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Wireless sensor network performance metrics for building applications

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ABSTRACT

Metrics are investigated to help assess the performance of wireless sensors in buildings. Wireless sensor networks present tremendous opportunities for energy savings and improvement in occupant comfort in buildings by making data about conditions and equipment more readily available. A key barrier to their adoption, however, is the uncertainty among users regarding the reliability of the wireless links through building construction. Tests were carried out that examined three performance metrics as a function of transmitter–receiver separation distance, transmitter power level, and obstruction type. These tests demonstrated, via the packet delivery rate, a clear transition from reliable to unreliable communications at different separation distances. While the packet delivery rate is difficult to measure in actual applications, the received signal strength indication correlated well with the drop in packet delivery rate in the relatively noise-free environment used in these tests. The concept of an equivalent distance was introduced to translate the range of reliability in open field operation to that seen in a typical building, thereby providing wireless system designers a rough estimate of the necessary spacing between sensor nodes in building applications. It is anticipated that the availability of straightforward metrics on the range of wireless sensors in buildings will enable more widespread sensing in buildings for improved control and fault detection.

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1. Introduction

Wireless communication technology opens up a wealth of opportunities for monitoring and controlling conditions within a building by easing the installation of sensors, actuators, and controllers. While building automation systems can currently operate heating, ventilating, and air-conditioning (HVAC) and lighting systems efficiently, the presence of more sensors and actuators throughout a building could further improve the comfort of occupants while reducing energy consumption. Additionally, extra sensors can augment the safety and security systems in a building. Wireless technology enables increased numbers of sensors, actuators, and controllers in a building by drastically reducing the cost and effort of installation. The elimination of signal wire also provides greater flexibility within spaces with adaptable configurations and permits sensing and control in historic buildings without damaging the structure.

The emergence of wireless technology in building applications is evidenced by the numerous articles that have documented its use in buildings [1–6]. The technology promises to play an even larger role in building operations with the recent efforts by the American Society of Heating, Refrigerating, and Air-Conditioning Engineers' (ASHRAE) Building Automation and Control Networks (BACnet) committee to develop methods to expand a BACnet network with ZigBee wireless mesh networks [7].

Despite the apparent ease with which people can deploy wireless sensors and actuators in a building, engineers and operators still have concerns and questions regarding the use of wireless technology in buildings. A measurement need identified in the Assessment of the United States Measurement System stated that "Potential end users of wireless sensor networks have shown reluctance towards using them in a wider range of applications because of uncertainty in the reliability of the wireless links" [8]. This paper summarizes some of the most critical issues with wireless system performance that inhibit their adoption and focuses on metrics to predict the performance and reliability of these systems, which will help users gain more confidence in their use.

2. Practical challenges

To determine the obstacles to adoption of wireless technology by the building industry, a literature review and interviews with building professionals were conducted. Details of that process are documented in Ref. [9]. Among the major perceived obstacles to the implementation of wireless sensor networks in buildings were reliability degradation caused by signal attenuation through the

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building structure, reliability degradation caused by interference, security, battery lifetime, initial costs, and ease-of-use. This paper will address the issue of reliability as it is affected by the building structure.

3. Reliability and reliability metrics

At its most basic level, a customer of a building automation system expects the same level of reliability with a wireless system as is seen with wired systems. For a broader range of applications, that reliability requirement may either be more or less severe. In a qualitative sense, reliability means that the desired data are sent to the receiver at the desired times, with little delay, and with minimal measurement error.

Defining reliability is itself a difficult endeavor, as it involves a number of issues and can be affected by numerous factors. Among the issues that make up reliability are data delivery, accuracy, and latency. Successful data delivery is dependent on a high quality radiofrequency (RF) link between the transmitter of data and the receiver. Accuracy of that data stream depends on the sensor itself as well as the RF connection. Accuracy at the sensor is a challenge regardless of the communication method and is, therefore, not an issue solely associated with wireless sensors. The RF connection will rarely result in a drop in accuracy of the data since data are transmitted in digital format and corruption of that data stream will typically result in data delivery problems as opposed to modified data values. Latency refers to the time between the measurement of data at a sensor and the receipt of that data at the data collection point. While data transmission by RF occurs at the speed of light (and, hence, causes little delay in obtaining the data), the design of the radio nodes and network can add delays to transmission by storing data or relying on multiple relays of messages. Such delays can often be mitigated through proper design of the system.

Successful data delivery, therefore, becomes the primary concern of users of wireless sensor networks in buildings. Ensuring that data can be delivered in a particular situation essentially entails assuring that the strength of the signal at the receiver is strong in relation to the surrounding noise. Eq. (1) provides the Friis free space equation that gives the power received by an antenna in the absence of interfering media [10]:

$$P_r(d) = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d^2 L} \tag{1}$$

where $P_r(d)$: received power; P_t: transmitted power; G_t: transmitter antenna gain; G_r: receiver antenna gain; λ: signal wavelength; d: distance between transmitter and receiver; L: system loss factor (associated with radio hardware).

