Multi-Carrier Backscatter Communication System for Concurrent Wireless and Batteryless Sensing

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***Abstract*—Wireless and batteryless sensing has recently attracted significant attention of researchers in IoT and WSN applications. It turns out to be more challenging when simultaneous data acquisition from multiple sensors is required. This paper introduces a non-orthogonal multiple access technique MSMA, using extremely simple wireless and batteryless sensor tags and a reader to support concurrent streaming from multiple sensors. By simultaneously handling non-orthogonal subcarriers, produced either by multiple or single sensor tag, it can realize concurrent sensor data streaming, which can be used in health monitoring of machinery and civil structures. The paper explains the two primary challenges in MSMA, the optimal assignment of subcarrier frequencies and the unavoidable harmonics from one subcarrier to others. Since the mutual interference among subcarriers is unevenly distributed over the available frequency band, random allocation of subcarrier frequencies may result in degraded system performance. Results show that the interference can be canceled out with the signal processing technique and the system communication capacity can be increased significantly with a proposed heuristic approach compared to random allocation of subcarrier frequencies to the sensor tags.**

I. Introduction

Internet of Things (IoT) is the buzzword these days, characterized by uniquely identifiable objects interconnected through the Internet. Wireless Sensor Networks (WSNs) go into similar lines, consisting of spatially distributed autonomous observing sensors, where each observing sensor is attached to an object accumulating relevant data according to its application [1], [2], [3]. The observing wireless sensors require data transmission for long duration or frequently. Moreover, some applications such as structural health monitoring (airplanes, artificial satellites and civil engineering structures etc.), require simultaneous data transmission from multiple sensors to detect damage and malfunction before a catastrophic failure. The key issues in such applications are demands for batteryless and wireless sensors together with the need for data collection from multiple nodes concurrently, making the conventional systems unsuitable.

Current low power technologies such as UWB, Zigbee and Bluetooth differ from backscatter device – passive RFIDs, which do not require a power source for data transmission. Figure 1 shows the basic components of the backscatter communication in an RFID system. In backscatter communication system the reader transmits a high power Radio Frequency (RF) signal or Continuous Wave (CW). To convey a binary message to the reader, RF tag antenna changes its impedance match so the binary data can be modulated on the backscatter signal. This way the tags can communicate with almost no power, by powering from the reader's RF signal. Further, the new generation RF tags are integrated with sensors with various sensing capabilities called sensor tags and use the backscatter system for transmitting sensor data to save communication energy [4], [5]. Since the conventional backscatter system does not support streaming data collection from multiple sensor tags concurrently, it is unsuitable for some applications. This paper explains Multiple Subcarrier Multiple Access (MSMA) system which enables the existing RF tags for streaming data collection concurrently.

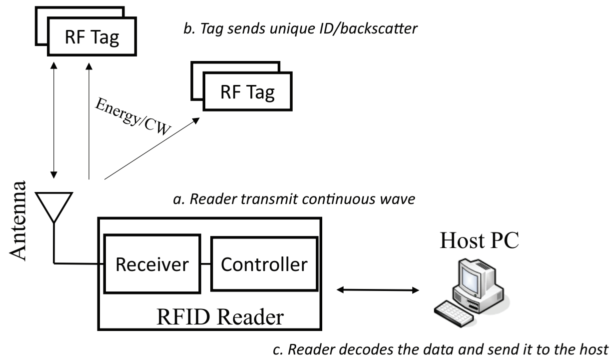

Fig. 1. Backscatter communication system in passive RFIDs

MSMA is a wireless technology for concurrent sensor data streaming from multiple sensors based on backscatter communication principle. It uses a set of subcarriers produced by multiple sensor tags which are operated in passive or battery assisted passive mode. MSMA is pseudo FDMA (Frequency Division Multiple Access) since it incurs mutual interference among the simultaneously operating subcarriers between the sensor tags and the reader. The mutual interference can be eliminated by signal processing techniques.

