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Wide-Area Long-Range Unidirectional Sensor (WALRUS) Network

Giovanni Vannucci, Darren Leigh, and Joseph Katz
Mitsubishi Electric Research Laboratories
Cambridge, MA 02139, USA
{vannucci | leigh | katz}@merl.com

Abstract—**Networks consisting of low-cost wireless sensors have been the subject of extensive research, with applications ranging from environmental monitoring to building control systems, to name a few. In this paper we consider networks intended to provide wide area coverage of one or more physical, chemical, or biological parameters. We envision a target average data rate per sensor of 1-5 bps and transmission ranges of up to 100 m. Unlike conventional networks, the goal of wide-area parameter characterization can be achieved even with less than 100% node reliability, a feature that allows us to propose a novel ultra-low-cost architecture based on redundant sensors. To achieve the low-cost goal, sensor nodes include no receivers, and they transmit their information to a central reader using radio backscatter. This communication modality makes it possible to achieve a few years of battery life with small and inexpensive batteries. Performance impact due to absence of individual reception acknowledgement in this unidirectional communication channel is offset mainly by transmitter spatial diversity achieved through deployment of additional nodes. We describe the design of the system and its components, and analyze its performance characteristics.**

1. Introduction

Recent years have witnessed dramatic progress in the area of wireless sensor networks [1], [2], [3], driven by a combination of advances in several interrelated technologies. These include (a) the overall cost reduction trends that have been the quintessential manifestation of Moore's law and have brought an ever increasing number of applications into the domain of commercial feasibility; (b) establishing world-wide standards such as IEEE 802.15.1 (Bluetooth) [4] and IEEE 802.15.4 (ZigBee) [5] for short-range wireless communications (as well as other longer range standards); (c) availability of the internet as the universal backbone carrier of information from a myriad of sensors and sensor systems; (d) development of new sensing technologies such as MEMS [6] that can be implemented in low-cost miniature forms; and (e) greatly enhanced demands for sensing capabilities (including wireless) due to environmental [7] and security [8] concerns. The scope of the applications has also greatly expanded, and it ranges from environmental monitoring [9, 10], water pollution monitoring [11], nuclear power plant monitoring [12], radiation detection [13], bridge safety [14], building control [15], animal tracking and control [16], ocean-related disaster management [17] and others.

A highly simplified block diagram of a wireless sensor network is shown in Fig. 1. It consists of sensor nodes that communicate wirelessly with the network infrastructure through either other sensor nodes or through special devices often referred to as base stations (or access points). Each of the sensor nodes incorporates one (or more) sensing functions, and one (or more) wireless communications means.

Research efforts in this area have addressed various aspects of the system. Some have investigated the network layer, for example routing algorithms in ad-hoc mesh networks [18] as well as management and security issues [19], [20], while others explored means of optimizing the physical layer of the sensor node through optimized circuit design [21], [22] and power scavenging [23]. Other groups demonstrated complete wireless sensor node systems incorporating a combination of some of the techniques mentioned above [24], [25], [26], [27]. Virtually all the research efforts involve radio-frequency communications, [28] describe a system based on tags operating in the optical regime.

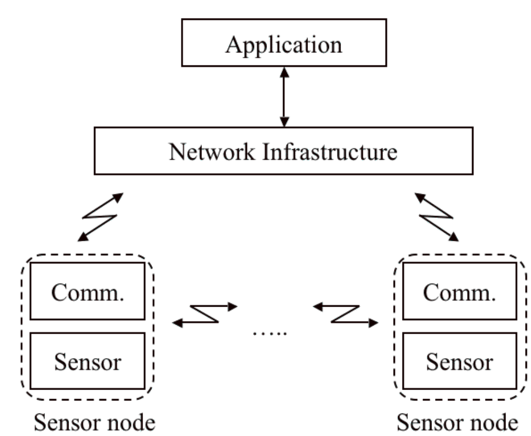

Fig. 1. Basic block diagram of wireless sensor network

RFID [29] is a somewhat related technology to sensor networks. Its development and usage has started a few decades ago, but it has only recently received widespread attention and development efforts, driven mainly by supply-chain management optimization initiatives [30]. In a typical application the RFID tag communicates to a reader (sometimes called an interrogator) its identification number, and in some cases also additional information stored in its memory. Some tags use active transmission, but most of the recent developments have focused on very-low-cost batteryless passive tags that receive the power needed for their operation from the energy in the reader field [31] and communicate with the reader using backscatter modulation [32]. This mode of operation also necessarily results in a restricted communication range, typically less than 10 m. An intermediate design, designated as semi-passive, is based on tags that include a battery, but like their passive counterparts, they too use backscatter (rather than active transmission) as the communication mechanism [33]. The battery is used only to operate the tag state machine and the backscatter modulator, and as a result it is possible for such tags to communicate over longer ranges. It is important to note that even though most RFID applications involve unidirectional information transfer, (i.e., reading the tag ID) all RFID communications protocols involve bidirectional communication exchanges between the tag and the reader.