While this equation is technically valid only in free space where no obstructions affect the signal, trends are still evident. Most notably, it can be seen that the received power decreases with the square of the distance between the transmitter and receiver and is directly proportional to the transmitted power. Additionally, the received signal strength is dependent upon the wavelength, but this relationship is less critical in applications of sensor networks in buildings since most hardware utilizes the 2.4 GHz Industrial, Scientific, and Medical Band.

A key factor that is not considered in Eq. (1) that affects the strength of the signal in building applications is the presence of obstructions. Walls, floors, doors, windows, equipment, and other features of buildings all have some effect on the transmission of wireless signals. While some materials may present little resistance to the propagation of RF messages, others (e.g., metals) may completely stop the propagation of those messages. Even in buildings that are built with materials that allow easy passage of wireless signals, interference from other devices that generate RF energy can affect the reliability of signal propagation, which is another factor absent from Eq. (1). These devices could be engineered to produce those signals as part of operation (e.g., cellular telephones) or could produce the RF as a by-product of operation (e.g., microwave ovens). In either case, the added noise could interfere with the RF signal being sent by the transmitter or could make interpretation of that signal by the receiver more difficult. To overcome one or both of these factors, sensor networks can be designed to overcome interference or effects of the building construction, thereby improving the system's reliability.

In this work, metrics for assessing reliability in building applications are explored. The metrics of interest to this discussion are:

3.1. Received signal strength indication (RSSI)

Received signal strength indication (RSSI) is a term used to describe the strength of a wireless signal. The units are either those of power (e.g., mW) or, more commonly, dBm = 10 × log(P_r/1 mW).[1] Circuits to determine RSSI are often placed on radio hardware, providing the ability to automatically determine RSSI in a variety of devices with wireless receivers. The algorithm used to determine RSSI may vary on different devices, so it is a measure that is most useful in assessing the effect of environmental factors on a particular radio. The drawback that has been observed with the use of RSSI as an indicator of the reliability of the wireless link is that it does not always correlate with the rate of reception of wireless packets (or, packet delivery rate, as will be discussed later). RSSI simply measures the strength of the signal regardless of the surrounding noise. A low-strength signal in a noiseless environment gets a low RSSI despite the fact that it has a better chance of transmitting data successfully than a high-strength signal in a noisy environment (which would receive a high RSSI).

3.2. Link quality indication (LQI)

The Institute of Electrical and Electronics Engineers (IEEE) 802.15.4 standard [11], the predominant standard for the physical aspects of low data-rate radio communications as used in the building industry, specifies the use of a link quality indication (LQI) to assess the quality of the communication link between a receiver and transmitter. This calculation is based on signal-to-noise ratio or energy density of the signal in the frequency band used by the standard and is typically computed over at least eight transmission cycles to estimate the link strength for a typical transmission. This value is unitless, and comparison of the numbers between different technologies is difficult. As with RSSI, this measure can be used to assess the environmental effects on a single transmitter/receiver pair. It provides a more thorough estimate of the quality of an IEEE 802.15.4 link than RSSI since it assesses all possible frequencies in the physical layer of the transmission. LQI is a valuable measure of reliability because much of the radio hardware used to implement wireless sensor networks automatically computes the value for the user.

3.3. Packet delivery rate (PDR) and packet error rate (PER)

At its simplest level, a reliable system is one in which each packet of data transmitted by the sensor is received correctly by the receiver. One way to measure reliability in this manner is to keep track of the number of messages sent by the transmitter and monitor the number of messages successfully received at the base

[1] It is NIST policy to use SI units in all its publications. In this document, however, "dBm" will be used to express the received signal power because of its commonly accepted usage in the field of wireless communications.

Table 1
Test conditions.

Parameter	Value		
Distance	1 m to distance where signal is lost		
Transmitter power	0 dBm, −10 dBm, −25 dBm		
Obstruction	Material	Thickness (cm)	Comments
	None	–	Open field (grass or pavement)
	Gypsum board	1.3	Outdoor Height = 1.2 m Width = 1.2 m
	Plywood	1.3	Outdoor Height = 1.2 m Width = 1.2 m
	Steel plate	1	Outdoor Height = 0.5 m Width = 0.5 m
	Concrete hollow block (without rebar)	19.5	Outdoor Height = 0.2 m Width = 0.4 m
	Brick wall	30 total; comprised of 3 bricks each = 9.5 cm plus two layers of mortar	Outdoor Part of existing wall Height = 3.4 m Width = 0.7 m
	Composite (plastic + metal) door	4.5	Exterior door Part of existing wall Receiver outdoors Transmitter indoors Height = 2.4 m Width = 0.9 m
	Interior office wall (metal panels)	10	Transmitter and receiver indoors

station. The reliability can then be expressed as the percentage of the total number of transmissions that are successfully received, or as a packet delivery rate. The inverse of this metric would be the packet error rate, which would equal 1 − PDR. This metric is independent of the system technology and, therefore, allows comparison between systems.