In [6] the feasibility study on simultaneous data collection from multiple sensor tags with multiple subcarriers has been done. Concurrent multiple access from simple sensor tags is usually realized by employing FDMA. But in the case of backscatter communication with a low function sensor tag, it is expensive to implement the adaptive channel filter for FDMA. Concurrent data stream with TDMA demands burst transmission, which is also impracticable in low function sensor tags. MSMA prefers analog transmission because it saves bandwidth and thus increases the number of subcarriers. Analog data transmission over a backscattered subcarrier can be found in [7] and a multiple carrier RFID system was proposed in [8] to extend the communications by powering with dedicated RW. Multiple carrier transmission is common place in OFDM or optical communications [9].

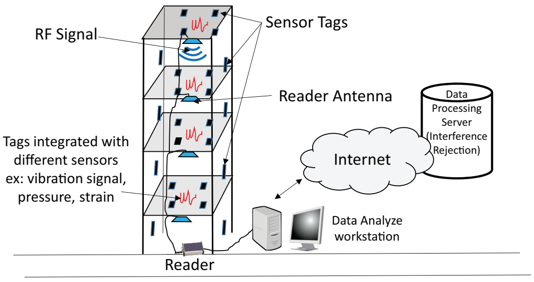

Fig. 2. An example of MSMA in civil structure health monitoring

A usage model of MSMA system is shown in Fig.2. Sensor tags are implanted in a building's walls, anchors and surface. The reader measures sensor data from multiple sensors to detect malfunctions and developing faults. The reader receives data from different antennae and sends to the data processing server through internet. The exciting forces creating structural vibration are sensed by sensor tags, data collected concurrently and can be analyzed in terms of magnitude or phase.

Section II reviews MSMA system in detail and its primary challenges. Section III explains the proposed solution and results and Section IV concludes the paper.

II. MSMA: Multiple Subcarrier Multiple Access

A. MSMA Study

MSMA uses backscatter communication principle to transmit sensor data, so the communication cost can be decreased. In conventional system, RF tags cannot hear each other and the tag to reader communication is based on slotted aloha to transmit the unique tag id. An RF tag requests a time slot by sending a random number to the reader which sends acknowledgment back to RF tag. Afterwards, RF tag sends its unique identity to the reader. If multiple tags tried at same time, reader treat it as collision and tag has to be try after waiting a random period.

Figure 3 shows a sensor tag with minimal modification in existing RF tag to produce the subcarrier in MSMA. The sensor analog/digital data modulates onto the subcarrier by different modulation techniques. Since the MSMA only requires an RF switch to realize a type of multiple access, no channel filter is required as in FDMA, no synchronized burst transmission required as in TDMA and no power control among sensors to equalize the reception power at the receiver required as in CDMA. It can be implemented into very tiny and low cost sensor tag, which we refer as Large Scale Integration (LSI) sensor, implanted into artifacts during their manufacturing process.

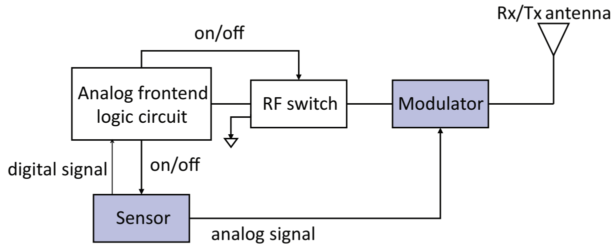

Fig. 3. Sensor tag with minimal modification in existing RF tag

An example of a 10 kHz subcarrier signal using amplitude shift keying modulation is shown in Fig.4. A square wave with 10 kHz frequency is treated as RF switch. The baseband signal is encoded with miller encoding and finally the modulated subcarrier signal is generated by taking XOR of miller encoding signal with the square wave. To better understand the modulated subcarrier signal digital modulation is considered whereas the experiment is done with the sensor tag which modulates the sensor data with analog modulation techniques as it saves the bandwidth and thus increases the number of subcarriers.

