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Chapter 5

Sensor Design for Harsh Environments: Material Science Perspective

This Chapter presents recent developments in material science that enable implementation and use of wireless sensors in harsh environments. The common property of passive sensors is variation of an electric property such as voltage or current with the measured parameter. As long as the relation between the changed electric current or voltage and the measurand is known, a fairly reasonable estimate can be obtained. Active sensors with radios, microprocessors, and batteries may not be easily placed in harsh environments such as high temperature areas. Passive sensors on the other hand, without onboard processing and battery, if designed with proper material may address this challenge. In this chapter, we study passive sensors modeling and design from material science and signal processing perspectives.

5.1 INTRODUCTION

Passive sensors refer to a class of sensors that does not include battery-powered electric components. As such they are rigid devices which can operate in extremely harsh environment. For instance, passive sensors can be used in temperatures as high as 1000 Celsius degrees. Further, they require minimal maintenance during their long lifetimes. Based on these fact, passive sensors are only solution for some applications (e.g. a jet engine temperature monitoring) and the most economical solutions for some other applications. The common sprit of passive sensor operation, regardless of their technological variations, is that they receive an interrogation signal and reflect it back to the interrogator for further processing.

The response signal may include controlled distortions and morphological features, which convey information about a parameter of interest such as stress, pressure, temperature, chemical particles and etc. Figure 5-1 depicts two examples of passive sensors. Surface acoustic wave sensor (left) built at the University of Maine (2008) operating at 103 MHz in FM band was used for measuring temperature. RFID based sensing using Alien Technology tags (right) operating at 900 MHz UHF band and University of Maine localization software were used in shape monitoring of inflatable space habitats (2011).

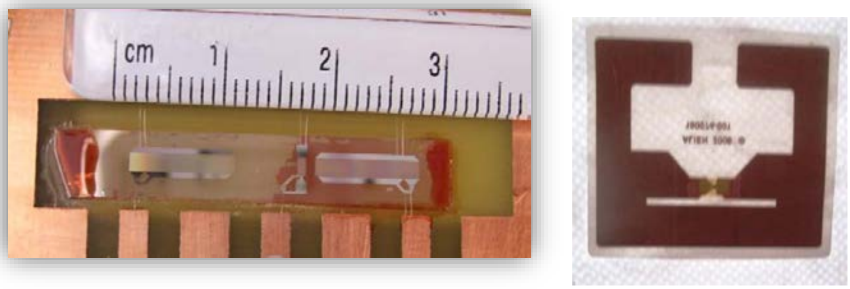

Figure 5-1 Some examples of passive sensors. Surface acoustic wave sensor (left), RFID based sensor (right).

An important challenge that arises in using passive sensors is the concept of interference, since these devices tend to respond in parallel and using conventional multiple access methods is challenging. Interference is an important phenomenon arises in wireless communication systems due to an undesired mix of intended signals with other signals. Interference can substantially deteriorate the received signal quality and corrupt the payload data. The interfering signal can be produced by other users in the system or by users of another system. Interference can also be due to malfunction of electric components by producing signals which violates subtle multiple access criteria. Interference is a well-studied concept in wireless community.

Comprehensive information about interference sources and interference management techniques can be found in communication system textbooks as well as review papers including [1] [2] [3] [4]. This chapter is devoted to study design of a measurement system composed of wireless passive sensors. The main focus is on the interrogation system design and interference mitigation techniques to improve measurement fidelity. Interested users are referred to [5] [6] for further details.

5.2 SENSOR RESPONSE SEPARATION

Multiple sensors responses may interfere with each other if not separated properly. In this section, sensor response separation in time, frequency and code domains are studied and several examples are provided for further clarity.

5.2.1 Time domain

The first approach to separate sensor responses is time domain separation. In this method, each sensor is designed in such a way that their responses are received at non-overlapping times at the interrogator, even though they all receive the interrogating signal at the same time. The main advantage of this method is in its simplicity at the sensor side as well as the interrogator side. In order to understand the limitations of this approach, the following example is presented next.