For end users, the most worthwhile metric for reliability is the packet delivery rate or packet error rate, but it is often easier to provide an instantaneous measure of the RSSI or LQI. Determination of the PDR or PER is not always possible in an application, since a radio receiver does not necessarily know about messages that were transmitted but were not received. This work attempts to evaluate the correlation between these three measures of reliability for building applications by evaluating data from a range of experiments through different building materials. The focus of the experiments was on degradation of reliability with distance and intervening material. Sources of electromagnetic interference, as would be generated from other devices operating at the same frequency range, have not been considered in these tests. It is anticipated that the result of this work will help users of wireless sensor networks develop measurement-based techniques to assess allowable separation distances between sensor nodes for particular building applications.

4. Experimental setup

To demonstrate the use of the different metrics for wireless sensor network reliability and to explore the relationships between these metrics, a series of tests were conducted with a single radio transmitting to a receiver. Since many applications in buildings will require low data-rate communications, hardware was selected that conformed to the IEEE 802.15.4 standard for low-rate wireless personal area networks (2.4 GHz band). Two different models of commercially available wireless sensor nodes were selected for evaluating the metrics. The two nodes shared the same hardware for generating and processing the radio signals, and this hardware provided a measure of both the RSSI and LQI. No difference was seen between the results using the two different brands of sensors, so sensor type did not become an independent factor in the experiments.

For these tests, the performance metrics were evaluated as a function of transmitter power, distance between the transmitter and receiver, and the type of building material placed between the transmitter and receiver. Table 1 describes the independent parameters varied in these tests. The dependent variables that were measured were the RSSI, LQI, and PDR.

The wireless transmitters were programmed to send messages with a length of 25 bytes at a rate of 10 per second. Among other items, the messages contained the node identification number and a count of the message number. It is acknowledged that the reliability depends upon the message length, but it was decided to keep the message length fixed in these experiments to eliminate that independent factor. The receiver was programmed to collect the messages from the transmitter and forward them through a serial connection to a computer where the messages were logged to a file. The message count sent by the transmitter in each message was used to determine if any messages were missed by the receiver.

Fig. 1 shows a schematic of the test setup. The tests were carried out in numerous locations. The base case where no obstruction is present was evaluated in an open grass field that allowed for a clear line-of-sight between the transmitter and receiver. Additional line-of-sight data were collected in a paved parking lot. To evaluate the effect of gypsum board, plywood, steel, and concrete block on the propagation of these signals, tests were conducted at the same location in the grass field, but the material was placed between the transmitter and receiver at a distance of approximately 1 cm from the transmitter. The height and width of these obstructions varied, but each was arranged such that the transmitter was spaced equally from each side and from the top and bottom edge of the material. For tests with the door, metal wall, and brick wall, components of an existing building were used. The transmitter was

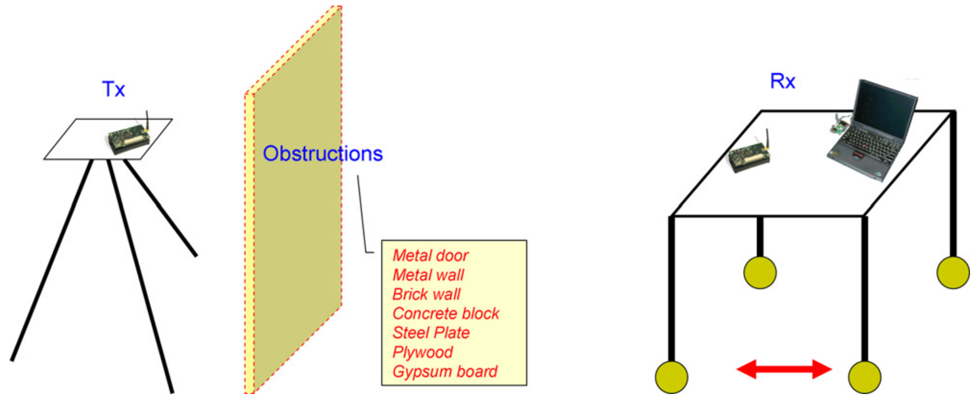

Fig. 1. Schematic of test setup.

once again placed approximately 1 cm behind the obstruction. The brick wall was an exterior feature of the building, and the transmitter and receiver were situated outdoors. For the test with a door, the transmitter was placed indoors and the receiver was situated outdoors. Tests with a metal wall as an obstruction were carried out completely indoors. Details of each material that served as an obstruction are given in Table 1.

The transmitter (Tx) was fixed at 1 m above the ground for all tests and was programmed to send messages at a specified power level. The receiver (Rx) and laptop computer for data collection were placed 90 cm above the ground on a cart. The horizontal and vertical distances between the transmitter and the edge of the obstruction varied, but the obstruction completely blocked the line-of-sight between the transmitter and receiver. The experiments started with the receiver positioned 1 m from the transmitter. The receiver was then moved away from the transmitter in increments of 1 m until the signal was lost. At each distance, data were collected for 30 s, providing 300 transmissions from the sensor node.

