Design of a CDMA-Based Wireless Data Transmitter for Embedded Sensing

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***Abstract*—Machine health monitoring is of critical importance to its safe and reliable operation. The emergence of wireless data transmission techniques has extended the scope of health monitoring to machine components and systems that are difficult to access or not suited for wired sensor data acquisition. This paper presents the design and prototype realization of a digital wireless data transmitter based on the code division multiple access technique. The design provides a generic solution for various applications in electronic instrumentation, measurement, and embedded sensing for machine condition monitoring and health diagnosis.**

***Index Terms*—Code division multiple access (CDMA), embedded sensing, wireless data transmission.**

I. Introduction

THE INCREASING demand on productivity and quality has led to widespread automation of manufacturing processes and equipment. Cost effective and efficient maintenance is needed to prevent costly machine failure-related downtime and ensure product quality. For the past decade, the state of technology for machine health monitoring has been continuously improved [1], [2]. However, the majority of the monitoring systems employed at the factory floor still require maintenance engineers to manually collect data and analyze them off-line. Furthermore, most of these systems require wire connections for data acquisition and transmission, which limit their utility and accessibility in many situations where space restriction, environmental or production constraints do not allow for such connections.

Wireless data transmission for embedded sensing and machine condition monitoring has been developed in recent years [3], [4] to overcome the restrictions of wired data collection. Because of constraints concerning the power supply, most of these systems operate on batteries and transmit data over a short distance to a data logging station nearby. A system has been introduced that extracts its power from an interrogating radio signal and therefore does not need a battery that needs to be replaced regularly [5]. Because of electromagnetic interference and other background noise that are commonly present in a realistic machine shop environment, and restrictions on the transmission power, a challenging issue in wireless data transmission is to design for low power, less circuitry complexity, and high reliability.

A low-power, compact digital wireless data transmitter employing the code division multiple access (CDMA) scheme has been designed, simulated, prototyped, and bench tested in a lab environment. The design provides a generic wireless solution for embedded sensing and measurement. Salient features of the transmitter include an interface to multiple sensors, and sharing of the save data receiver by multiple transmitters. To enable low-cost system realization, the design was exclusively based on commercial off-the-shelf components (COTS), instead of on customized application specific integrated circuits (ASICs). Using surface mount packaging, all the components of the transmitter could be accommodated within an area of about half the size of a credit card, making the transmitter well suited for structural integration into machines. Since the components are all available in the form of IC dies, the entire design can be further miniaturized into a single hybrid chip for applications in highly restrictive spaces.

II. Signal Modulation Techniques

In order to transmit data wirelessly in an air channel, a modulation scheme is needed in order to translate the data symbols to variations of a carrier wave of specified transmission frequency. Three major types exist for digital data modulation: amplitude shift keying (ASK), frequency shift keying (FSK), and phase shift keying (PSK) [6]. While the ASK technique uses amplitude variations of the carrier wave to represent the symbols transmitted, the FSK uses different frequencies for each symbol. The PSK utilizes the phase shift of the carrier for symbol representation.

The robustness of wireless data transmission is measured by the probability of a symbol error, which is dependent on the signal-to-noise ratio (SNR) that measures the strength of the transmitted signal with respect to that of the background noise. For comparison purposes, a SNR of 8 dB is assumed for the present study. At this value the maximum probability of symbol error for all three modulation techniques considered would be less than 4%.

A. Amplitude Shift Keying (ASK)

The ASK technique modulates the data by assigning each symbol a different amplitude level, e.g., two levels for binary data. For application in a metallically sealed machine environment such as a bearing housing where signal reflections may superimpose each other, an ASK receiver may not be able to distinguish between the original signal and the reflected one, leading to data misinterpretation. Hence, ASK was not considered for the present application.

B. Frequency Shift Keying (FSK)

The FSK technique employs different frequencies for different symbols transmitted. To ensure reliable transmission, the difference between any two frequencies used has to be at least

$$\Delta f_{\min} = \frac{1}{2T} \tag{1}$$

Manuscript received May 29, 2001; revised October 8, 2002.