Example: Consider a sensor network with 50 nodes each responding to the interrogating signal after a pre-determined internal delay *j* ms for sensor *j*. Assuming that distances between sensors and the interrogator is negligible compared to the speed of light (or RF waves), what is the upper bound on sampling frequency?

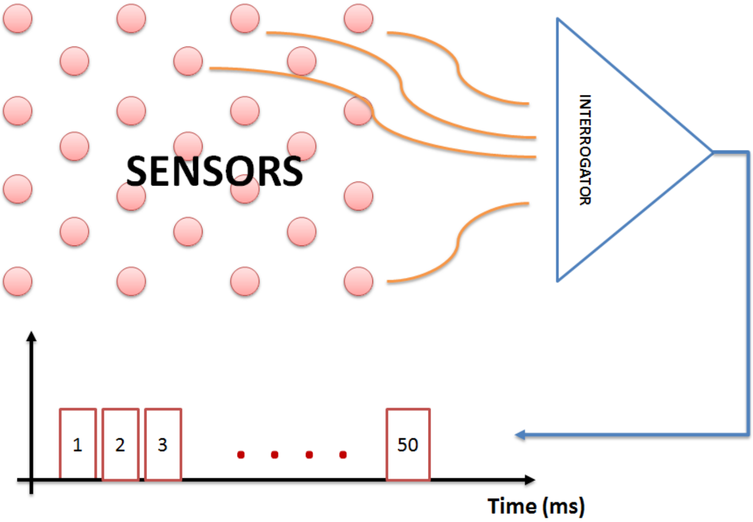

Figure 5-2 Time separated sensor responses.

Solution: After the first interrogating signal is transmitted, the first sensor will respond with a 1 ms delay, the second sensor responds with 2 ms delay, and so forth. The last sensor will respond after 50 ms. Therefore, in between each two interrogating signals there is a 50 ms delay. This renders the maximum frequency to be less that 1/50 ms or 20 Hz. The previous example, illustrated one of the shortcomings of sensors that are designed using this method, with time separated responses. The sampling rate limitation may not be as important when estimating a slow changing parameter such as temperature, but it is a limiting factor when fast changing parameters such as structural modes of vibration are estimated. The next method of separation will address this limitation.

5.2.2 Frequency domain

In addition to the time domain separation discussed in the previous section, sensors response may be separated from each other in frequency domain. For example, dividing a pre-determined bandwidth to several sub-channels, enables all sensors in a network to respond at the same time. This method practically can samples fast changing parameters as fast as the interrogator can handle. Let us study another example to understand the limitation of this approach.

***Example**:* A 100 node sensor network is operating on a licensed band from 895-896 MHz. Assuming that all sensors have sub-channels with similar bandwidths allocated to them, what is the main limitation of this sensor network when it comes to sampling?

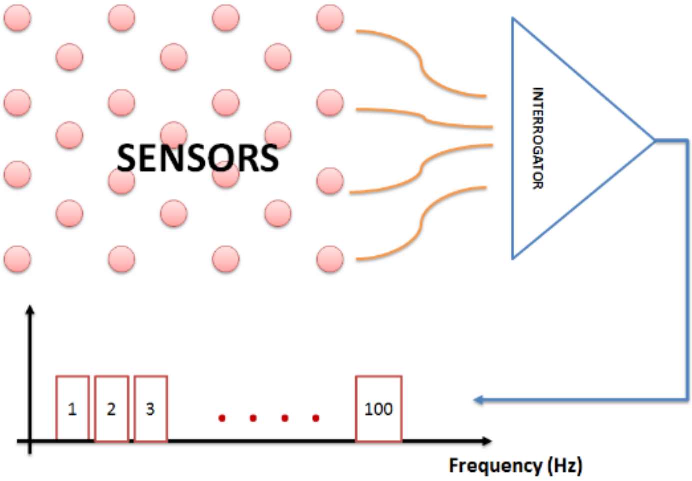

Figure 5-3 Frequency separated sensor responses.

