfer to remote monitoring and display systems. Other systems use temperature sensors that transmit digitized data over a two-wire bus (Pfeuffer, GmbH). The inherent advantage of this system may be less susceptibility to signal noise.

An alternative to the above systems is use of wireless sensors to transmit digitized temperature data. Kiefer (2002) describes wireless sensor technology as not particularly new although, development has been hindered by size and power requirements for electrical functions. Nearly all of these limitations have been overcome and continue to be improved upon.

Present development of wireless sensors covers a broad range of interests that share much in common with development of wireless devices that use Bluetooth™[*] technology. Rajaravivarma et al. (2003) provide a basic overview of a commercial wireless sensor development platform.

Because many wireless sensors are designed for battery operation, they can be deployed by simply placing them wherever needed. In addition, wireless sensors can be programmed to form their own ad hoc network to relay data over relatively long distances (Ye et al., 2002). Networking is essential if sensors are buried in grain and are out of transmission range to a central receiver or gateway. Some apparent advantages of these sensors over other systems would be easier deployment in grain storage that may require temporary monitoring. Their design can incorporate the addition of new sensors that would monitor other grain attributes and to monitor other areas of the grain handling system such as motor temperature, belt alignment, or fill level. There is also the potential that sensors could travel with the grain throughout distribution. Some disadvantages could be cost and inability to provide spatial orientation in the grain without a support cable.

Current designs of networked sensors typically include a micro-controller, a RF transceiver, and a sensing element such as a thermistor. This basic design allows adaptation of other sensors

[*] Bluetooth is a trademark Telefonaktiebolaget L M Ericsson, Sweden

without additional wiring, and provides a platform with sufficient computational and control power for sophisticated sensing and networking. Current sensors can be designed to be battery-operated for more than a year. While these devices are designed for indoor and outdoor use where communications ranges are typically 30 to 300 m, little work has been done on adapting them for transmitting through a medium such as grain.

In late 1980s, the FCC committed certain parts of the RF spectra to unlicensed use for development of various low-power devices. Sections of spectra released were 902-928 MHz and 2.4-2.483 GHz, and since then this region has been used for a number of common devices such as cordless phones, microphones, and more recently wireless piconet devices for computers. In 1997, an additional 300 MHz of unlicensed spectrum, 5.150-5.350 and 5.725-5.825, was released. Unlicensed spectra is controlled under FCC Part 15, Radio Frequency Devices regulations which apply limitations on transmission field strength, spurious emissions, and spread-spectrum implementation (Rappaport, 2002). These regulations are imposed to allow a large number of devices, with limited transmission range, to exist within a relatively small area.

Development of FCC Part 15 devices has been broad, although one major focus has been development of wireless networks that devices will use to communicate with each other. Types of networks these devices use can be split into two categories of either WLAN (wireless local area network) or WPAN™ (wireless personal area network). The former can be considered a wireless replacement or extension for conventional wired networks. An example might be the connection of laptop computers in a large building complex. WPAN™* networks perform at a more localized scale and are suitable for connecting small personal devices to each other and to a PC. The technologies differ in three fundamental ways: 1) power levels, 2) control of the media and 3) life-span of the network. Both technologies use the 2.4 GHz band, although WLAN is shifting towards 5 GHz which allows faster transfer rates. Earlier development used the 902-928 MHz spectra primarily because hardware devices were easier to design, although this region is limited to use in the USA, Australia, Israel, and to some extent Canada and Mexico. Devices designed for 2.4 and 5 GHz can be implemented worldwide with fewer limitations.

The Institute of Electrical and Electronic Engineers (IEEE) continues to develop standards for both networks under the 802.11 and 802.15 working group committees. Bluetooth specifications fall under the 802.15 working group. A brief comparison of specifications shows that 802.11a allows 40 Mbps in the 5.8 GHz band, and 802.11b operates at 11Mbps in the 2.4 GHz band with communications up to 50 m. Bluetooth operates at 1 Mbps and communicates at a range of up to 10 m. An IEEE 802.15 Coexistence Task Group 2 for WPAN is developing practices to facilitate coexistence with WLAN (802.11).