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Digital Object Identifier 10.1109/TIM.2002.808020

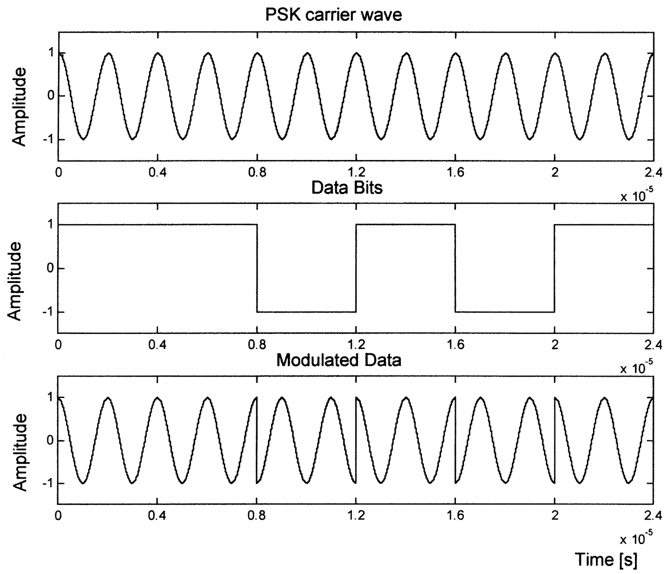

Fig. 1. Data transmission of a string 110,101 using PSK modulation.

where T is the duration of a symbol [7]. For binary data transmission, the probability of error is given by

$$p_e = \frac{1}{2}\, e^{-\rho_b/2} \tag{2}$$

where ρ_b represents the SNR per bit. For a SNR of 8 dB, the probability of bit error is $p_e \approx 2 \cdot 10^{-2}$. Employing symbols that comprise more bits will reduce the error probability, but will increase complexity in the filtering and decoding hardware on the receiver end. Such complexity would further lead to increased power consumption, which is detrimental to the bearing condition monitoring application. Therefore, the FSK technique was not considered for the present design.

C. Phase Shift Keying (PSK)

In the PSK technique, the carrier wave by itself represents a symbol, whereas all other symbols are defined by the phase shifts from the phase of the carrier. For a binary signal, the phase shift for the second symbol, i.e., the second logic value, will be 180°. In Fig. 1, a binary data signal "110 101" is illustrated, together with the carrier wave and the modulated signal. The logic level of 0 is represented by -1, since the receiver cannot differentiate no-transmission and transmission of 0. It can be seen that whenever the logic level of the data changes, a phase shift of 180° occurs in the modulated signal.

The probability of a symbol error for transmitting a binary data using PSK is given as [7]

$$P_2 = 1 - \int_{-\infty}^{\sqrt{\rho_b}} \frac{1}{\sqrt{2\pi}}\, e^{-(t^2/2)}\, dt. \tag{3}$$

If the quadrature phase shift keying (QPSK) technique is used that transmits two bits at the same time, then the error probability can be calculated as

$$P_4 = 1 - \left(\int_{-\infty}^{\sqrt{\rho_b}} \frac{1}{\sqrt{2\pi}}\, e^{-(t^2/2)}\, dt\right)^2. \tag{4}$$

For an assumed SNR of 8 dB, the probability of error for transmitting a symbol using the binary PSK is about $p_e \approx 0.01\%$, and for QPSK $p_e \approx 0.02\%$. To compare them on a bit-error basis, the symbol-error probability has to be translated into a bit-error probability. This depends on the mapping of the four possible bit combinations of QPSK to the four different phases. For the present transmitter design, the Gray code has been used that maps the bit combinations in such a way that with each 90-degree phase shift, only one of the two bits changes its logic level. The relationship between the symbol and bit error probability can then be approximated as

$$p_{e_{bit}} \approx \frac{1}{2}\, p_e. \tag{5}$$

This means that with QPSK, it is possible to transmit twice as much data within the same period of time as with the ordinary binary PSK, while maintaining the same low probability of error. For SNR values greater than 8 dB, which are more likely available in a realistic environment, QPSK even has an advantage over the binary PSK, which was a major consideration for the present design. This result, however, cannot be transferred simply to other modulation variations that combine more than 2 bits in one symbol.

Employing QPSK instead of binary PSK requires additional operation steps, either by adding specialized hardware components or a software implementation. Given the tight space available for the bearing system to be monitored in the present study, software implementation was adopted. The effort to modulate a signal with QPSK instead of binary PSK is about 2.5–3 times as much due to the need to separate the data signal into two streams, mixing the two streams with orthogonal sine waves, and combining them back into one transmission stream. On the other hand, if the relationship between the computational time and power consumption of the signal processor can be assumed to be linear, then QPSK is advantageous in terms of the power consumption over binary PSK, when the modulated data are to be transmitted multiple times for enhanced data reliability [8]. Given all these advantages, QPSK has been chosen for the present transmitter design.