5. Assessment of range of reliability

The experiments were used to assess the allowable distances between transmitter and receiver that would result in "reliable" data transfer. The maximum distance for reliable communication will be called as the range of reliability. Figs. 2–4 show plots of the three metrics as a function of distance for a test with no obstruction in an open field and with transmitter power set at 0 dBm. Data from such a situation can serve as a baseline for performance within a building. Open field data are typically repeatable and are often the only data on allowable range that are provided by vendors. For each metric, a curve of form $a \times \exp(bx) + c \times \exp(dx)$, where x is distance and a, b, c, and d are coefficients, was fit through the data. The trends shown in these plots are typical of other tests. RSSI is shown in Fig. 2. At each distance, the average RSSI measured for the 300 transmissions is plotted along with error bars of $\pm$one standard deviation (σ). The maximum σ is $\pm$2 dBm. The accuracy in the RSSI measurement reported by the radio vendor is $\pm$6 dBm. Taking the Type A uncertainty to be 2 dBm and the Type B uncertainty as 6 dBm, the combined standard uncertainty in the RSSI measurement is 6.3 dBm. The downward trend of RSSI with distance matches the expected decrease in the signal strength with the square of distance as described by Eq. (1). The oscillations in the data at approximately 10 m were seen in most of the tests. While the source of those oscillations is not clear, it is thought that reflections from the ground may interfere either constructively or destructively with the signal at that location. Fig. 3 shows the data for LQI on a normalized scale from zero to 100. The data are once again plotted as the average of the LQI computed over the 300 transmissions at each distance and

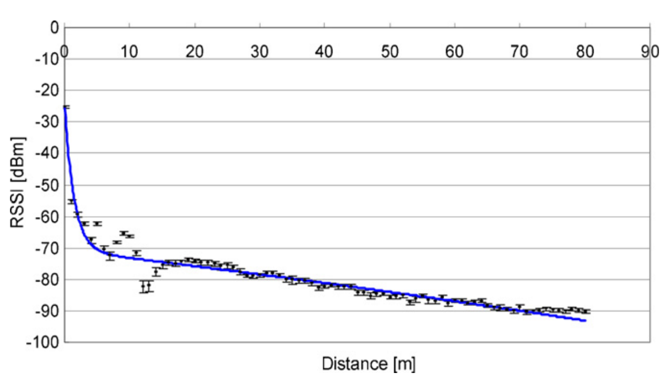

Fig. 2. Received signal strength indication vs. distance for transmission in an open field at 0 dBm.

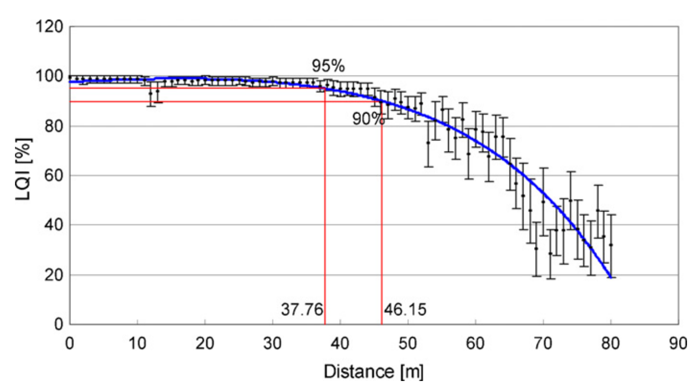

Fig. 3. Link quality indication vs. distance for transmission in an open field at 0 dBm.

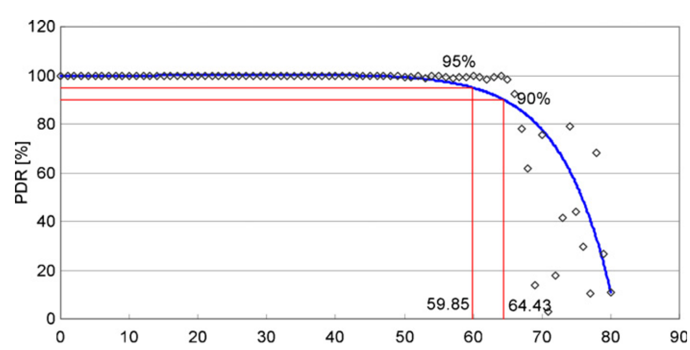

Fig. 4. Packet delivery rate vs. distance for transmission in an open field at 0 dBm.