The significance of regulations, standards, and development of compliant wireless grain sensors is that greater flexibilty in design is available by using the extensive amount of hardware developed for similar devices. Other benefits include use of existing devices for hardware interfaces. While compliance does limit the amount of transmission power, there is some selectivity on the transmission frequency used, namely 900 MHz, 2.4 GHz, or 5 GHZ.

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* WPAN is a trademark of the IEEE, Piscataway, NJ

Objectives

RF transmission distances through grain from a low-power (battery-operated) device are unknown and was the focus of this study. Specific objectives of this research were to select the

RF frequency range that maximizes transmission range through grain and to experimentally determine transmission distances that can be achieved by wireless sensors with low transmission power. Low transmission power arises from having a limited power source and also complying with regulations under FCC Part 15, Radio Frequency Devices.

Procedures

Attenuation of radio frequencies in grain can be calculated by Equation 1 (Nelson, 1996) for the condition $\varepsilon'' << \varepsilon'$.

$$\alpha = 8.686\, \pi\, \varepsilon'' / \lambda\, (\varepsilon')^{0.5}$$

Where:
α represents attenuation in dBm per meter of path length, (dBm/m);
λ is the free-space wavelength for the frequency, (m) and
ε' and ε'' are the dielectric constant and loss factors respectively.

Dielectric constants are frequency and moisture-dependent but do not vary greatly. At a constant moisture content, from 900MHz to 10GHz for a grain such as wheat, ε' changes from approximately 3 to 2.5 and ε'' from .3 to .25. (Nelson, 1996). Within this frequency range, attenuation is more heavily influenced by wavelength. Using these values, attenuation is approximately 11-15 dBm/m for 900 Mhz (0.333 m wavelength), whereas attenuation values at 2.4 Ghz are 30-40 dBm/m. Because less attenuation is predicted in the 900 MHz region, this frequency range was selected for sensor operation.

A wireless sensors evaluation kit (Dust Inc., Berkeley, Ca) was used to determine signal strength attenuation as a function of grain depth. The kit contained 10 sensors, referred to as motes, a gateway to communicate with the motes via a PC, and software. Motes are designed for sensor network development, are programmable, and can be interfaced to user-designed sensors through a hardware interface plug.

As supplied, the motes transmit on a single frequency (915 MHz) at a power level of about 1 mW using a coil quarter-wave antenna. They have spread-spectrum capability, although this requires additional programming. Individual motes consist of a micro-controller, RF transceiver chip, flash memory, and an integrated thermistor for demonstration purposes (Fig. 1). Motes are powered by a 3-V lithium battery with a capacity of 1000 mAhr, which can provide up to four years operation depending on usage. Mote costs are approximately $150 each in small quantities. The resident mote program, as supplied, does not have network capability with other motes but can be programmed for this by the developer. It does, however, provide RF communication with a gateway connected to a PC. Through the gateway connection, a PC program displays temperature data from each mote, as well as battery voltage and signal attenuation. Attenuation is a standard measurement for most wireless devices, as it allows the adjustment of transmit power to an adequate level for communication. This is important for a battery-operated device since most of the power consumption is used in transceiving signals. Attenuation measured by the gateway was used in this study to determine the transmission loss from each mote as a function of transmission distance through wheat.

Three motes placed in an acrylic housing designed so that they could be buried in grain to specific depths and then retrieved by a tethering cable were used in tests. Placement in the grain was done by pushing the acrylic housing from the top of the grain surface using a push rod (Fig. 2). The tethering cable and push rod were marked to indicate depth. Motes were initially pushed to the maximum depth of 2 m; the push rod was then removed and partially extracted after signal measurements to obtain decreasing depths. A steel grain bin filled with wheat was used for tests and was located at the USDA-ARS GMPRC facility (Grain Marketing and Production Research Center, Manhattan, KS).