III. Multiple Access Methods

In order to accommodate multiple transmitters with one data receiver and achieve design flexibility and extensibility, a multiple data access scheme needs to be implemented. This can be achieved by assigning each transmitter a distinct feature, e.g., a certain frequency, a time slot, or a code. Accordingly, three design options were considered in the present design: frequency division multiple access (FDMA), time division multiple access (TDMA), and code division multiple access (CDMA) techniques.

A. FDMA Technique

In FDMA, each transmitter has a frequency exclusively assigned to it. This enables the transmitter to send data at any time regardless of other transmitters. Since absolute real-time monitoring systems are usually not needed in a production environment, a transmitter will need to send data only at specified intervals, leaving the assigned frequency unused most of the time.

B. TDMA Technique

A single carrier frequency can be used by several transmitters, if it is ensured that at no time more than one transmitter sends data simultaneously. Accordingly, each transmitter is assigned a time slot for signal transmission. The time slots need to be synchronized between all the transmitters in the system. This requires that for each transmitter, a separate receiver is implemented, and the receiver must be "on" at all times, increasing the power consumption of the circuitry.

C. CDMA Technique

The CDMA technique can be divided into frequency-hopping (FH) and direct-sequence (DS) CDMA. Both methods have in common that a unique code is assigned to each transmitter. This code is a pseudo-noise sequence, meaning that it will appear to be noise unless it is known to be a code. Hence, the transmission can only be decoded by a receiver that knows the codes used.

Both versions of CDMA require a much higher bandwidth than an uncoded transmission. In FH-CDMA, the higher bandwidth is divided into small bands, each having the bandwidth of an uncoded transmission. While sending the data, the used band is changed according to the assigned code. In DS-CDMA, the code bits have a higher frequency than the data bits, employing an integer multiplication factor (i.e., the spreading factor). This factor was chosen as 4 for the present study, based on the available on-chip memory in the digital signal processor (DSP) used. Hence, the original data bit stream is multiplied by the code bit stream. Since the data is transmitted over a broad frequency band at each fixed point in time, the receiver can decode the data even if a part of the bandwidth is superimposed by an unrelated transmission [9]. Hence, DS-CDMA has an advantage over FH-CDMA, because the data can be transmitted even when a particular frequency is not usable due to noise.

As an example of DS-CDMA, the top section of Fig. 2 shows the first 12 bits of a pseudo-noise sequence, and the middle section of the figure shows the first 3 bits of the data that are to be coded. The data bits have the duration of 4 μs. The CDMA code bits have a duration of one quarter of that of the data bits, according to the selected spreading factor of 4. The data stream is multiplied by the code bit stream, and the result is shown in the bottom part of the figure.

For the present design, the pseudo-noise sequence has a bit length of 31 bits. This results in 33 orthogonal sequences and subsequently, 33 transmitters to be accommodated within the transmission system. For installations requiring more transmitters, longer code sequences need to be used. This can be readily implemented, as the modification is only needed at the receiver side.

IV. Transmitter Design

Although several wireless transmitters are commercially available on the market, they were not appropriate for the intended bearing condition monitoring application, because their fixed design, geometry, and packaging forms make it difficult for them to be structurally adapted and integrated into the bearing system to be monitored. Second, they contain a receiver circuitry to allow for full-duplex data communication and error correction. However, such a circuitry requires significantly increased power supply and additional space to physically accommodate the extra components. Given that the RF transmission alone would account for over 30% of the

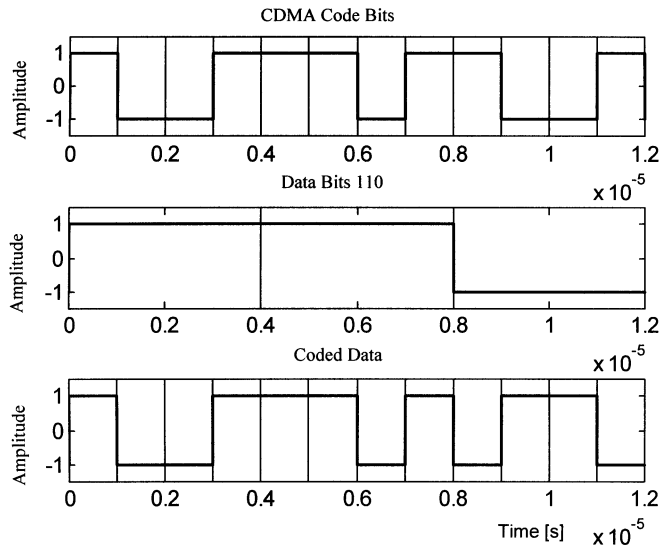

Fig. 2. Data coding of 110 bits using the CDMA technique.

power consumption of the entire circuitry, and the receiver section drains more power due to the higher number of components, commercial transmitters were not energy-optimized in view of power consumption and battery life, and were therefore not appropriate for the present application.