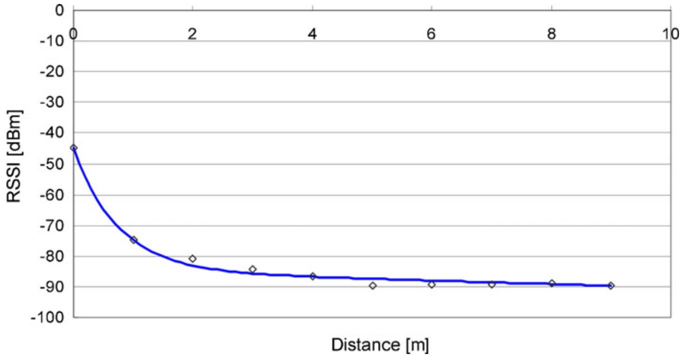

Fig. 5. RSSI vs. distance for transmission in an open field at −25 dBm.

error bars provide the uncertainty based upon the σ of those 300 measurements. It is interesting to note that the uncertainty increases with distance (and with decreasing LQI). The data show a gradual decline in LQI with distance, with significant scatter appearing in the data beyond approximately 50 m. On the plot, approximate distances where the LQI drops to 95% and 90% are determined based on a curve fit to the data. Fig. 4 shows data on the PDR. The data show that nearly all packets are delivered with distances up to approximately 65 m after which the delivery rate drops dramatically and demonstrates significant scatter. This finding is interesting, as it suggests that the range of reliability has a clear demarcation between strong and poor reliability. Despite this steep drop in PDR, a curve was fit to the data to allow for approximation of the distances of 95% and 90% PDR. Determining the uncertainty for PDR is difficult, as the computation is based upon division of discrete numbers. Based on the data, however, the uncertainty in PDR beyond the distance where it falls from nearly 100% is extremely high based upon the range of values that were attained at adjacent distances. Based on such an analysis, one could state that the uncertainty in each reading approaches 50%; for all practical purposes, however, the large uncertainty at these distances simply indicates that the distance is beyond the range of reliable communications.

Plots such as those shown in Figs. 2–4 were generated for all transmitter power levels and for all obstructions. The trends were similar for all plots, though low power levels and highly obstructive materials resulted in scattered data even at low distances. For example, Figs. 5–7 show data for open field measurements at a power level of −25 dBm, and Figs. 8–10 show data for propagation through an exterior brick-faced wall at 0 dBm. Uncertainties are similar to those shown in Figs. 2 and 3 and are not shown in subsequent plots. The distances displayed are much smaller than for the case of open field propagation at 0 dBm. Curve fits are challenging for LQI and PDR at large distances, but the region of high PDR is well represented by the curve fits and, hence,

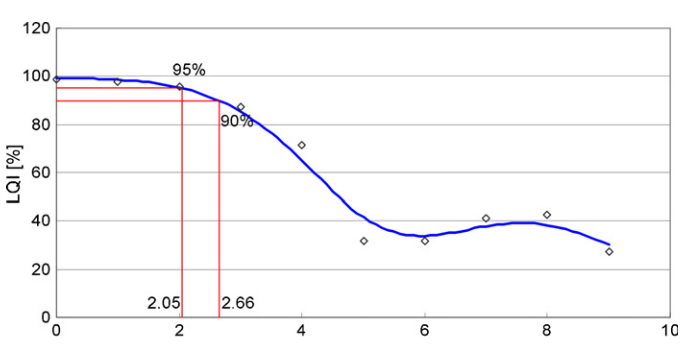

Fig. 6. LQI vs. distance for transmission in an open field at −25 dBm.

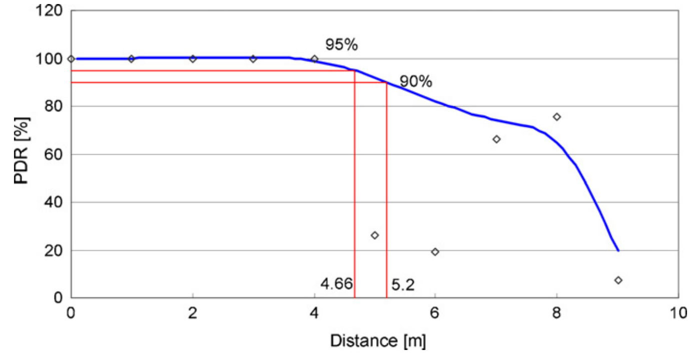

Fig. 7. PDR vs. distance for transmission in an open field at −25 dBm.

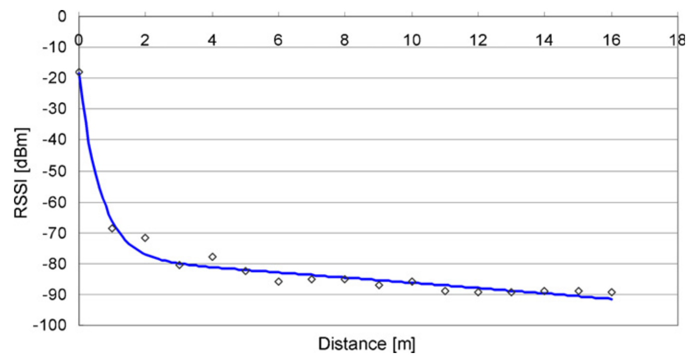

Fig. 8. RSSI vs. distance for transmission through brick wall at 0 dBm.