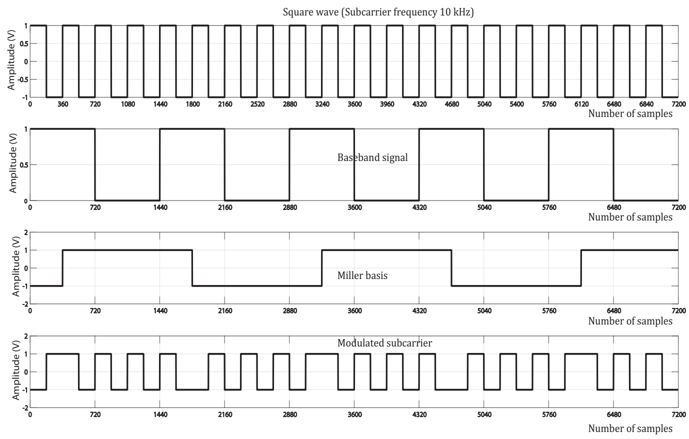

Fig. 4. Miller encoded modulated subcarrier signal for a sensor tag

The time domain signal (square wave as in Fig.4) for a subcarrier of frequency f_s can be represented by an infinite repetition of the elemental signal as in Eq.1.

$$\begin{aligned} s_e(t) &= -A_s & -\frac{T_s}{2} \le t \le 0 \\ s_e(t) &= A_s & 0 \le t \le \frac{T_s}{2} \end{aligned} \quad (1)$$

The subcarrier signal in time domain shown in Eq.1 can be expressed as a summation of fundamental frequency components using Fourier series

$$s_e(t) = \frac{A_s}{2} + A_s \sum_{n=1}^{\infty} \frac{1-\cos n\pi}{n\pi} \sin 2n\pi f_s t$$
$$= \frac{A_s}{2} + \frac{2A_s}{\pi}\left(\sin 2\pi f_s t + \frac{1}{3}\sin 6\pi f_s t + \frac{1}{5}\sin 10\pi f_s t..\right) \tag{2}$$

From Eq.2, It can be seen that harmonic components emerge at odd multiples of primal subcarrier frequency with decaying power, where A_s and f_s denotes the amplitude of subcarrier signal and its frequency respectively. Each sensor tag generates harmonics at odd multiples of its primal frequency, and can be represented as in Eq. 3. T_i shows the original data of sensor tag transmitted on subcarrier i and the R_i is received data on the subcarrier i.

$$\begin{Bmatrix} R_1 \\ R_2 \\ R_3 \\ \vdots \\ R_9 \\ \vdots \end{Bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 & \cdots \\ 0 & 1 & 0 & 0 & \cdots \\ \frac{1}{3} & 0 & 1 & 0 & \cdots \\ \vdots & & & & \cdots \\ \frac{1}{9} & 0 & \frac{1}{3} & 0 & \cdots \\ \vdots & & & & \ddots \end{bmatrix} \begin{Bmatrix} T_1 \\ T_2 \\ T_3 \\ \vdots \\ T_9 \\ \vdots \end{Bmatrix} \tag{3}$$

Since the matrix in Eq.3 is lower triangular, T_i can be recovered from received signal R_i by forward substitution method as in Eq.4

$$\begin{aligned} T_1 &= R_1 \\ T_2 &= R_2 \\ T_3 &= R_3 - \frac{1}{3}R_1 \\ T_9 &= R_9 - \frac{1}{9}R_9 - \frac{1}{3}R_3 \end{aligned} \tag{4}$$

Figure 5 shows the received signal power and interference power for six sensor tags located at different distance. The center frequency and subcarrier bandwidth is considered 916.8 MHz and 10 KHz respectively. It can be seen that subcarrier-1 (SC-1) generates its first harmonic on SC3 and the second harmonic on SC5 with decaying power.