The digital data transmitter developed in this study transmits a data stream at 2-s intervals, with the bandwidth of up to 3 kHz. A 12-bit resolution is needed to provide proper data resolution. To allow for a generic solution, the analog-digital converter TLV2543 was selected, which provides an interface connection for up to 11 sensors. It also features a power-down mode, during which no data is read from the sensors. The CDMA encoding and QPSK modulation for data transmission are performed by a DSP of type TMS320VC549, which was chosen because of its low power consumption (0.54 mW/MIPS) and its power-saving modes. Sampling every 2-s long data interval with a sampling rate of 6 kHz and 12-bit resolution would result in a data output rate of 72 kBit/s. To store this amount of data onto the DSP on-chip memory with a 16-bit data width without wasting memory space (due to the data length mismatch), the 12-bit data samples were stored as direct bit strings without any 4-bit prefix. Thus, every four 12-bit samples were stored in three DSP memory locations of 16-bit width each, occupying a memory space of $(2 \bullet 6000 \bullet 12)/16 = 9$ kWords. For the subsequent CDMA coding, the 9 kWords of data were spread by the pre-selected factor of 4, resulting in a total memory need of 36 kWords. The CDMA code was placed in a ring buffer. Four code bits were used to replace every one bit in the data sample. The code bits were taken from the ring buffer such that the seventh data bit would be replaced by the last three bits and the very first bit of the ring buffer. This scheme is repeated until all data bits were substituted by the CDMA code bits.

The CDMA data coding has two advantages. First, it allows for multiple transmitters to share the same frequency band, as the receiver can distinguish and identify every specific transmitter by the employed code, which is unique to every specific transmitter. Second, since the energy of the transmitted data is spread over a broader frequency band than required when using a conventional transmission scheme, even if a portion of the frequency band is distorted due to noise contamination, only part of the energy in the transmitted data is lost. Consequently, it is still possible to reconstruct the entire data correctly, which would not be the case when using conventional data transmission approaches.

To ensure data transmission integrity over a wireless link, usually a checksum is added to the data sample transmitted, which is recalculated at the receiver end. If a mismatch is identified, a retransmission is requested from the transmitter. Since the transmitter does not include a receiving section on its circuitry for the purpose of component count and power consumption reduction, it cannot perform an inquiry-based data retransmission. To improve transmission integrity, each data sample is transmitted three times consecutively. On the receiver end, the transmissions are subsequently compared with each other for consistency. Since erroneous transmissions are mostly caused by uncorrelated background noise contaminations, it is highly unlikely that the noise persists in such a way that the three consecutive transmissions would be equally distorted and hence, that an erroneous data set would be used. Furthermore, a signal filtering algorithm can be implemented on the receiver end for enhanced transmission integrity.

To enable consecutive data transmissions, all the data needed must be stored in the DSP memory at the same time. As the selected DSP has only 32 kWords memory space, which, in addition to data, must also hold a look-up table for data modulation as well as provide memory-mapped registers, it is necessary to compress the data. This was accomplished by employing the Lempel–Ziv-1977 (LZ77) data compression algorithm. The algorithm utilizes dictionary-based compression that recognizes repeating patterns in the data and places these patterns into a dictionary. The patterns within the data are then replaced by references to the dictionary entries, and the compressed data are stored together with the dictionary. Depending on the regularities in the data, the achievable compression may vary between 1–90%. As the bearing signals contain repetitive, periodic waveforms that lead to periodic bit patterns, it is expected that a compression ratio of 50% can be achieved.

The compressed data are CDMA coded and subsequently QPSK modulated. For data modulation, the coded bits are sent alternately into two streams. One stream replaces a given bit pattern by a full sine wave, with its sign being dependent on the logic level of the bit pattern. The second stream replaces its bits by a cosine wave. The two bit streams are subsequently added together to form the QPSK data. This process is simplified and accelerated by a look-up table, which maps two consecutive bits to a phase shift. The final sine wave output is stored in another look-up table. Based on the phase shift, an offset for access to the sine look-up table is then selected. In Fig. 3, a flowchart of the data transmission sequence is shown.