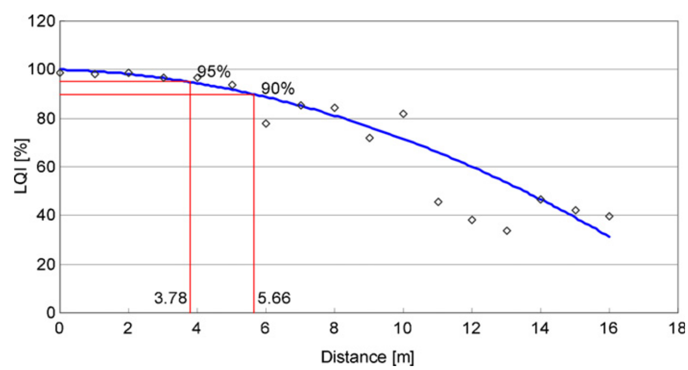

Fig. 9. LQI vs. distance for transmission through brick wall at 0 dBm.

the 95% and 90% PDR levels based on these curve fits predict the range of reliability relatively well.

A key component of this work was to investigate the relationships between the three metrics that could be used to assess the

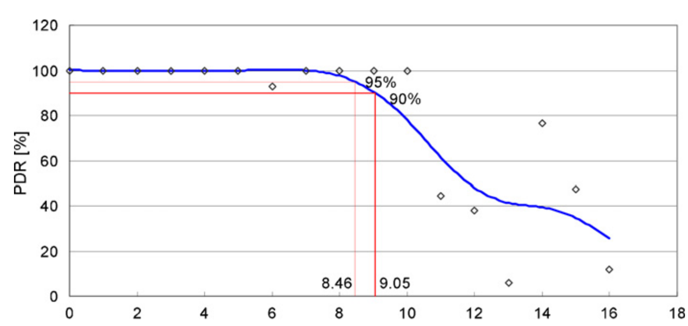

Fig. 10. PDR vs. distance for transmission through brick wall at 0 dBm.

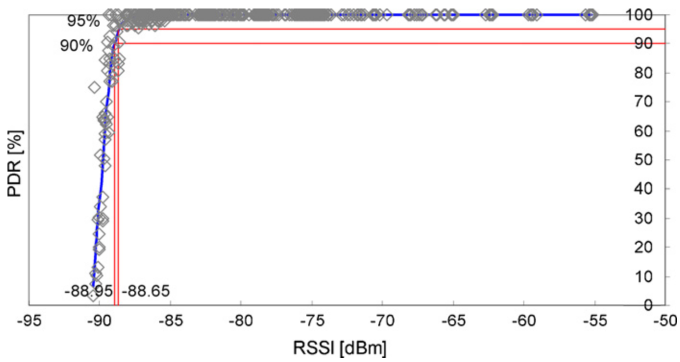

Fig. 11. Packet delivery rate vs. RSSI for transmission in an open field at 0 dBm and no obstructions.

reliability of a wireless connection. Figs. 11 and 12 show plots of RSSI and LQI, respectively vs. PDR for transmission on grass at 0 dBm. One can see that there is a clear RSSI value that corresponds to a jump in PDR towards 100%. The relationship between LQI and PDR does not result in as clear a threshold between low values of PDR and high values of PDR. Once again, curves have been fit to the data to try to estimate values of RSSI and LQI that correspond to 95% and 90% values in reliability. Fig. 13 shows a bar chart of the RSSI at the 90% and 95% PDR levels for all materials and line-of-sight measurements taken on both pavement and grass (labeled "Pavement (LOS)" and "Grass (LOS)," respectively) tested at a power level of 0 dBm. The RSSI corresponding to the desired reliability levels are essentially independent of material type, with an average RSSI of −87.9 dBm and a σ of 0.6 dBm as the threshold for 90% PDR and an RSSI of −87.5 dBm and a σ of 0.8 dBm for 95% PDR. Results at lower power levels were similar, with a 95% PDR achieved at −87.9 dBm (σ = 0.6) at a transmission power of −10 dBm and a 95% PDR achieved at −87.4 dBm (σ = 1.0) at a transmission power of −25 dBm. A clear threshold near −87 dBm exists that separates reliable data transmission from unreliable transmission for the equipment used in this study and for the relatively noiseless environment in which these sensors were tested.

6. Equivalent distance

Spacing between sensor nodes and receivers of the data from those nodes is a key component in knowing the required density of transmitters in a wireless sensor network. As previously mentioned, the only range that is specified by vendors is typically for line-of-sight operation. Here, it is proposed to use an equivalent

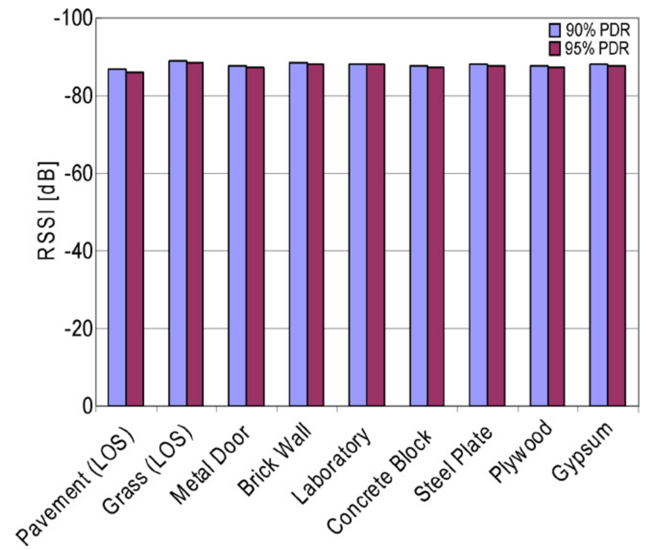

Fig. 13. RSSI at 90% and 95% PDR's for different materials, signals transmitted at 0 dBm.

distance to translate data from line-of-sight operations to that which could be obtained in applications in and around buildings. This distance is called the range of reliability.