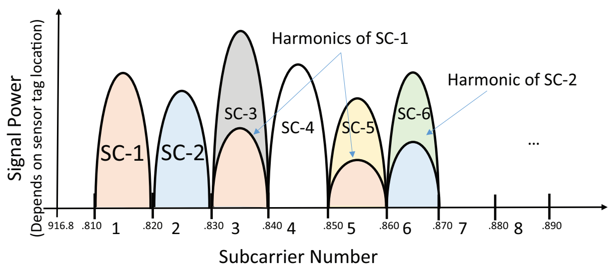

Fig. 5. An example to show harmonic interference on different subcarriers

Figure 6 shows the work flow of MSMA. The reader inventories the sensor tag in its reading zone based on frame slotted ALOHA. Reader runs a subcarrier allocation scheme and assigns subcarrier frequency to each sensor tag based on their location. Next, the reader broadcasts the *start* command to the inventoried sensor tags for starting data stream. Reader collects the continuous streaming data and forwards it to data processing server. Finally, the data processing server runs the harmonic cancellation method to cancel out the mutual interference and demodulates the sensor data.

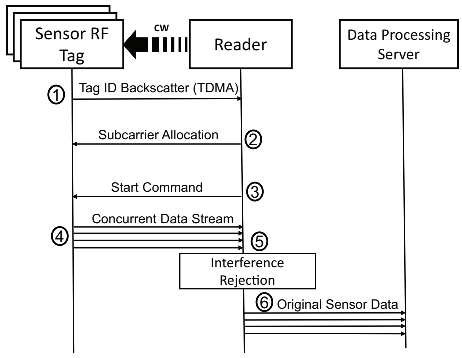

Fig. 6. Complete work flow of MSMA system

B. MSMA Challenges

There are two main challenges in MSMA as follows.

- Subcarrier Assignment: MSMA allows multiple sensor tags to communicate simultaneously. After the inventory phase, Reader allocates subcarrier frequencies to sensor tags for streaming their data. As the sensor tags usually are located at locations tailored to the application, Signal to Interference and Noise Ratio (SINR) of a tag-to-reader link depends on the tag's location and propagation characteristics. Since a subcarrier which is close (frequency-wise) to the powering continuous wave from the reader produces more harmonics into the rest of the channels than a subcarrier farther from the CW, it is desirable to allocate frequency bandwidth to the sensor tags in an efficient way to improve the overall communication capacity of the system. In MSMA, SINR of a sensor tag depends on the other subcarriers too, making it hard to determine a closed form optimal solution. In [10] various subcarrier allocation schemes have been studied.
- Harmonics Cancellation: In MSMA, the unavoidable mutual interference among subcarrier can be eliminated by the harmonic cancellation method. Harmonic of a subcarrier can be derived after measuring the primal subcarrier accurately. The main problem in this method is to measure the accurate phase delay and carrier delay of primal subcarrier as subcarrier fluctuates from the original frequency.

III. Proposed Solution and Results

The first problem of optimal assignment can be solved by a heuristic scheme. A subcarrier always produces interference at odd multiples of its frequency. The SINR received by the reader for a sensor tag depends on the location of sensor tag and the harmonic interference power on its operating subcarrier frequency. With this observation the proposed heuristic