Four attenuation readings from each mote were taken at each depth over a period of ten minutes. The gateway receiver, connected to a laptop, was also repositioned to determine variance in received signal strength at three different locations (Fig 3). Additional attenuation measurements were taken with three motes within the office and lab structure at the GMPRC to determine the maximum signal attenuation that occurs before motes are unable to communicate. This was done by gradually increasing the distance of the motes from the gateway until communication was lost. This data was used to provide reasonable estimates of the maximum grain depth that the motes can communicate to when combined with measured-attenuation and grain-depth data. This value was termed T_{max}. Minimum attenuation was also determined, similarly to the maximum, by observing the minimum attenuation value that occurs when motes are in close proximity to the gateway. This represents a baseline for comparison with other loss factors and was termed $T_{min.}$ The minimum attenuation is most likely attributed to the antenna and receiver characteristics.

Results and Discussion

The average T_{max} and T_{min} values for individual motes ranged from -104 to -107 dBm and –55 to -53 dBm, respectively. Overall averages of T_{max} and T_{min} were 105.5 dBm and 54 dBm, respectively.

Average signal attenuation from the combined data of mote gateway depths are shown in Fig. 4. Also shown are the overall averages of T_{max} and T_{min} values. This data indicates that motes are approaching a communication range of a little more than 2 m on average.

Variation of signal strength with depth, Fig. 5, deviates substantially from the average at most depths and is typical of small-scale fading problems of indoor radio communications systems (Rappaport, 2002). This type of fading occurs at sub-wavelength position changes between receiver and transmitter and is due to destructive interference between multi-path signals arriving at the receiver. Within a steel structure, such as a grain bin, destructive interference could be substantial due to high reflectivity. ANSI/IEEE Std 802.11 (1999) contains a two-dimensional contour map of signal strength within a typical office room, which illustrates the problem of multi-path fading.

Considering a theoretical loss of 15 dBm/m from Equation 1, total loss at 1-m and 2-m depths would be the baseline minimum –53 + –15 = –69 dBm and –(53+30) = –83dBm, respectively. Average measured values were –73 dBm and -104 dBm, respectively. Discrepancies between these emphasizes the reason that working models describing RF signal strength are built exclusively upon measured data.

Conclusions

Wireless sensor motes, with limited transmitter power, were able to communicate reliably through grain over a 2-m distance to a gateway. At the transmission power levels used, this would appear to be approaching their limit.

Signal strength as a function of transmission distance through grain showed typical small-scale fading patterns, i.e. sub-wavelength changes in position caused high variability in signal strength. Theory on RF attenuation in grain gives a rough approximation on experimental transmission signal loss but does not provide the accuracy desired to determine RF range. The 2-m transmission range allows reasonable spatial resolution for monitoring grain conditions such as temperature, although sensors would have to be networked in order for data to be sent to an external gateway.

Wireless sensors can provide an alternative method to monitor stored-grain temperature although advantages and disadvantages compared with conventional wired monitoring systems needs to be explored. This should include design flexibility of both systems to accommodate sensors for purposes other than temperature, cost of sensors, situational advantages such as use for permanent or temporary storage monitoring, and reliability.

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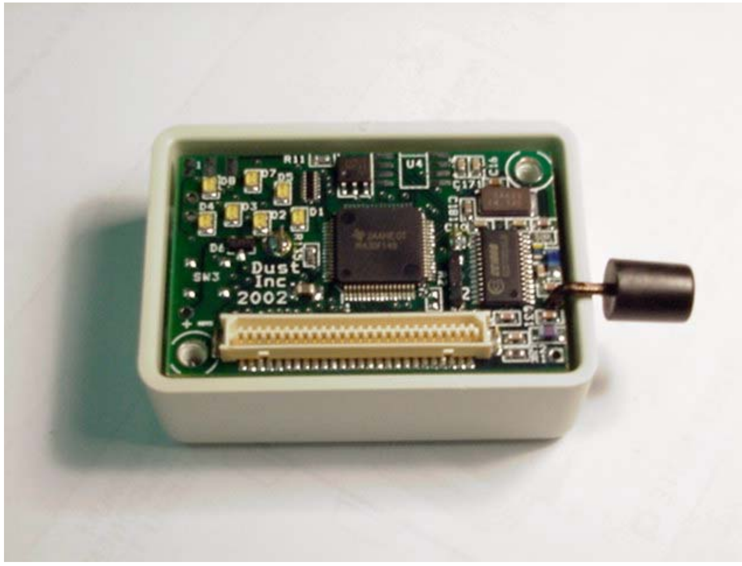