The frequency of the sine wave input into the RF interface is 78.125 kHz. The sine wave is approximated with 16 samples per wave by the DSP. The digital-to-analog (D/A) converter requires 16-bit data transmission for each sample to be converted. Therefore, a clock frequency of 1.25 MHz was needed for the serial communication between the DSP and the D/A converter. To up-convert this signal to the carrier frequency of 2.4 GHz, a mixer has been implemented that multiplies the modulated

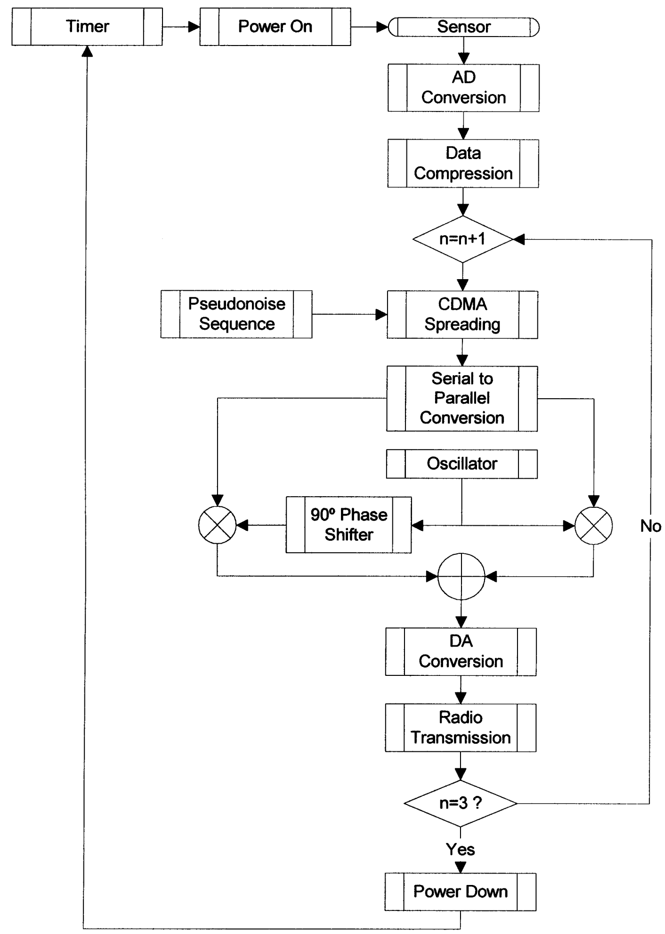

Fig. 3. Flowchart for data transmission sequence.

and coded DSP signal with the carrier signal from a local oscillator. The up-converted signal is subsequently transmitted to air via a $\lambda/4$ monopol antenna. The RF interface was designed and implemented using a minimum number of discrete components, i.e., an oscillator for generating the 2.4 GHz carrier frequency, a mixer for the up-conversion, and an RF amplifier. No filters were used both at the base band and for the RF frequencies to reduce circuit complexity and power consumption. To further minimize the hardware, both the CDMA spreading and QPSK modulation were implemented through a software code written in the C language. Such a software-focused approach ensured a flexible design that can be readily upgraded or adapted to other applications. This is advantageous over other commercial off-the-shelf (COTS) solutions.

To ensure program safety for data compression, modulation, and data coding even in the event of a depleted battery, the program is stored in a flash memory chip AM29LV400. The flash memory further stores a sine wave table such that the wave form for the QPSK modulation and the pseudo-noise sequence does not need to be re-calculated every time. In Fig. 4, the principal design of the transmitter is shown.

The design has been prototyped on a conventional printed circuit board, using the Surface Mount Technology (SMT), as shown in Fig. 5. Since the flash memory chip was available only in a different package than the PCB had been designed for, pin adaptation was needed. The overall size of the transmitter, using