A few recent investigations have considered various possibilities of combining aspects of conventional wireless communications systems with those of RFID. Adding an RFID tag capability to an embedded wireless node to provide an out-of-channel wakeup mechanism is described in [34]. Sensors that use communication means of passive RFID tags are analyzed and demonstrated in [35], and a variant method, using surface acoustic wave resonators is presented in [36]. In [37] a basic comparison between wireless sensor networks and an active RFID system is described, pointing to the differences between their multi-hop and single-hop architectures, respectively. Finally, analysis of a system consisting of transmitter-only active RFID tags is provided in [38].

In this work we describe a novel ultra-low-cost architecture for wireless sensor networks comprising of a large number of sensors that are intended to provide wide area coverage of one or more physical, chemical, or biological parameters. We envision such systems to be useful in applications with target average data rate per sensor of 1-5 bps and transmission ranges of up to 100 m. To achieve these goals, the sensor nodes, similarly to semi-passive RFID tags, transmit their information to a central reader using radio backscatter. In order to achieve further cost reduction, the sensor nodes include no receivers; the communication in the system is unidirectional, from the nodes to the receiver. This communication modality makes it possible to achieve a few years of battery life with small and inexpensive batteries. As we will show below, performance impact due to absence of individual reception acknowledgement in this unidirectional communication channel is offset by transmitter spatial diversity achieved through deployment of additional nodes, as well as by repeated transmissions. Compared with [38], we propose semi-passive (rather than higher-cost active) architecture, consider several channel access methods (in addition to TDMA), and provide actual experimental results.

It is important to note that the use of unidirectional links is not suited to all applications. In many systems, an acknowledgment channel is required to achieve a high probability of successful message delivery. However, our target application is outdoor environmental monitoring (for example, pollutant monitoring of an industrial plant site). In this case, effective monitoring requires the collection of periodic measurements from a large number of sensors randomly scattered over an area. If, at any given time, a subset of the sensors fail to report a measurement, it is not a problem, as long as there is redundancy in the number of deployed sensors. The substantial reduction in cost afforded by the simplified unidirectional link more than offsets the cost penalty due to the need to deploy redundant sensors. Furthermore, in our network protocol, we also exploit this sensor-fault tolerance to simplify the multiple-access scheme. The result is a sensor node design that is much simpler than competing solutions. In applications that require a large number of sensors and are tolerant of some level of missing data, our proposed architecture provides a very cost-effective solution.

The outline of this paper is as follows. Section 2 describes the intended applications for the system. An overview of the backscatter radio link architecture is provided in Section 3, and Section 4 follows up with an analysis of the link margin, followed by a discussion of the signal-to-noise (SNR) and bandwidth requirements of the system in Section 5. The subcarrier modulation scheme is proposed in Section 6, and the modulation and channel access scheme are described in Section 0. Finally, Section 8 quantifies the expected performance of the multiple-access scheme, and Section 9 concludes the paper with a brief discussion of our experimental results.

2. Target Application

It helps to have a concrete model for a target system: We envision an outdoor field 100-200 m across. Over this field, a number of sensors are scattered uniformly. The objective is to characterize one or more environmental parameters (e.g., temperature, humidity or pollutant concentration) with thorough coverage over the entire field. To accomplish this, we envision several hundred (perhaps up to a thousand) sensors that continually report the values of those parameters. We assume that each sensor provides a parameter update several times per minute, and that each update requires about 15-20 *information* bits, which corresponds to an average information rate of a few bits/s per sensor. (Note: we draw a distinction between *information* bit rate and transmitted data rate. To achieve the desired reliability, it may be necessary to use forward error correction (FEC) and/or retransmission, so that the actual transmitted data rate may have to be higher than the *information* bit rate.)

In the center of the field, a radio base station collects sensor transmissions. Our goal is to make the sensors as simple and as inexpensive as possible, while concentrating the more costly signal-processing functionality in the shared base station. Also, target battery life for sensors is ten years; therefore, low power consumption is essential.

As mentioned in the introduction, the goal of environmental monitoring can be successfully accomplished even if a large fraction of the sensors are non-functional at any given time, as long as redundant sensors are deployed. For example, if the system requires 500 randomly-scattered sensors for adequate monitoring, but 700 sensors are actually deployed, the system will be able to tolerate the failure of up to 200 sensors. These can be "hard" failures (for example, due to hardware or battery malfunctions) or "soft" failures (for example, if interference temporarily prevents reception from a specific sensor). As we shall see, by allowing such failures, we can greatly simplify the design of individual sensors. In particular, our multiple-access scheme makes no effort to avoid mutual interference between sensors and, thereby, requires no coordination of sensor transmissions. Sensor design becomes extremely simple, and the reduction in sensor cost more than offsets the need for additional sensors.