Solution: The total available bandwidth of 1 MHz is divided among 100 sensor, providing 10 KHz bandwidth to each sensor. This sub-channel allows for communicating a signal with 5 KHz bandwidth sampled at Nyquist rate. Phone quality voice is one example of such a signal measured in distributed sensor network for surveillance\ and monitoring. This examples shows the main limitation comes from the original total bandwidth allocation. For instance, if a video network where to operate with 6 MHz channels per sensor, 600 MHz bandwidth was required.

A hybrid solution that allows sensors to operate on various bands and respond at various times, may allow for using even more sensors without the need for large amounts of bandwidth. A third degree of freedom is explored in the next section.

5.2.3 Code domain

Code domain separation can be used by itself or in conjunction with other methods such as time and frequency and can add another degree of freedom to design phase. This method, also called Code Division Multiple Access (CDMA) allows the sensors to respond at the same time on the same frequency band. The sensors are designed in such a way that each response is orthogonal to the others allowing for matched filter detection at the interrogator. Several families of orthogonal codes are available for such sensor designs. One point to consider is that all these digital codes will be implemented in sensors with analog response, which renders the signals to be quasi-orthogonal. Therefore, the optimization of signals correlations should take sensor response into the account when selecting good codes. There are various techniques to design codes for Direct Sequence Spread Spectrum (DSSS) systems. A desired property of these codes is a low pairwise cross correlation to minimize the undesired interference effects [7]. A popular variant of these codes is Gold codes which are easy to implement for conventional transceivers using simple components such as shift register and basic arithmetic operations. An implementation of Differential Reflective Delay Line (DR-DL) sensors based on gold codes using Surface Acoustic Wave (SAW) devices is presented in [8].

Example: The following codes of length 8 chips are used to provide multiple access in a DSSS system. Binary Phase Shift Keying (BPSK) is used for modulation.

$C_1 = [00001111], C_2 = [11110001], C_3 = [00110011]$

The respective signals are depicted in Figure 5-4. Which pair of the codes provide a better separation property?

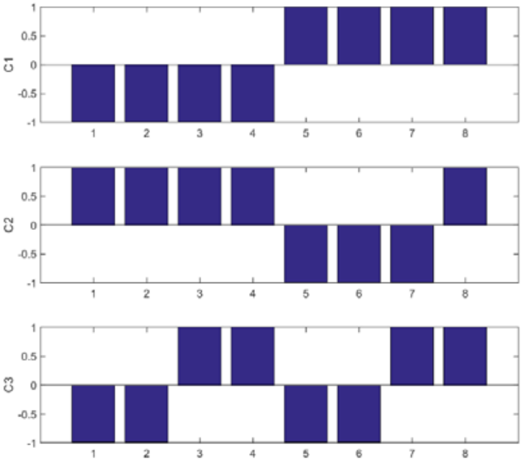

Figure 5-4 Code separated sensor responses.

Solution: We first obtain the BPSK modulated signals by mapping (0→-1, 1→+1). Note that this mapping is arbitrary and (0→+1, 1→-1) can be used as well. The resulting modulated codes are:

$$B_1 = [-1\ -1\ -1\ -1\ +1\ +1\ +1\ +1]$$
$$B_2 = [+1\ +1\ +1\ +1\ -1\ -1\ -1\ +1]$$
$$B_3 = [-1\ -1\ +1\ +1\ -1\ -1\ +1\ +1]$$