Figure 1. Mote with the top cover removed. Main IC components are the micro-controller, RF controller, antenna, and interface plug for adding user-designed sensors which interface directly to the micro-controller. Battery is tab-soldered to the bottom of the board. Mote dimensions are 50 x 38x 19 mm.

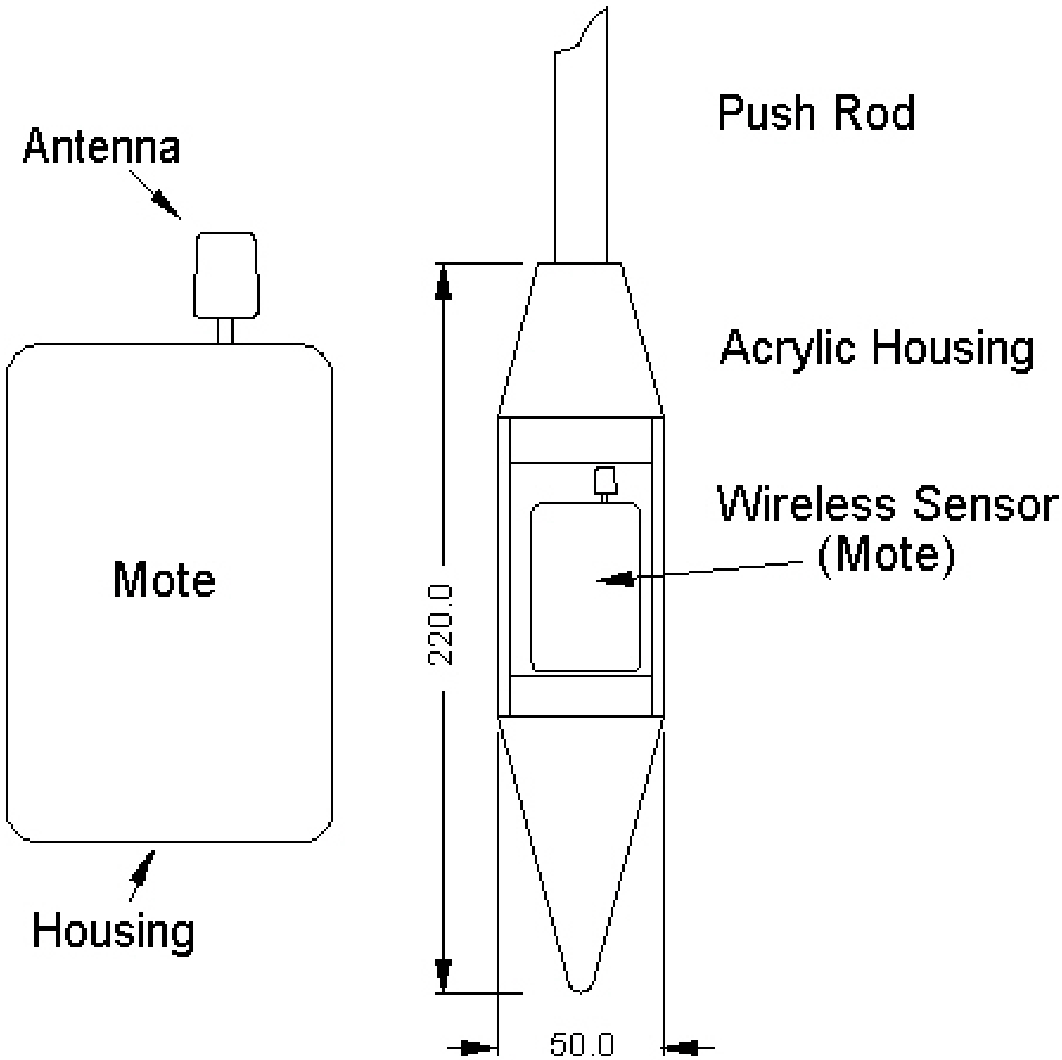


Figure 2. Acrylic housing constructed to place motes in grain. Dimensions are in mm.