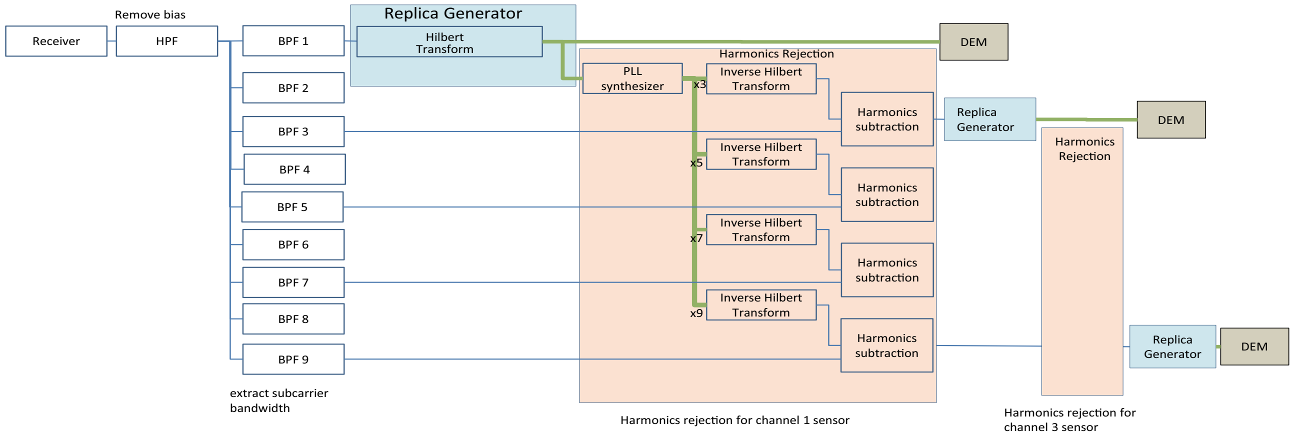

Fig. 7. MSMA Harmonics Rejection Receiver is constructed both in Simulink and Experimental System.

scheme gives priority to allocate first one-third band to sensor tags which are geographically farther located. By allocating farther tags to first one-third band decreases the harmonic power in the available band and improves SINR. The random allocation scheme assigns subcarriers to the sensor tags in a random fashion. The communication capacity is measured with the Shannon capacity formula. A simulator is developed in Matlab for simulating subcarrier allocation schemes. Sensor tags are randomly and uniformly distributed in a circular region of radius 10 meters and the reader is located at the center. The minimum distance between the reader and the sensor tags is set to 1 meter. Figure 8 shows the average communication capacity for the random and heuristic scheme. It can be seen that the heuristic scheme has better performance compared to the random allocation scheme.

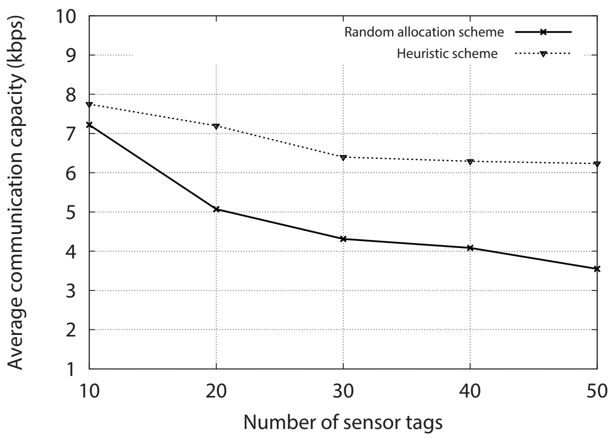

Fig. 8. Comparison of average communication capacity for random allocation scheme and heuristic scheme

The second problem of harmonic cancellation method is implemented in LabView software. An experiment to emulate a scenario of two sensor tags is considered where the subcarrier frequency of sensor tags is taken in such a fashion so the 1st sensor tag (10 kHz subcarrier) produces harmonic on the 2nd sensor tag (30 kHz subcarrier). The signal generator emulates as a reader sending continuous wave 916.8 MHz at 0 dBm. The combined signals from two sensor tags are received by software defined radio (SDR) device (NI USRP 2950R) which converts received analog signals into IQ data. A Recursive Least Square (RLS) method is developed to calculate the carrier delay. As the subcarrier frequency and phase always fluctuate from its original frequency, to cancel out the interference effect accurate frequency and phase tracking is required. Phase Locked Loop is implemented which is commonly used to calculate frequency and phase error in signal processing. Figure 7 shows the basic blocks of LabView demodulation program for nine sensor tags.