Now we calculate cross-correlation among the codes as follows:

$$\mathrm{Cross}(\mathrm{B_i}, \mathrm{B_j}) = \frac{1}{n}\left|\sum_{k=1}^{n} B_{ik}B_{jk}\right|$$

where B_{ik} is the k$^{\text{th}}$ chip of code B_i and $n = 8$ is the length of each code. We obtain:

$$\mathrm{Cross}(\mathrm{B_1}, \mathrm{B_2}) = \frac{|-6|}{8} = \frac{3}{4}$$
$$\mathrm{Cross}(\mathrm{B_1}, \mathrm{B_3}) = \frac{|0|}{8} = 0$$
$$\mathrm{Cross}(\mathrm{B_2}, \mathrm{B_3}) = \frac{|2|}{8} = \frac{1}{4}$$

The results suggest that $(\mathrm{B_1}, \mathrm{B_3})$ is the best choice. In fact, they are fully orthogonal codes as part of the well-known Walsh Codes widely used in CDMA systems.

5.3 PASSIVE SENSOR MODELING

The essence of passive sensor operation is based on inducing controlled changes in the response signal which depends on a physical parameter under measurement. Hence, response signals convey useful information about an environmental or a physical parameter which can be extracted by advanced signal processing methods. Wireless passive sensor network typically comprise multiple passive sensors, one or multiple interrogators, a receiver and a data fusion center.

The interrogator, receiver and the processing units are typically combines into one computer-based system called interrogation system. The interrogation module operates similar to a wireless transceiver by propagating a radio wave to the surrounding passive sensors. The electromagnetic waves are received by the passive sensors and reflected back after some distortions which depend on the physical parameter under measurement. The interrogator receives the reflected signals and extract measurement information based on the changes on the received signals.

There are different types of sensors to realize a mapping from a physical parameters such as temperature, stress, and light into signal distortions. Here, we focus on a specific class of passive sensors built using SAW technology. The majority of these devices operate based on the fact that the shape of sensors change with a parameter under measurement. For instance variation of temperature causes contraction or expansion of the device.

SAW sensors are built in different types in order to incorporate the physical changes into the response signals. The idea of resonation-based sensors is to map the measurand to the resonance frequency. The interrogator typically transmits a broad-band signal, but the reflected signal includes a peak at a resonance frequency which is related to a specific parameter under measurements [9]. For instance, SAW resonators are proposed to implement vapor sensors, where the resonance frequency is a function of temperature and humidity [10].

A more advanced version of these devices are developed in the University of Central Florida by using orthogonal frequencies, where different reflectors have different resonance frequencies and combination of these reflectors can be used to realize multiple access for systems with more than one sensor [11].

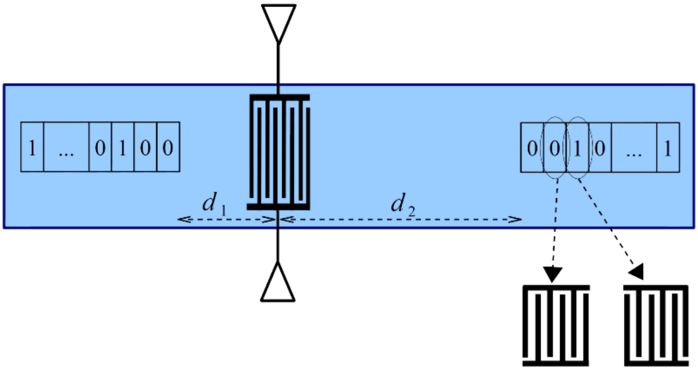

Figure 5-5 A block diagram of a differential reflective delay line based on SAW technology.

Here, we turn our attention to a new variant of SAW sensors called DR-DL devices. The operation of devices are based on techniques borrowing from spread spectrum systems by producing CHIP sequences using a special structure called reflectors. These devices are built in the University of Maine and the idea is to use orthogonal binary codes to enable multiple access systems similar to DSSS systems in wireless networks.