3. Backscatter Radio Link Architecture

As already mentioned, in systems where there is a single base station serving a large number of nodes, it is advantageous to minimize the complexity of the nodes at the expense of some complexity in the base station. Backscatter radio [32], [35] provides the simplest radio communication solution for such nodes. Fig. 2 illustrates the principle of backscatter radio systems. The base station provides an unmodulated radio signal, while the node antenna is designed to reflect the signal as efficiently as possible. The node includes circuitry to make the phase of the reflected signal either the same or opposite that of the incident signal. This way, the node can modulate the reflected signal and, thereby, convey a message back to the base.

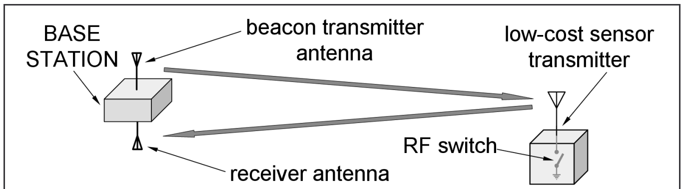

Fig. 2. Principle of operation of a backscatter radio link

The "circuitry" required for the phase modulation is simply a switch: if the antenna port is shorted, the signal is reflected with a phase inversion; if it is left open, the signal is reflected with the same phase. Therefore, the only radio components required by a backscatter transmitter are the antenna and an RF switch. This extreme simplicity insures that, even as the cost of conventional radio transmitters continues to go down, the backscatter transmitter will continue to be, by far, the least expensive solution.

Besides simplicity, another important advantage of backscatter radio is that no RF power needs to be provided by the node. The amount power needed to flip the switch connected to the antenna port depends on how the switch is implemented. In our lab, we have tested a standard low-cost CMOS 3-state logic output as an RF switch at ~1 GHz, and we have found its performance to be surprisingly good (specifically, we found a reflection efficiency near 10% at 900 MHz). With continuing advances in CMOS technology, it is easy to envision that backscatter communication will provide the best opportunity for ultra-low-power operation.

The main disadvantage of a backscatter radio link is its limited range. Because the reflected radio signal is not amplified, the strength of the backscattered signal received by the base station suffers path attenuation twice. Therefore, in free space, where path loss increases with the square of distance, the strength of the backscattered signal falls off with the *fourth* power of distance. In practical wireless systems, the power law is even worse, as we shall see.

Backscatter communication is frequently chosen for batteryless (passive) RFID tags, where power for the digital circuitry is derived from the radio signal itself. Such systems are limited to a *very* short range by the requirement that the received signal be strong enough to provide enough voltage to operate the unit. At such close range, the strength of the backscattered signal is, usually, more than adequate for detection by the base. By contrast, in our target system, which has to comply with transmitted power limitations imposed by regulatory agencies, the desired range of ~100 m means that there will not be enough signal to provide power to the tag. Accordingly, sensor nodes will require a battery; the low power requirement of backscatter radio makes it possible to achieve the desired battery life of 5-10 years.

As mentioned in the previous paragraph, at the target range of ~100 m, the strength of the radio signal received by the sensor antenna is not sufficient to turn on a rectifier diode. Therefore, even just to *detect* the presence of the signal itself, an amplifier is needed. This represents an undesirable level of complexity when compared to the extreme simplicity of the backscatter transmitter. Accordingly, we have formulated a communication protocol that does not require the detection of a signal from the base. The sensor node modulates the phase of the backscattered signal continuously, whether or not there is a signal to backscatter. Because of the very low power level required to operate the RF switch of Fig. 2, such continuous operation is consistent with long battery life.

This "blind" operation of sensor nodes has important consequences. First, transmissions from different nodes cannot be coordinated; therefore, collisions will be frequent and the communication protocol will have to be designed to withstand that. Second, acknowledgment of error-free receptions will not be available, so that forward error correction (and detection) is the only available option for error control. Third, the sensors will not know how far they are from the base and, therefore, they will not be able to adjust the strength of the backscattered signal accordingly. The signal from nearby sensors will be many orders of magnitude stronger than the signal from distant sensors. Modulation and detection schemes will need to have sufficient dynamic range to handle the situation.

In the following sections we discuss the details and operating parameters of our implementation.