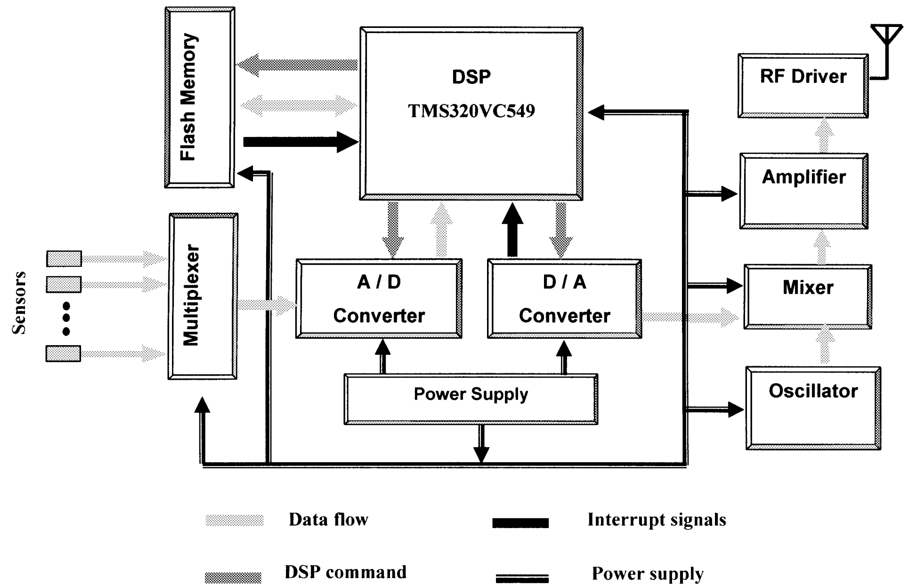

Fig. 4. Schematic of the transmitter circuitry.

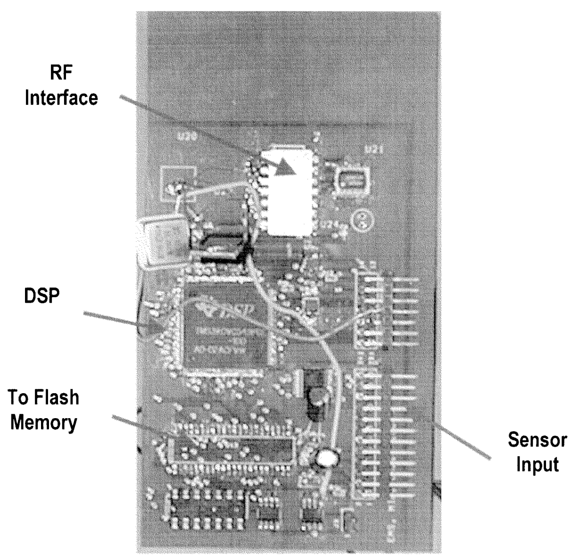

Fig. 5. Prototype of data transmitter based on the CDMA technique.

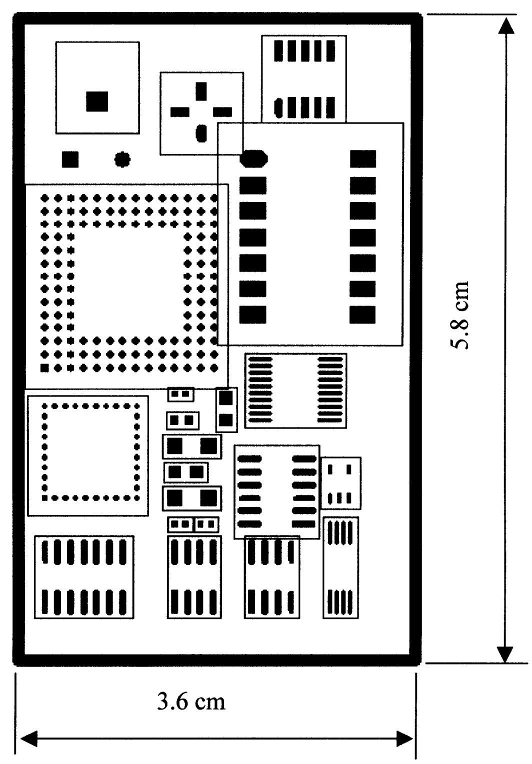

Fig. 6. Dimensions of the transmitter board.

discrete components and SMT packaging, measured about 3.6 $\times$ 5.8 cm, which is less than half the size of a credit card (Fig. 6). The complete system consisting of data transmitter, receiver, sensors, and sensor signal conditioner is shown in Fig. 7.

V. Simulation

The performance of the designed CDMA transmitter was evaluated using the software *MatLab* with *Simulink.* A random bit generator was employed as the data source. These data were first mapped to $+1$ and -1 to be multiplied by the CDMA code bits. The CDMA code bits were programmed in a repetitive sequence block, repeating the code in a loop. The two bit streams were multiplied in the next step. The resulting coded data stream is split up into two branches, with the even numbered bits into the upper branch, and odd numbered ones into the lower branch. Each branch was then modulated by a carrier wave of 2.4 GHz. As the two wave forms have a phase shift of 90° to each other, the upper branch is represented by a cosine wave, and the lower branch by a sine wave. Both branches were then added together. For the simulation, the RF transmission and receiving sections were assumed to be without losses. The transmission path was modeled as an additive white Gaussian noise (AWGN) channel to simulate the time-delayed transmissions, superposition, and interference within an enclosed machine environment.