Each sensor is composed of an antenna, an Inter Digital Transducer (IDT), and two series of reflectors with mirrored patterns, all printed on a temperature sensitive substrate such as Lithium Niobate Y Z - LiNb03. The electromagnetic wave is received by the antenna and is converted to acoustic wave by the IDT. The received electromagnetic wave induces an electric voltage difference between the upper and lower bars of the IDT, which energizes the free electrons on the substrate with crystal structure. The vibrating electric charges generate acoustic waves that can easily propagate through the device surface. These acoustic waves hit the two sets of reflectors in both sides of the devices and reflected back towards the IDT in middle. The reflected acoustic waves are converted back to electromagnetic signals and propagated back by the antenna. Since the distance of two reflective fingers in both sides of the device from the IDT is different, the received signals do not overlap.

Let us note that a key property of surface acoustic waves is their relatively lower propagation velocities which is 100,000 times slower than that of an electromagnetic wave. As such, relatively small distances are translated into measureable propagation delays. Another key property of the utilized piezo-electric material is that its length changes with temperature almost linearly over a wide temperature range. If the temperature rises, the relative distance between the reflectors increases and as such the arrival time difference between the two copies of the received signal increases. Therefore, using a simple mapping table, the temperature can be measured. These devices are rigid with a wide range of operations that can go up to 1000 Celsius degree and hence are of particular interest in extremely harsh environment, where the conventional battery-operated sensors fail.

Example: A SAW-based passive senor of type DR-DL is deployed to measure temperature inside a jet engine. During a test phase, the interrogator sends a single pulse and inspects the reflected signal. The received signal includes two pulse sequences whose relative distances changes with temperature. The following table shows the results of training phase:

Temperature (Celsius)	T1=100	T2=200	T3=?
Distance between pulses	t1=5 μsec	t2=5.5 μsec	t3=7.5 μsec

Find the temperature for the third measurement (T3). If the velocity of acoustic wave is 3×10^3 m/sec, find the device expansion coefficient versus 1 degree of temperature change.

Solution: We assume a linear operation. Therefore, the rate of device expansion versus temperature is: (t2-t1)/(T2-T1) = $(5.5\times10^{-6}-5\times10^{-6})/(200-100)= 5\times10^{-9}$ sec/Celsius. T3 can be easily found as T3=T1+ (t3-t1)/ $5\times10^{-9}=100+2.5\times10^{-6}/5\times10^{-9}=100+500=600$. Note that 1 degree of temperature variation translates into 5×10^{-9} sec, which is equivalent to physical expansion of d= $5\times10^{-9}\times3\times10^3$ =15µm.

In DR-DL sensors, multiple access is enabled using reflectors with unique patterns. This unique patterns are also considered device IDs and can be used for identification purpose. The reflectors have two polarizations to representatives of digits +1 and -1 as depicted in Figure 5-5. In BPSK modulation, the signals for digits +1 and -1 are simply flipped versions of the same sine wave. Therefore, we can have multiple sensors operate in parallel with negligible interference. Gold codes can be used to realize a good separation property. The reflectors have mirrored patterns, and as such the reflected signal includes two copies of the same bitstream with different delays. The following figure demonstrates a sample impulse response of a DR-DL sensor with pattern 11001, where each reflector includes 3 fingers.

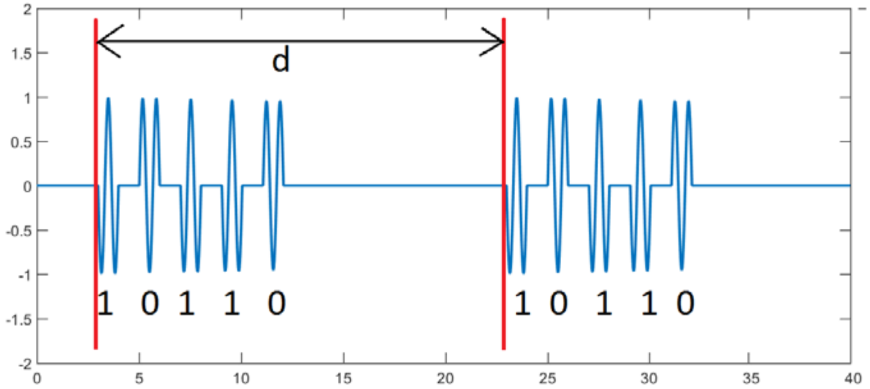

Figure 5-6 A sample impulse response of a SAW-based passive sensor of type DR-DL with pattern: 10110. The impulse response includes two BPSK modulated bit-streams of pattern 10110 with different delays. The distance between the two patterns (d) is proportional to the length of the sensors and conveys information about the current temperature, stress or pressure; hence can be used to measure these parameters.