4. Link Budget

In this section we compute the available signal-to-noise ratio (SNR) when the sensor node is at a distance of 100 m from the base with reasonable assumptions for the various parameters of the backscatter radio link. Our starting point is the free-space radio propagation law described by the Friis formula [39],[40]:

$$L = P_R / P_T = G_T G_R / [(4\pi)^2 (d/\lambda)^2] \cdot \qquad (1)$$

The formula gives the link loss, L, expressed as the ratio of received power, P_R, to transmitted power, P_T. Here, G_R and G_T are the gains of the transmitting (base) and receiving (sensor) antennas, respectively; d is the distance between the two antennas; and λ is the wavelength. The Friis formula applies to free space; in our case, however, we don't have free space. We assume an open field with the base antenna mounted on a pole of height h_T and the sensor antenna mounted at a height h_R. Fig. 3 shows the configuration and highlights the fact that, in addition to the direct path, there is a path reflected off the ground. This is a well-studied configuration [39]; it is found that path loss is (on average) close to that predicted by (1) up to the distance

$$d_0 = 4\pi h_T h_R / \lambda \cdot \qquad (2)$$

At larger distances, when $d > d_0$, signal strength falls off as the fourth power of distance (instead of the second power); i.e., path loss is approximated by

$$L = G_T G_R (h_T h_R / d^2)^2 \cdot \qquad (3)$$

We note that, even though this expression is only applicable to open-field line-of-sight (LOS) situations, the empirical expressions used to characterize non-line-of-sight outdoor propagation also exhibit a fourth-power law with distance [41]. In practice, the loss predicted by (3) is close to that predicted by such empirical expressions (i.e., within 10 dB or so). This gives us confidence that we can use (3) to model a wide variety of conditions as long as we allow some margin in our SNR calculations.

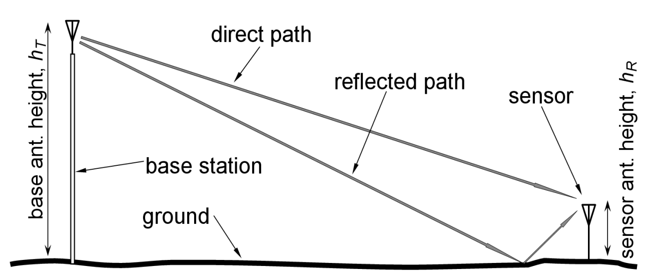

Fig. 3. Configuration of base station and sensor antennas. We assume a relatively flat field with the base station located in the center. Both base station and sensor antennas are vertically polarized and omnidirectional (in azimuth).

In a backscatter system, the signal experiences path loss twice as it travels from the base to the sensor and back. Additionally, we must include the reflection efficiency of the sensor, η, which includes the effects of non-ideal switch behavior, impedance mismatch and resistive losses in the sensor antenna. Table I lists typical parameter values applicable to our system. Antenna gains assume vertically polarized antennas with elevation gain but omnidirectional in azimuth. The table also includes the noise figure, NF, of the base station receiver and the calculated SNR at the base station receiver. The SNR is computed as the ratio E_b/N_0, where E_b is the energy per received *information* bit ($E_b = P_R/R$, where R is the *information* bit rate) and N_0 is the power spectral density of the noise. More specifically,

$$\mathrm{SNR} \triangleq E_b / N_0 = (P_T L^2 \eta / R) / (kT_0 \, NF), \qquad (4)$$

where the noise is assumed to be thermal noise (enhanced by receiver noise figure); i.e., k is Boltzmann's constant and T_0 is the receiver temperature of 300 K. (Note that this assumes that the receiving antenna in the base station has the same gain as the transmitting antenna.)

The last three rows of Table I show results computed from the system parameter values listed in the previous rows. We see that, for this implementation, we get an SNR of 36 dB at 100 m. In the next section we discuss SNR requirements; however, it is obvious that such a large SNR provides a comfortable implementation margin. Note also that the transition distance — the distance, d_0, from where propagation loss is described by (3) instead of (1) — is considerably less than our target range of 100 m. For sensors more than d_0 from the base, received signal strength decreases as the *eighth* power of distance, so that a small change in sensor distance will result in a large change in received signal strength. Thus, we may regard the 100 m range as both a reasonable goal and a practical upper limit: even a modest increase in this parameter will cause a large reduction in achievable SNR. On the other hand, if unforeseen factors reduce the available signal, a modest *decrease* in this parameter will provide a large SNR improvement.

TABLE I -- SYSTEM PARAMETER VALUES

Parameter	Symbol	Value	Units
Transmitted power	P_T	30	dBm
Base antenna gain	G_T	9	dB
Base antenna height	h_T	3	m
Sensor antenna gain	G_R	3	dB
Sensor antenna height	h_R	0.25	m
Maximum distance	d	100	m
Wavelength (@ 1 GHz)	λ	0.3	m
Reflection efficiency	η	–10	dB
Noise Figure	NF	10	dB
Information bit rate	R	5	bit/s
Computed Values			
Transition distance	d_0	31.4	m
One-way path loss	L	–70.5	dB
Signal-to-Noise Ratio	E_b/N_0	36.0	dB

5. SNR VS. BANDWIDTH REQUIREMENT

The SNR required by the backscatter receiver in the base station depends on a) the chosen modulation scheme; on b) the amount and type of error protection provided; and on c) the desired error rate. As already observed, error-detection with retransmission is not an option; therefore, forward error correction (FEC) is the only feasible error-control technique. It is advantageous that FEC *encoding* algorithms are generally of low complexity, as this operation will be performed in the low-cost sensor. The more complex *decoding* algorithm will be implemented in the base station receiver where a higher degree of complexity is acceptable.