The received signal was demodulated on the receiver end. The demodulation causes a time delay of one-bit duration. As the

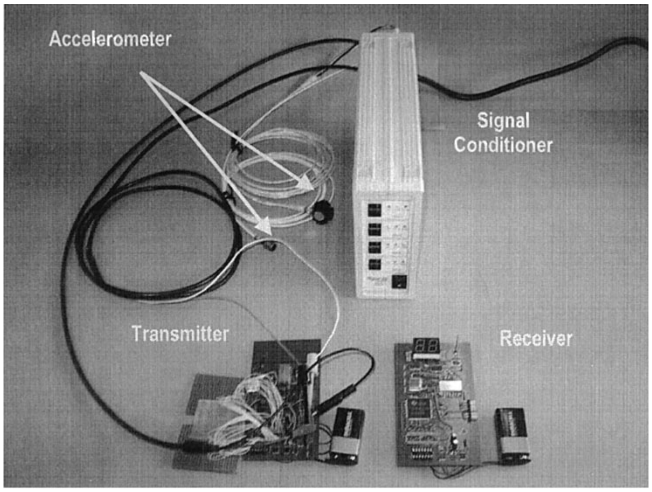

Fig. 7. Transducer system consisting of sensors, signal conditioner, transmitter, and receiver.

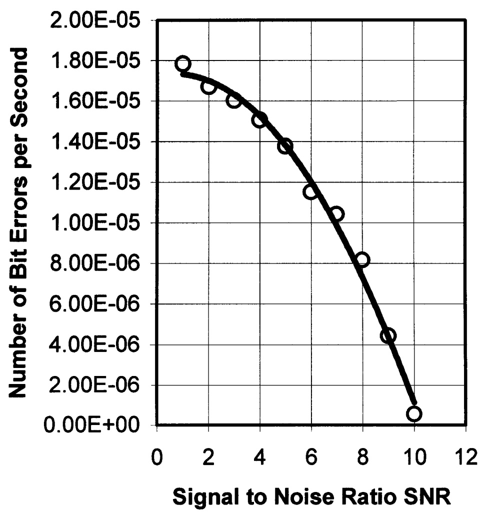

Fig. 8. Bit error probability versus signal to noise ratio (SNR).

time delay is known in the simulation, decoding of the CDMA spreading was correlated to the coding bit sequence.

As the result of the simulation shown in Fig. 8, to achieve an error probability of 10^{-5}, which is considered the theoretical minimum value for an error-free transmission because of the amount of data to be transmitted, a SNR of 7 dB will be required. For more reliable data transmission with a lower error probability (e.g., 10^{-6}), a SNR of about 9.6 dB would be required.

VI. EXPERIMENTAL EVALUATION

The designed system was experimentally evaluated in two aspects. First, the signal strength of the transmitted signal with respect to the transmission distance was investigated to establish the maximum possible transmission range. Second, the actual power consumption of the transmitter was measured.

Experiments have been conducted in a lab environment. The signal strength was measured for a transmitter–receiver distance that varied from 15 to 300 cm to obtain a general trend. Two test

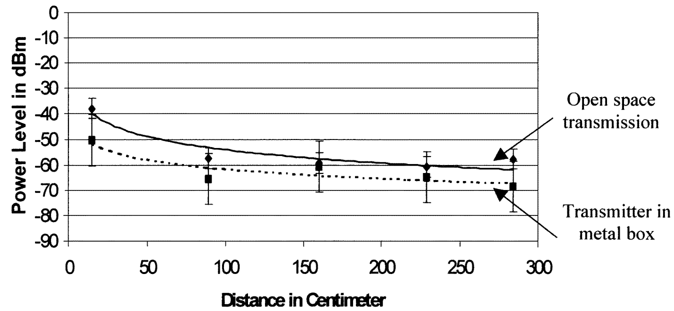

Fig. 9. Signal strength of transmitter in free space and when enclosed in a metal box.

configurations were used: 1) transmitter unobstructed on a workbench and 2) transmitter enclosed within a metal casing. In the latter situation, the casing has a nonmetallic opening of 2×30 cm that was covered by a plastic plate of 3 cm. The opening was not directed toward the receiver. This situation can be considered as a typical arrangement for a transmitter embedded within a machine environment. As shown in Fig. 9, both the open space and shielded transmissions have shown a general distance-dependent decrease of the signal strength. For open space transmission, the signal strength decreased from about −40 dBm when the transmitter and receiver were at close distance to about −60 dBm at a distance of 2 m. When the transmitter was enclosed in the metal box, the field strength was at about −50 dBm in close proximity, and dropped to about −65 dBm at 2 m. Table I shows the averages of five measurements for both cases, as well as the maximum deviation of a measurement from the average. In addition, it shows the relative error of the measurements, which is defined as the difference between the mean value and the maximum deviation, divided by the mean value.