Finally, we note that analytical modeling of SAW devices are based on considering the first order terms and using simplifying assumptions such as the full absorption of leaking signals at the endpoints of the device. However, these assumptions do not hold in practice. Further, fabrication variations impact the device operation and should be taken into account. Therefore, finding a reliable analytic model for a passive sensor can be extremely challenging. One shortcut for this problem is using computer-based software solutions [12] [13].

5.4 INTERROGATOR DESIGN

In Section 5.3, fundamentals of a SAW sensor operation is provided. In DR-DL devices, similar to other types of SAW devices, an electromagnetic wave is radiated by the interrogator. One of the drawbacks of passive sensors is their limited transmission powers, since the reflected signal is significantly weaker than the interrogation signal. The main reason for this issue is that passive sensors are not equipped with any sort of amplification modules in contrast to active sensors. This is an important drawback of these devices which restricts their operation distances to as low as few meters.

In order to enhance this property, instead of using a single pulse by interrogator, we can use a sequence of pulses with a pattern matching the time reversal of the target device’s reflector pattern. The only cost paid is a slightly loner interrogation phase, which is acceptable in systems with slow-varying measurands. In this approach, the response signal is the convolution of the input signal and the impulse response with the reversed patterns. Consequently, it includes two large pulses. However, if the interrogation signal pattern does not match the time-reversal of the undesired device pattern, the response signal is more like a random noise. Therefore, this method reduces interference among devices operating at the same frequency.

Figure 5-7 illustrates this concept by presenting the response signal of a target device with pattern 01001010, as well as that of an interfering device with pattern 11100111. The interrogation signal pattern is 01010010, which is the time-reversal of the target sensor's pattern. The target sensor exhibits a response signal with two large peaks whose distances can be used to measure a parameter of interest. Figure 2-8, represents an actual response signal obtained using the SAW sensors built in the University of Maine [8].

Practical implementation of interrogator can be done based on various platforms. One popular option is using FPGA boards due to their flexibility, robustness, high performance signal processing and wireless connectivity [8] [14]. However, specific radio line and antennas shall be designed for a better performance.

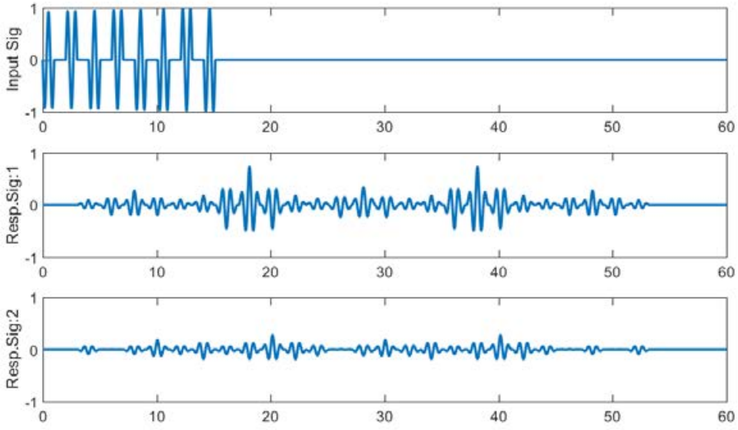

Figure 5-7 An illustrative example of the operation of DR-DL sensors. The interrogation signal pattern is 01010010. The target sensor (sensor 1) whose pattern 01001010 is the time-reversal of the interrogation signal presents a response signal with two strong peaks. The distance between the peaks is proportional to the temperature and can be used to read the temperature. The second sensor with a different pattern of 11100111 exhibits a noise-like response signal and hence does not significantly interfere with the target sensor.