Fig. 14 shows a bar chart of the range of reliability for all materials and line-of-sight measurements on both pavement and grass (labeled "Pavement (LOS)" and "Grass (LOS)," respectively) at a transmission power level of 0 dBm. Uncertainties on these values are significant (on the order of 10%), largely because of the difficulty in fitting curves to the raw data. For example, it is not expected that signals propagating through gypsum board would have a larger range than those traveling in a line-of-sight scenario. Nevertheless, these data will be used to provide general conclusions on the results.

For the equipment used here, the maximum distance between transmitter and receiver to assure reliable operation would be approximately 65 m. Plywood and gypsum board obstructions had little effect on this distance. The concrete block partially diminished the signal, but the other obstructions all significantly degraded the signals. Fig. 14 presents "equivalent distances" for a 90% or 95% PDR. For example, one could state that the equivalent of a 65 m range in line-of-sight operation would be approximately 20 m when the signal propagated through the door that was tested.

Table 2 summarizes the data obtained with obstructions by showing the percentage of the line-of-sight range for 95% PDR in

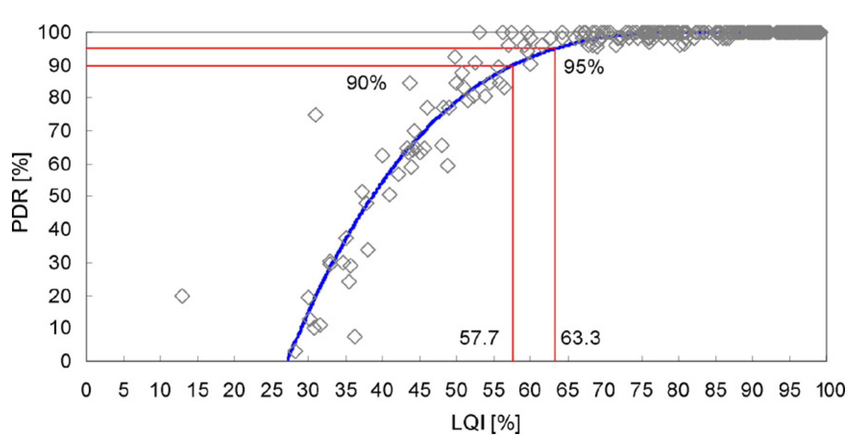

Fig. 12. Packet delivery rate vs. link quality indication for transmission in an open field at 0 dBm and no obstructions.

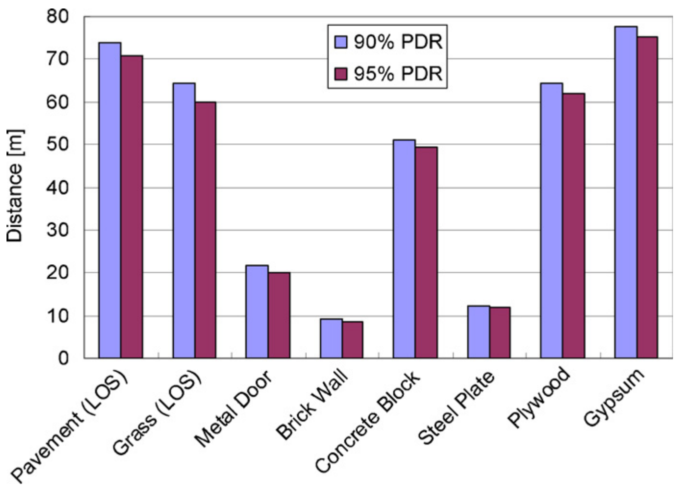

Fig. 14. Maximum separation distances between transmitters operating at 0 dBm and receivers to attain packet delivery rates of 90% and 95%.

Table 2
Percent of line-of-sight range obtained with obstructions for 95% PDR.

Obstruction	0 dBm	−10 dBm	−25 dBm
Gypsum board	126[a]	62	82
Plywood	105[a]	98	68
Concrete block	82	27	58
Door	35	1	–
Steel plate	20	13	–
Brick wall	14	9	4

Range of reliability for line-of-sight transmission at 0 dBm: 60 m.
Range of reliability for line-of-sight transmission at −10 dBm: 39 m.
Range of reliability for line-of-sight transmission at −25 dBm: 4.7 m.
[a] Uncertainties in measurements likely account for the unexpected results where ranges with obstructions exceed those obtained in a line-of-sight configuration.

the open field that yields the same reliability with an obstruction. Tables such as these can be used to provide equivalent distances to those reported by vendors for line-of-sight operation. This data set is limited to the particular technology tested here, but metrics such as these would be extremely valuable to designers of wireless sensor networks in buildings to provide a rough idea of the necessary spacing of radios in the sensor network.