We have a range of possible choices: at one extreme, we could use little or no FEC with some simple modulation scheme such as FSK or BPSK, in which case we'll need an E_b/N_0 as high as 7-10 dB [42] and the implementation will be simplest. At the other extreme, we can use extensive amounts of FEC, but we are limited by Shannon's capacity, which says that we can do no better than $E_b/N_0 = \ell n\, 2$ (about –1.5 dB). In practice, even very powerful FEC codes require at least 1-2 dB of E_b/N_0 [43] so that the choice of coding scheme will, at most, make a 6-8 dB difference in the required SNR. (Note: these specific numbers assume a target bit-error rate in the range of 10^{-3} to 10^{-4}, but the general considerations are also valid at other target bit-error rates).

Because of the eighth-power law mentioned before, the benefit of reducing the required SNR is not great, and it comes at the cost of increased bandwidth (due to the increased FEC overhead). As we shall see, it is desirable to keep signal bandwidth low in order to avoid collisions between sensor transmissions. In Section 9 we will determine the optimal amount of FEC coding to use: we will find that only a small amount of FEC is best, requiring an E_b/N_0 in the range of 5-8 dB with little bandwidth expansion (much less than double). With this E_b/N_0 requirement, we see that the SNR calculated in Table I includes a comfortable margin of ~30 dB to allow for the possibility of unforeseen impairments. This margin also gives us confidence that the 100-m objective can be achieved in a wide variety of environments, even if they do not exactly conform to the line-of-sight model of Fig. 3.

6. Subcarrier Modulation

In Sec. 3, we explained how the backscatter signal can be modulated by opening or closing a switch connected to the sensor antenna. More precisely, modulation is accomplished through a device whose RF impedance can be controlled electrically: switching the device between two different impedance values causes the reflected signal to switch between two different complex values. In principle, more than two different impedance states could be used to implement arbitrary modulation schemes; in practice, two states is the limit.

With only two states, we can always model the backscatter as if it were produced by a perfect on-off switch coupled to a perfect antenna by a lossy transmission line (with η being the round-trip loss). The situation is illustrated in Fig. 4. The two points labeled **A** and **B** represent the two impedance states of the reflecting device; it is clear that the device is far from a perfect on-off switch. However, the reflected signal can be modeled the combination of a *fixed* (unmodulated) reflection, represented by the midpoint **M**, superposed on top of a weaker reflection whose phase modulation is a perfect 180° inversion. In the example, the reduced amplitude of the signal from **M** to **A** (or to **B**) is equivalent to a signal loss of 10 dB.

The fixed component is just one of many reflections from all sorts of environmental reflectors, including the sensor's own mechanical enclosure, rocks, the ground and any other objects within range of the base station transmitter. All these reflections combine to produce a single, large, unmodulated signal received at the base station along with all the modulated signals reflected by all the sensors.

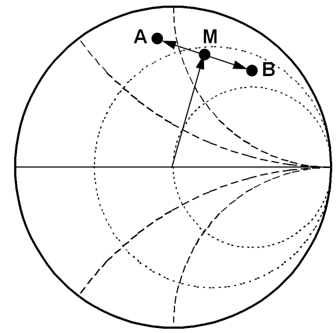

Fig. 4. Smith-chart diagram of reflected RF signal. An imperfect switch that alternates between points **A** and **B** can be modeled as a fixed reflection to **M** superposed with a perfect (but lossy) switch.

This overall "unmodulated" signal is unmodulated only in the sense that there is no deliberate modulation; however, there are plenty of "natural" and "man-made" sources of modulation. Motion and vibrations result in doppler shifting of reflected signals, and the normal operation of electrical and electronic devices results in modulation of reflected radio waves. Fluorescent lights are particularly bad offenders, as the glowing gas plasma is a good conductor of electricity whose conductivity varies according to current flow. The signals reflected by all such unwanted reflectors are collectively referred to as "clutter" in radar systems.

Clutter is an important source of impairment in backscatter systems. In the calculations of Table I, we assumed that only amplifier noise is present. For that assumption to be valid, we must make sure that clutter is well below amplifier noise. Experience shows [44] that clutter occurs mostly at modulation frequencies in the audible range, so that by driving the on-off switch at rates higher than 30 kHz or so clutter can be made manageable. This is accomplished by driving the RF switch in the sensor with a periodic waveform (subcarrier) at a frequency larger than 30 kHz. The subcarrier, in turn, is modulated with the (FEC-encoded) information bits.

The backscattered signal will thus consist of two symmetric sidebands above and below the incident signal frequency at an offset equal to the subcarrier frequency. The bandwidth and spectral shape of the sidebands are determined by the modulation scheme. Different sensors can use different subcarrier frequencies to insure that their signals do not overlap. In the next section we discuss the modulation scheme and the problem of assigning different subcarrier frequencies to different sensors. Fig. 5 shows the power spectrum of the aggregate signal received by the base station; the different heights of sidebands from different sensors are meant to highlight the variation in backscattered signal strength as a function of distance from the base.