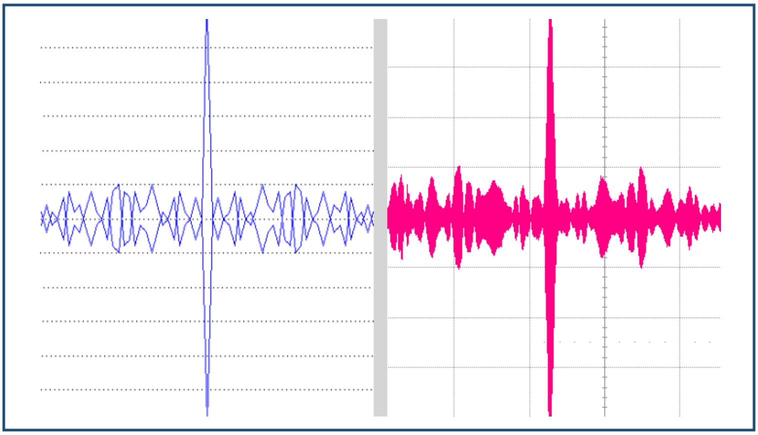

Figure 5-8 Theoretically driven response signal vs. a measured response signal for DR-DL sensor. Figure is from [8]**.**

5.5 INTERFERENE MITIGATION

In order to obtain accurate sensor measurements, it is desired to have an interference-free communication from the sensors to the reader using one of the aforementioned multiple access methods. However, complete elimination of interference is not feasible. Firstly, interfering signals may be related to a system other than our designed system, and hence out of our control. Secondly, the above transmission systems rely on idealistic assumptions which do not often hold in practice. For instance, in time domain multiple access methods as elaborated in section 5.2.1, full separation among different sensors' pulses demand for utilizing fully rectangular time-domain pulses. However, a rectangular pulse includes infinite frequency spectrum and hence is not practical, and we usually settle in using pulses with interfering tails, which cause Inter Symbol Interference (ISI). Further, full synchronizations is hard to achieve in practical systems. Other multiple access methods are also prone to interference due to imperfect electric components and antennas, fabrication artifacts, Doppler effects due to the mobility of sensors, loss of frequency synchronization and nonzero cross-correlation among codes in CDMA. Therefore, dealing with interference in sensors systems is unavoidable. Two major approaches include interference avoidance and interference management.

In the first approach, techniques are used by the transmitter to minimize the level of interference. The most recent one is interference alignment by employing pre-codes in the transmitters to align all interfering signals into one direction to be easily filtered out by the receiver [15]. However, these methods can not be directly implemented on passive sensors and they require more advanced signal processing in the interrogator side, which can be considered as a potential future research direction.

In the second approach, advanced signal processing are used in the receiver to eliminate interfering signal after occurrence. Advanced methods such as parallel interference cancelation (PIC), serial interference cancelation (SIC), matched filtering, and channel equalization are used in order to separate the desired signal from the interfering signals [16]. This is more crucial in passive sensors, since due to the lack of flexibility in the sensor sides, the level of interference level is higher than usual which urges for a more intelligent reader to polish the received signal.

Ideas are recently proposed to use directional antennas and beamforming techniques to reduce interference level in passive sensor networks [17]. In this work, the authors proposed to use a cyclic array antenna with 16 antennas, where only 4 adjacent antennas are active at each time point. The selection of active antennas is performed electronically by controlling the feeding current, which enables steering the propagation direction towards the target sensor location. The 3rd order Chebyshev polynomial $T\,(x) = 4x^3 - 3x$ is used to adjust feeding current amplitudes to minimize the side lobe level with respect to the given main lobe width. This work proposes a two-step interference reduction algorithm, where in the exploration phase, the existing sensors are recognized and in the measurement phase, the target sensors are read by respective interrogation signals. This flexible approach enables using a universal interrogation system with any set of sensors with arbitrary patterns. Figure 5-9 presents a block diagram of this interrogator along with the simulated antenna pattern using 4nec2 software.