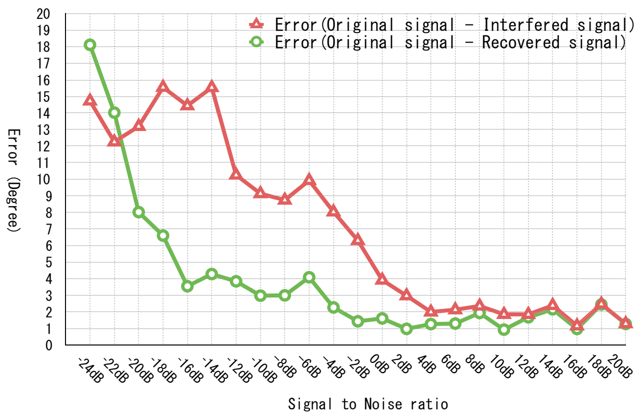

Fig. 9. Error between original signal and recovered demodulated signal by varying SINR

Figure 9 shows the accuracy of interference method. It can be seen that the accuracy is improving as the SINR received by reader increases. Also, it shows that the interference rejection technique works and keeps accuracy under 4 degree when the SINR is -16dB.

IV. Conclusion

Multiple Subcarrier Multiple Access is a promising technology for streaming data collection concurrently from sensor tags, enables the wireless and batteryless health monitoring of machinery and structures. The subcarrier is generated by an RF switch with digital control and analog sensor data is phase-modulated onto the subcarrier. A problem in MSMA is unavoidable harmonic interference, but can be canceled out with the harmonic cancellation method. The accuracy of the method depends on the received SINR by the reader and can be enhanced by allocating subcarrier frequencies efficiently.

Acknowledgment

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References

[1] Adee, Sally. "Wireless sensors that live forever." IEEE Spectrum 47, no. 2 (2010): 14-14.

[2] Analog Devices, MEMS wireless vibration sensing enables remote monitoring of industrial machine health, Analog device news release, June 4, 2013.

[3] Wang, Ziyang, Frank Bouwens, Ruud Vullers, Frederik Petr, and Steven Devos. Energy-autonomous wireless vibration sensor for condition-based maintenance of machinery. IEEE, 2011. Sensors, (2011), pp.790-793.

[4] Saldanha, Nancy, and Donald C. Malocha. "Pseudo-orthogonal frequency coded wireless SAW RFID temperature sensor tags." IEEE transactions on ultrasonics, ferroelectrics, and frequency control 59, no. 8 (2012).

[5] Vahedi, Ehsan, Rabab K. Ward, and Ian F. Blake. "Performance analysis of RFID protocols: CDMA versus the standard EPC Gen-2." IEEE Transactions on Automation Science and Engineering 11, no. 4 (2014): 1250-1261.

[6] Igarashi, Yuki, Yuki Sato, Yuusuke Kawakita, Jin Mitsugi, and Haruhisa Ichikawa. "A feasibility study on simultaneous data collection from multiple sensor RF tags with multiple subcarriers." In RFID (IEEE RFID), 2014 IEEE International Conference on, pp. 141-146. IEEE, 2014.

[7] ISO/IEC 18000-6, Information Technology - Radio frequency identification for item management- , Part 6 Parameters for air interface communications at 860 MHz to 960 MHz, (2010).

[8] Liu,H.,C., Ciou,J.,P., 寠抉 erfomance analysis of multi-carrier RFID systems 寠? International Symposium on Performance Evaluation of Computer and Telecommunication Systems, vol.41, pp.112 寠?16, (2009).

[9] Teramoto S., Ohtsuki T.,Multiple-Subcarrier Optical Communication Systems With Subcarrier Signal-Point Sequence? IEEE Trans. Communications, vol.53, no.10, (2005), pp.1738-1743

[10] Rajoria, Nitish, Yuki Igarashi, Jin Mitsugi, Yusuke Kawakita, and Haruhisa Ichikawa. "Comparative analysis on channel allocation schemes in multiple subcarrier passive communication system." IEICE Transactions on Communications 98, no. 9 (2015): 1777-1784.