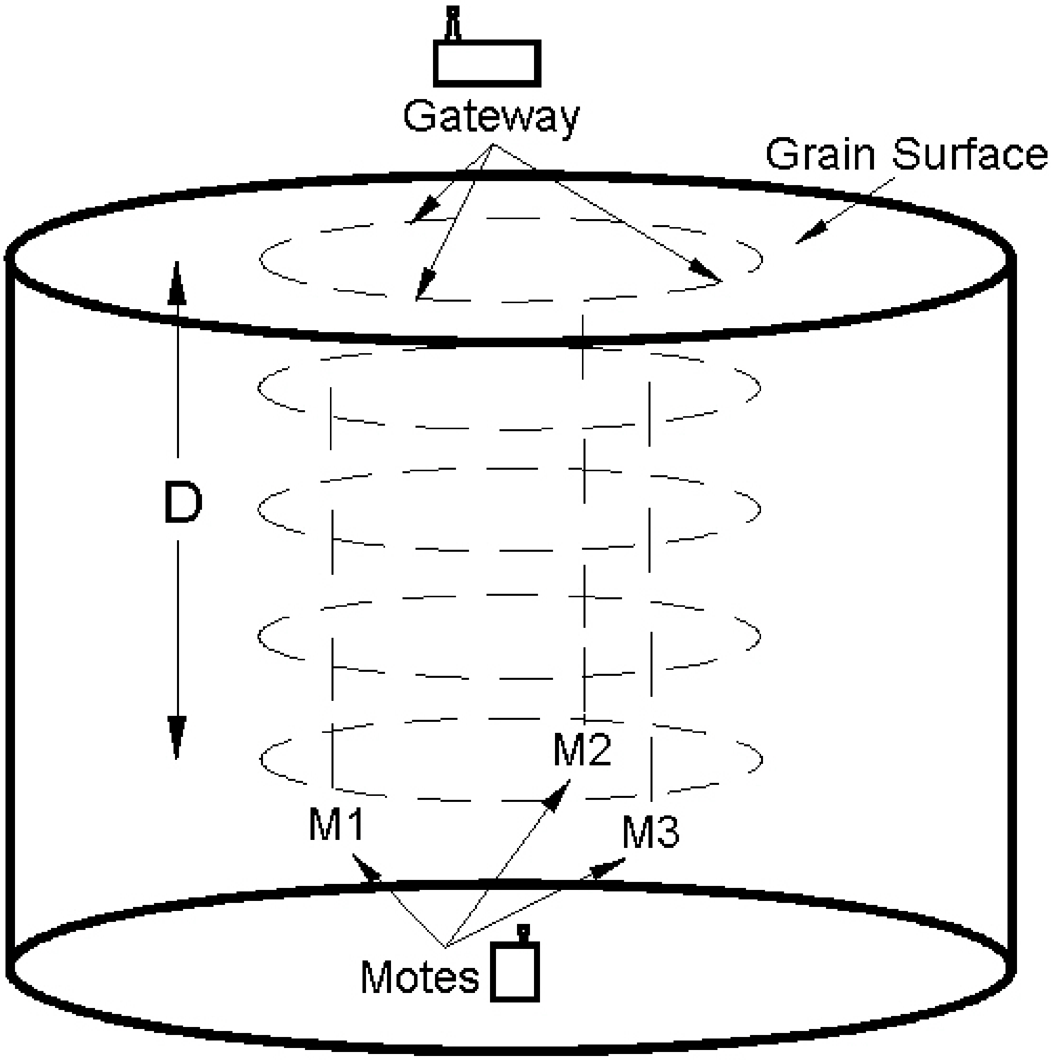
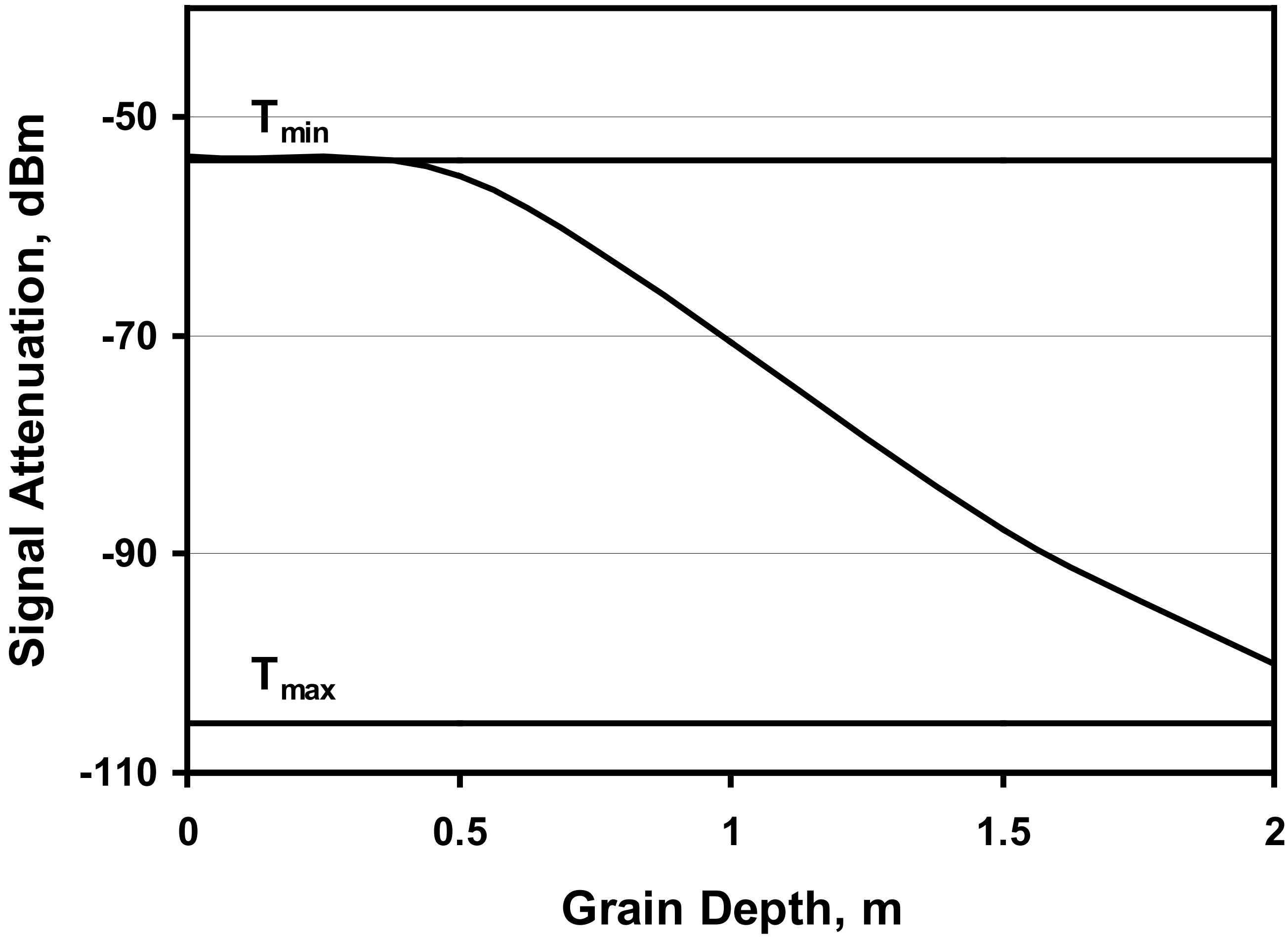
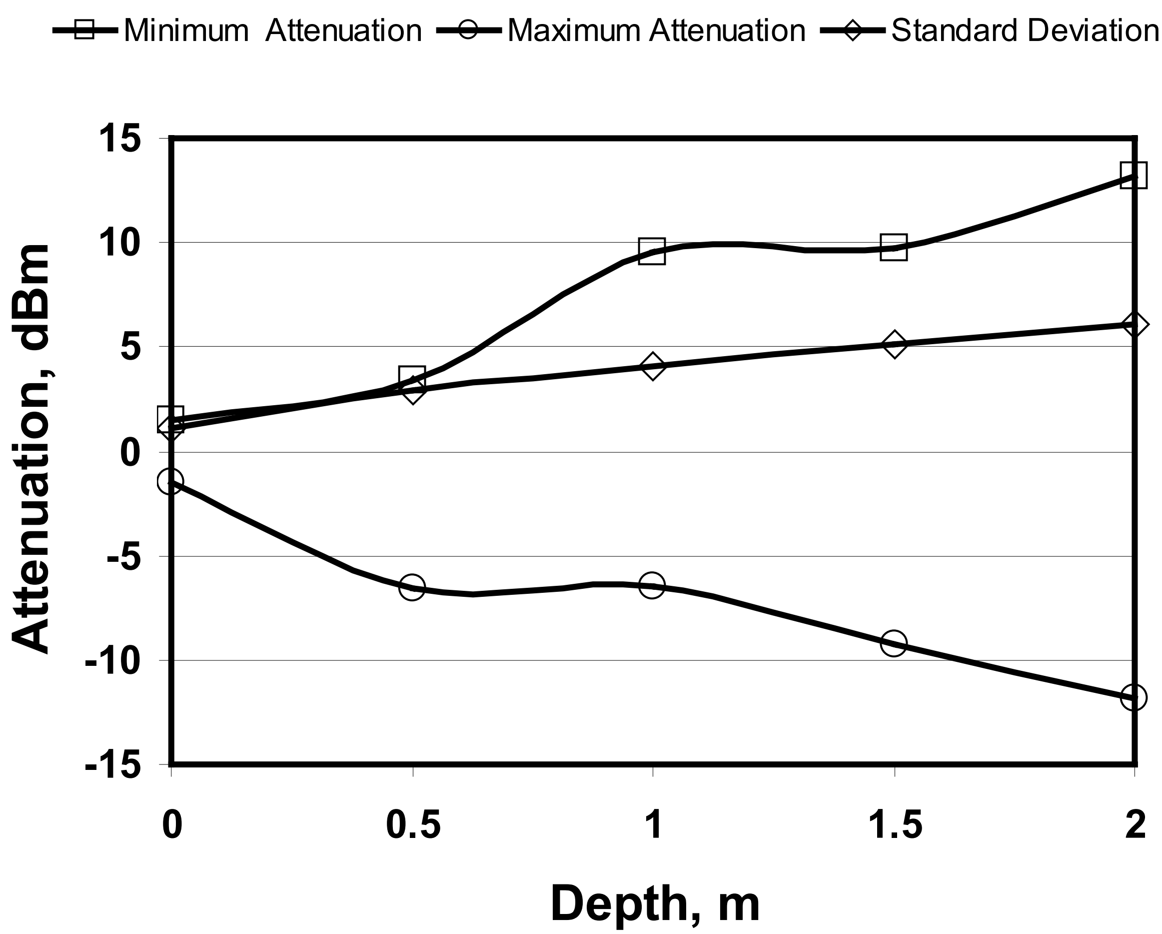


Figure 3. Mote and gateway placement within grain for measurement of signal attenuation. The drawing is not to scale. Motes were placed in the circular section with an approximate radius of 0.5 m. D is grain depth.



solid curve. T_{min} is the average minimum attenuation observed at any position. T_{max} is the maximum attenuation observed before communication is lost.



gateway positions. Min/max values are shown as differences from the mean attenuation value. Standard deviation is calculated from all mote data at the specified depth.