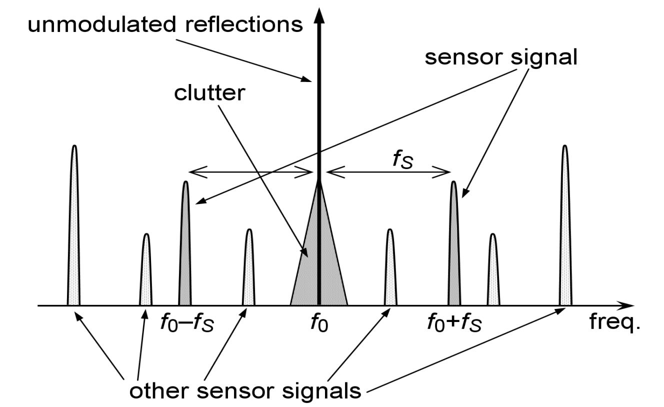

Fig. 5. Spectrum of signal received by the base station. A particular sensor uses a subcarrier at frequency f_S to produce a pair of symmetric sidebands at a distance f_S from the incident signal. Different sensors can use different subcarrier frequencies to avoid overlapping with one another.

7. Multiple Access and Modulation Scheme

The goal of supporting as many as one thousand sensors requires a multiple-access technique that is effective even though we cannot coordinate the signals from different sensors. In the previous section we hinted that different sensors can use different subcarrier frequencies to avoid mutual interference. More generally, we have examined the feasibility of the three main multiple access techniques (Code Division; Time Division; Frequency Division). Our conclusions are below.

Code-Division is typically useful in systems where coordination is not possible, as it relies on the (quasi-) orthogonality of different spreading codes to avoid mutual interference. In our system, it could be easily implemented at low cost through digital techniques. All sensors could use the same subcarrier frequency, and each sensor could modulate its subcarrier at a high chip rate to occupy a wide bandwidth. Implementation with standard CMOS logic is straightforward. However, Code-Division suffers from the so-called "near-far" problem, which is a consequence of the imperfect orthogonality of spreading codes. In backscatter systems, the near-far problem is exacerbated by the round trip which doubles the loss and the dynamic range. For example, using the parameters of Table I and equations (1)-(3), we find that a sensor at a distance of 10 m from the Base is received 60 dB stronger than a sensor at the maximum distance of 100 m. For the base to be able to detect the distant sensor over the interference from the nearer sensor, the spreading codes need to have a processing gain well over 10^6. (And this is not even the worst case). Clearly, the amount of spreading required is excessive and Code Division is not feasible for backscatter systems.

Time Division has the advantage of virtually perfect orthogonality between signals: if the transmissions from two different sensors occur at different times, there will be no mutual interference, even if one is much stronger than the other. Indeed, TDMA is widely used in systems where it is possible to coordinate individual transmissions. Even in uncoordinated systems, time division is still effective at the cost of reduced throughput; for example, the ALOHA technique [45] can be used to easily achieve throughput efficiencies in the 10-15% range. In our system, we could easily implement a modified version of ALOHA (without acknowledgments). The ALOHA concept requires that data be transmitted in short bursts at a high data rate; specifically, burst duration must be short enough that the probability of collisions is reasonably small. In our system, our goal to support as many as 1000 sensors means that each sensor would have to transmit with a duty cycle of much less than 1/1000. Unfortunately, the power of the signal backscattered by an individual sensor is fixed, so that, as the transmission data rate goes up, the transmitted energy per bit, E_b, goes down in proportion. So, for example, if we choose a duty cycle of 1/10000, (corresponding to a ~20% chance of collisions) the SNR computed in Table I becomes -6 dB instead of 36 dB. Clearly, Time Division is a suitable solution only in coordinated systems or systems with a very small number of sensors. In such systems, it may be acceptable to give up some SNR margin for the convenience of using Time Division. In our system, the goal of supporting a large number of sensors at large distances makes Time Division not feasible.

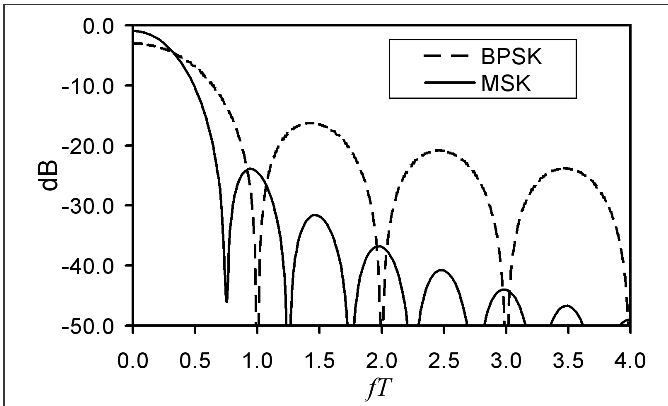

Fig. 6. Comparison of power spectra of BPSK- and MSK- modulated signals. The horizontal axis is the normalized frequency; i.e., the frequency, f, multiplied by the bit period, T.