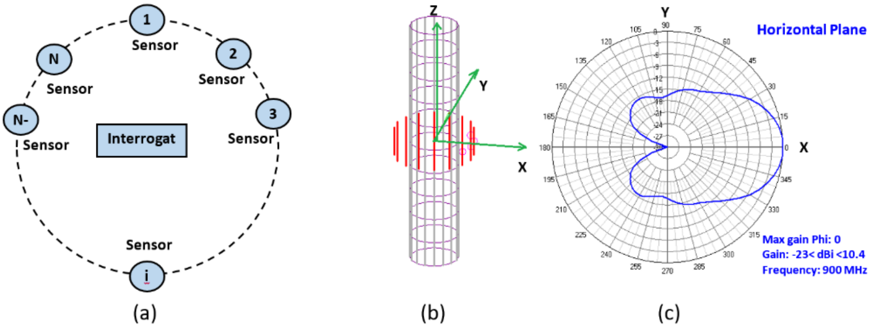

Figure 5-9 (a): The system model with one interrogator module and multiple passive sensors; (b): the designed circular array antenna with 4 active antennas out of 16 total antennas; (c): the resulting propagation pattern. The input current is obtained using 3rd order Chebyshev polynomial and simulated using 4nec2 software. The 3db main lobe width is 40 degrees and the main lobe to side lobe ratio is 15db. Figure is from [17]**.**

5.6 DESIGN CHALLENGES

Using passive sensors for field monitoring and data aggregation in harsh environment is still in its beginning stages. Sensor fabrication, sensing and communications algorithms are under study by several research groups in academia and industry to further leverage this technology in real world applications such as space exploration [17], remote sensing [18], wearable biosensors [19], RFID-based navigation [20], underwater application [21] , structural health monitoring [22], and even passive WiFi [23]. There are several challenges which limits the applicability of these devices including i) short communication ranges (in terms of few meters), ii) interference management, iii) more efficient transducer design, iv) realistic modeling of devices including non-linear terms and v) fabrication cost. In this section, we addressed the two important aspects of communication ranges and interference management through using directional antenna arrays and advanced signal processing methods. Various models including conceptual models [24], differential equation-based models [25], models based on coupling of modes theory [26], mathematical models [27], and recently simulation-based models [28] are proposed in the literature. However, the need for a unified model for different types of passive sensors as well as computer-based simulation environments, similar to antenna simulators, is an essential need to improve the sensing and interrogator design by considering more realistic model for the utilized sensors.

To reduce the implementation cost, the idea of using commercial software defined radio and embedded systems [29] as well as low-cost printable sensors [30] is under investigation.

5.7 CONCLUDING REMARKS

This chapter presented recent developments in passive sensor design with a special focus on SAW devices. We reviewed Multiple Access (MA) techniques developed for passive sensors to realize a scalable passive wireless sensor networks, where multiple passive sensors are read by a single interrogator module in a cluster. This approach enables a new generation of applications and improves the performance of current single-sensor systems.

A recently developed passive sensor, the so called differential reflective delay line based on SAW technology is elaborated in full details as an illustrative example. In these devices, chip sequences with high autocorrelation to cross-correlation values based on Gold codes are used to eliminate the interference effect. However, this technology is still in the beginning stages and there are many research challenges yet to be solved.

Current analytical models are too basic and more accurate models can be developed by considering second term effects and relaxing simplistic assumptions such as linear operations, and loss-less acoustic wave propagation through the device surface.

Also, most current interrogation systems use transmission techniques that are primarily designed for wireless networks with active node. However, a more elegant interrogation signal design can further improve the performance of these systems. Interference mitigation using new chip design, directional antennas and beamforming is another potential research direction.

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