Despite the large uncertainty in these numbers, a few trends can be observed. Gypsum board and plywood show very little resistance to the propagation of wireless signals, an observation that is confirmed by the low dielectric constant of these materials. As expected, metallic materials created an environment with a much lower range of reliability. While it appears that the presence of obstructions results in a larger percentage decrease in the range of reliability at lower powers, these findings are likely more a result of the fact that the maximum range for line-of-sight is small and that the scatter in data at these small distances further complicates the curve-fitting. For these power levels, the practical conclusion from the data is that the signal is extremely limited and that the designer should consider using larger power levels.

It can be argued that the use of curve fits is not appropriate given the scatter in the data. Curve fits have been utilized here to allow the end user the ability to determine the allowable distances given different levels of reliability. In some situations, a user may be willing to sacrifice some reliability to decrease the density of the sensors. The scattered data here suggest that a steep drop-off in PDR with distance does not allow a dependable prediction of a distance at which PDR is, for example, 50%. For this equipment, the PDR data beyond a certain distance indicate that the equipment can give a wide range of reliability numbers.

7. Conclusion

Wireless sensor technology promises the ability to monitor many points in a building, but the practical concerns of signal reliability in different built environments continue to lead to reluctance in their use. In this work, three metrics were considered for use in assessing the reliability of a wireless link for signal propagation. For tests using hardware meeting the IEEE 802.15.4 standard for low data-rate communications in a low ambient noise environment, the packet delivery rate was an effective metric for reliability that showed a clear threshold from reliable to unreliable communications at a received signal strength indication of approximately −88 dBm. As the PDR is difficult to measure in real time, the RSSI is clearly a valuable metric in predicting reliability.

The PDR can be used to provide users a gauge of the maximum distance between the transmitter and receiver over which reliable communications can occur. As data on radio range are typically only provided for line-of-sight applications, data were presented on the maximum distances at which a PDR of at least 95% was attained when each obstruction was present compared to that distance for line-of-sight applications. While the distance data possess a significant amount of uncertainty because of challenges in fitting data, the data can be used to give rough estimates to designers of wireless systems of the maximum spacing between transmitters and receivers for given construction materials.

The techniques described here could be used with a wider range of equipment and obstructions to provide useful data to installers of wireless sensor equipment. Since the radios used in the current experiments are those used in the majority of commercially available wireless sensors, these data are valuable for many installations of wireless sensor networks. A valuable extension of this work would be to carry out the experiments on a wider range of building materials and assemblies and to carry out a more thorough set of experiments to develop improved statistics on signal reliability. It appears that the wireless connections between radios experience stochastic effects, so statistical descriptions of the reliability may be an appropriate approach. Additionally, the vast differences in building types may make stochastic predictions of the reliability more feasible than other techniques as a general tool for wireless system designers. The work described here can be used as the framework for further development of appropriate metrics for the reliability of wireless sensor networks in buildings.

References

[1] M. Kintner-Meyer, M.R. Brambley, Pros & cons of wireless, ASHRAE Journal 44 (11) (2002) 54–61.
[2] M. Kintner-Meyer, M.R. Brambley, T.A. Carlon, N.N. Bauman, Wireless sensors: technology and cost-savings for commercial buildings, Teaming for Efficiency: Proceedings of the 2002 ACEEE Summer Study on Energy Efficiency in Buildings 7 (2002), 7.121–7.134.
[3] J. Wills, Will HVAC control go wireless? ASHRAE Journal 46 (7) (2004) 46–52.
[4] W.M. Healy, Lessons learned in wireless monitoring, ASHRAE Journal 47 (10) (2005) 54–58.
[5] J. Raimo, Wireless mesh controller networks, ASHRAE Journal 48 (10) (2006) 34–38.
[6] J. Ruiz, Going wireless, ASHRAE Journal 49 (6) (2007) 33–43.
[7] J.P. Martocci, BACnet unplugged: ZigBee and BACnet connect, ASHRAE Journal 50 (6) (2008) 42–46.
[8] D.A. Swyt, An Assessment of the United States Measurement System: Addressing Measurement Barriers to Accelerate Innovation, 2007 NIST Special Publication 1048.
[9] W.M. Healy, W.S. Jang, Practical Challenges in Wireless Sensor Network Use in Buildings, 2008 NIST Technical Note 1604.
[10] T.S. Rappaport (Ed.), Wireless Communications: Principles and Practices, Prentice Hall PTR, Upper Saddle River, NJ, 2002.
[11] IEEE, IEEE 802.15.4 Wireless MAC and PHY Specifications for Low Rate Wireless Personal Area Networks (WPANs), 2006 Piscataway, NJ.