Frequency Division also has the advantage of nominally perfect orthogonality between signals: the spectrum of Fig. 5 shows signals from different sensors as completely disjoint entities. In practice, however, careful filtering of the transmitted signal is required. Without filtering, the signal spectrum exhibits sidebands that can extend far from the center and cause interference to other signals even at a very different subcarrier frequency [42]. For example, BPSK is commonly used in backscatter systems because of its ease of implementation. The power spectrum, $S_B(f)$, of a BPSK-modulated signal is shown in Fig. 6; we see that, while the 3-dB bandwidth is only about the same as the bit rate ($1/T$) the power spectrum falls off very slowly as a function of frequency. The asymptotic behavior at large frequencies is

$$S_B(f) \approx 1/(2\pi Tf)^2 . \tag{5}$$

Fig. 6 also shows the power spectrum, $S_M(f)$, of an MSK-modulated signal. We see that it falls off much faster and, indeed, its asymptotic behavior is

$$S_M(f) \approx 1/(5Tf)^4; \quad (6)$$

i.e., the power spectrum falls off as the *fourth* power of frequency rather than the *square*. Since both spectra apply to unfiltered signals, it is clear that MSK yields a better approximation of the idealized diagram of Fig. 5. Regarding the issue of practical implementation, MSK can be realized by modulating the frequency of the subcarrier oscillator [42]. In our system, it is not necessary for the subcarrier frequency to be accurate or stable (more on this in the next section) so that we can use a simple R-C oscillator to generate the subcarrier. This kind of oscillator is easy to frequency-modulate.

Based on the foregoing discussion, we have chosen Frequency Division as our multiple-access technique, with MSK modulation of the subcarrier.

8. Multiple-Access Performance

As mentioned above, to avoid mutual interference between sensors, it is important that different subcarrier frequencies be assigned to different sensors. Since no coordination is possible, we simply assign random subcarrier frequencies to sensors over a certain range of frequencies, B. This scheme has the advantage that it does not require an accurate oscillator, (such as, for example, a crystal-controlled synthesizer) thus reducing implementation costs. Of course, some of the sensors will, by chance, have a frequency too close to that of other sensors and the Base will not be able to decode their signal. We need to pick a frequency range, B, large enough that the probability of such "collisions" is acceptably small.

How small is small enough depends, of course, on what mitigation techniques we use to compensate for the collisions. For example, in frequency-hopped spread-spectrum systems, [46] frequency assignments are updated frequently, so that collisions result in short random bursts of bit errors; appropriate FEC encoding is applied to the transmitted data, so that the error bursts can be tolerated.

In our system, we would like to avoid the complexity associated with frequency-hopping spread-spectrum techniques. We observe that the goal is to characterize some environmental variable over a given coverage area. With a large number of sensors scattered randomly over the area, even if a small fraction of them is not functioning, the goal is achieved nonetheless. Indeed, it will be necessary, in any case, to deploy extra sensors to allow for failures due to malfunctions, aging, etc. We can simply regard frequency collisions as an additional cause of failures and deploy additional sensors to compensate for it. If the incidence of frequency collisions is small, the lower cost will justify the additional sensors.

The random frequency assignment to sensors may occur at the time of manufacture, so that each sensor has a fixed backscatter frequency; alternatively, each sensor may be designed to generate a range of possible frequencies. In the latter case, the sensor would, from time to time, switch to a different frequency within its available range. Similarly to frequency hopping, this will insure that the signals from all sensors will be detectable by the Base at least some of the time. We are currently examining implementation feasibility with standard CMOS techniques for both options.

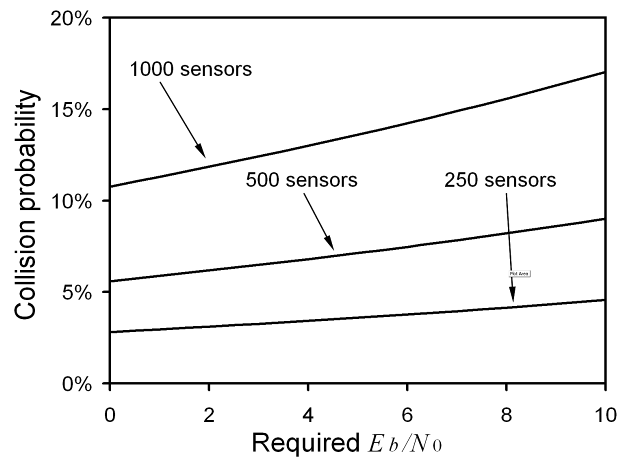

Fig. 7. Performance of random subcarrier-frequency assignment. The curves show the probability of frequency collision for a sensor at the edge of coverage.