Increasing the distance further did not cause any appreciable signal strength decrease in both cases. From the signal trend analysis, it is concluded that the current design is able to ensure reliable transmission within a few tens of meters, which is acceptable for many practical applications. As for the power consumption, it is estimated that the transmitter should be able to operate on a set of batteries for a minimum period of three months, which is considered practical for machine maintenance purposes. The current consumption of the transmitter in the power-down mode was measured as 4 mA. When actively transmitting at 100 MHz, the total power consumption of the transmitter was measured to be 150 mA. Reducing the clock frequency and transmission speed will reduce the power consumption, however leading to a prolonged transmission time. For a full cycle of measurements, including the data compression, coding, modulation, and three consecutive transmissions, the active transmission period for the transmitter is less than 90 s. If 10 data transmissions were scheduled for each working day of 8 h, a total of 7.5 h active-on time would be needed for a period of 3 months. Batteries that are capable of providing peak current of 150 mA intermittently for 3 months are commercially available in small packages that are suited for machine-embedded applications. For applications requiring an extremely small space, the RF amplifier in the present design can be replaced by other low-power models, at the price of reduced transmission range. It is thus apparent that a trade-off needs to be made to achieve optimized performance for each specific task.

TABLE I
MEASUREMENT RESULTS AND RELATIVE ERROR

Distance (Tr/R)	Open Space Transmission	Maximum Deviation	Relative Error	Enclosed in Metal Box	Maximum Deviation	Relative Error
15 cm	-38.0 dBm	2.0 dB	5.2 %	-50.5 dBm	2.5 dB	5.0 %
89 cm	-57.3 dBm	7.7 dB	13.4 %	-65.7 dBm	1.7 dB	2.6 %
160 cm	-59.3 dBm	3.3 dB	5.6 %	-60.7 dBm	1.7 dB	2.8 %
229 cm	-60.7 dBm	3.7 dB	6.1 %	-64.7 dBm	4.7 dB	7.3 %
284 cm	-57.7 dBm	5.3 dB	9.2 %	-68.7 dBm	3.7 dB	5.4 %

VII. CONCLUSION

A compact, low-power digital wireless data transmitter based on the CDMA-coding technique has been designed, simulated, prototyped, and experimentally tested. The design demonstrates the feasibility of employing a sophisticated transmission scheme in an embedded sensor for machine health condition monitoring. Focusing on the space constraints and power efficiency during the design phase has reduced the number of components to a minimum. All the employed components of the prototype are available on IC dies, and thus can be integrated into a multi-chip module that fits on a centimeter-sized substrate. The software implementation of the CDMA coding allowed for easy extensibility of the present design to accommodate future modification needs.

While the lab tests conducted have verified the design and performance of the developed wireless data transmitter, it has been planned that more systematic experiments will be conducted in the future to investigate the utility of such an integrated sensing approach for the condition monitoring of bearings in a realistic machine setup. Specifically, the test will compare the presented CDMA sensors with wire-based sensors and sensors that incorporate an ASK-based commercial data transmission system. The comparative study will provide input to performance improvement over the prototype design and direction for further wireless sensing research.

Although the CDMA data transmitter was specifically designed and tested for embedded sensing and condition monitoring for bearings, the technical approach presented is applicable to the design of a wide range of electronic instruments, such as data loggers, data acquisition cards, or hand-held metering devices, that can benefit from wireless data communication through the addition of a CDMA-based module. More recently, the development of wireless instrumentation and computational devices has been further energized by the debut of Bluetooth technologies [10]. Given the broad-based design goals of Bluetooth (e.g., carrier frequency of 2.4 GHz, support to data, voice, as well as audio signals, and data link required for only a short distance), the targeted application sectors (e.g., computer peripherals, hand-held PDAs, laptops), and reported initial difficulty in its market introduction, it is anticipated that alternative wireless designs, such as the one developed in the presented CDMA data transmitter, will continue to play a valid and active role in scientific research, electronic instrumentation, and a wide range of industrial applications.

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