In order to quantify system performance, we have performed a Montecarlo simulation of this multiple access technique. The results are shown in Fig. 7. In addition to the parameters of Table I and the use of MSK modulation, we have assumed a value of $B = 130$ kHz for the subcarrier frequency range and a rate of 15/16 for the FEC code. The 130-kHz value results from the assumption that backscatter subcarrier frequencies range from 65 kHz to 195 kHz. This is a range that we expect to be easy to realize with low-cost CMOS techniques, and is compatible with low power consumption.

Fig. 7 shows the probability of a frequency collision for a sensor located at the edge of coverage. As such, this is a worst-case situation; most sensors will experience a lower collision probability. The probability is given as a function of required SNR (Eb/N_0) for three different cases. As expected, collision probability is roughly proportional to the number of sensors deployed, and increases as the required SNR increases. Note that, for a rate-15/16 FEC code, the required E_b/N_0 is in the 6-8 dB range. It is clear that a number of sensors even as large as 1000 is not unreasonable.

9. Optimizing the FEC Code

In any communication system, the use of FEC involves a tradeoff: powerful codes offer large coding gains which reduce the required SNR at the cost of increased bandwidth. Depending on which is more valuable (bandwidth or SNR) the system designer will have to decide the best compromise between the two. In our system, the situation is easier to analyze because the total available bandwidth is fixed (at 130 kHz in the example of Fig. 7) so that the use of FEC does require additional bandwidth. It is true that the *individual* bandwidth required by a single sensor *will* increase and, thereby, cause increased interference to other sensors. So we see that, on the one hand, FEC allows operation at reduced SNR while, on the other hand, it decreases the available SNR because of the increased interference. There may or may not be an overall improvement in system performance, depending on whether or not the coding gain is larger than the SNR reduction.

TABLE II – PARAMETERS OF BCH CODES

block size (bits)	parity bits	info. bits	coding rate	required Eb/N_0 (dB)
255	0	255	1.000	10.5
255	8	247	0.969	8.9
255	16	239	0.937	8.0
255	40	215	0.843	6.8
255	56	199	0.780	6.5
255	76	179	0.702	6.2
255	132	123	0.482	6.0

For a fair assessment of the effectiveness of FEC, we need to compare codes of different rates but approximately equal complexity. (It will always be true that a code of greater complexity yields better performance than one of lower complexity). Figure 9.23 of [42] examines a family of BCH block codes all with the same block length (255 bits) but with different numbers of parity bits. Table II summarizes the parameters of these codes. (The first row corresponds to no FEC coding.). The last column shows, for each code, the Eb/N_0 required to achieve a bit-error rate of 10^{-6}.

For each one of these codes, we have computed system performance with our Montecarlo simulation. (Fig. 7 corresponds to the third code in Table II). The results are shown in Fig. 8, which plots the collision probability as a function of FEC code rate. The rightmost dots (code rate=1) correspond to the uncoded case.

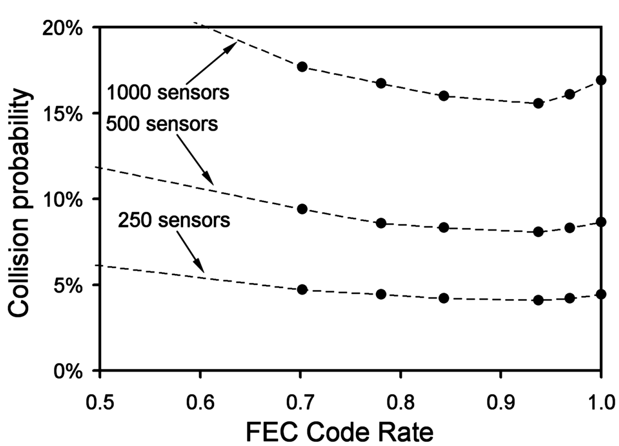

Fig. 8. Performance comparison of BCH codes all with the same block size (255 bits) but different code rates.

We note that the use of FEC coding does provide some performance improvement for code rates near unity where there is a substantial reduction in required Eb/N_0 at the cost of moderate redundancy. (See the first few lines in Table II). At lower code rates, the Eb/N_0 reduction is not sufficient to offset the bandwidth expansion caused by the greater redundancy, and system performance worsens.

More important, the optimal region is broad and shallow, which means that the amount and type of FEC coding is not a critical consideration. Indeed, even with no coding at all, the probability of collisions is only slightly worse than the optimum.

10. CONCLUDING REMARKS

We have built a simplified prototype to test the feasibility of this technique. While we have not yet deployed a large enough number of sensors to verify the validity of the simulation results, our preliminary measurements are consistent with expectations.

As interest in low-cost sensors continues to increase, we feel that the techniques outlined in this paper can be employed to achieve sensors that are substantially less expensive than with many currently-proposed techniques.

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