"An Active Tagging System Using Circular-Polarization Modulation"

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Abstract—An active read/write microwave tagging system using circular polarization modulation as novel modulation scheme for RFID systems is presented. The proposed modulation scheme reduces demodulation complexity and power consumption on the battery powered tag. Additional coding of the circular polarization modulated data reduces transmission errors due to polarization inversion at multipath propagation. In multiple reader environments the main jamming threat occurs from power carriers of different interrogators. A combination of circular polarization modulation and frequency hopping is presented that shows an increased immunity against multipath phenomena for multiple tag and multiple reader environments.

Index Terms—Microwave tagging system, RFID, circular polarization modulation, frequency hopping.

I. INTRODUCTION

In recent years, there has been growing interest in the development of communication systems for the localization and the identification of objects [1], [2]. Examples of major applications for tagging systems operating in the 2.4-GHz and 5.8-GHz ISM bands are security systems, access control and identification systems for industrial automation. Microwave tagging systems can be divided into three types.

Remotely powered fully passive tags (type 1) have to be operated in the near field region of the interrogator antenna. Therefore, they are used only for short transmission distances [3]. A second type of tagging system (type 2) uses battery powered tags that show a lifetime of several years as the power supply is only used for the low frequency signal processing unit consuming a few µW. Due to power economy no RF generator is available on such a tag, hence a passive reflex modulator is used for the communication from the tag to the interrogator. The loss of the passive reflex modulator converts directly into a decrease of transmission distance [4]. A third type of tagging system (type 3) uses an active modulator on the tag to increase transmission distance. Since the active RF modulator consumes much more battery power than the baseband signal processing circuits, the decrease in battery lifetime has to be weighted against an increase in transmission distance.

This paper presents a novel active tagging system (type 3) for the 2.4-GHz ISM band using circular polarization modulation. The advantages of the proposed modulation scheme are (1) to lower demodulation complexity on the tag, (2) to enhance interference resistance at multipath propagation and (3) to allow the use of an easy to manufacture and high efficient active modulator.

II. DESCRIPTION OF THE TAGGING SYSTEM

A block diagram of the interrogator is depicted in Fig. 1. Switches SwA, SwB, and SwC are used to select betweenTx and Rx operation. The interrogator is connected to a personal computer (PC) that acts as a terminal. A microcontroller in the interrogator handles the serial interface to the PC and performs signal processing tasks required to communicate with the remote tag.

Transmission of data from the interrogator to the tag proceeds as follows. First, the binary data is coded to be insensitive to polarization inversions by attaching the data bits to symbols that will be decoded on the tag by an EXOR relation. For instance a logical zero is coded by the symbol ‘00’ and a logical one is attached to the symbol ‘01’ (Fig. 2(b)).

After that, the coded data is circular polarization modulated. The circular polarization modulator (CPM)

Fig. 1. Interrogator block diagram. Switches are in Rx position.
consists of a frequency synthesizer operating in the 2.4-GHz ISM band and a 50 Ω terminated single-pole, double-throw (SPDT) switch. The output signal of the CPM is fed over two switches that are used to select between Tx and Rx operation, to a circularly polarized antenna (Fig. 1). A dual-polarized antenna in conjunction with a quadrature hybrid as polarizer is used to form the circularly polarized antenna with switchable polarization sense. As illustrated in Fig. 2(c) a ‘0’ of the coded binary data is transmitted as right-hand circularly polarized (RHCP) wave and a ‘1’ is represented by a left-hand circularly polarized (LHCP) wave.

Compared to a conventional ASK modulation scheme frequently applied to RFID systems, where in the simplest form a threshold voltage is used for decision between logical ‘0’ and ‘1’, the advantage of the presented circular polarization demodulator is that no measures have to be taken for adjusting a decision threshold voltage. This is because only the instantaneous power between two signals is relevant for the demodulation. Therefore, also linear polarized jamming signals are suppressed when a perfect circularly polarized antenna is assumed splitting the linear polarized signal equally to the demodulation paths of the left-hand and right-hand circularly polarized signals. Compared to conventional FSK, circular polarization modulation has the advantage of using the whole transmitted power for the information bearing signal. FSK needs an additional carrier when demodulated by simple RF detectors.

The transmitted circular polarization modulated waves are received by the circularly polarized antenna of the tag whose block diagram is shown in Fig. 3. For the circular polarization demodulator a very simple circuit topology has been chosen. It consists of a circular polarized antenna which is able to separate received waves of opposite polarization sense, two identical passive RF detectors, and a low power CMOS comparator. The two RF detectors are connected to the mutually isolated antenna ports of the antenna polarizer for rectifying the incident waves. The output voltage of the RF detectors is fed to the input ports of the comparator whose output signal corresponds to the coded baseband signal of the transmitted data sequence. A microcontroller samples the output signal of the comparator.

In order to demonstrate that the system is insensitive to polarization inversions, it is assumed in Fig. 2(d) and Fig. 2(e) that the strongest received signal is bit-inverted. This means that the transmitted LHCP waves are received as RHCP signals and vice versa. By performing an EXOR relation between the sampled data at t=nT and t=(n+1)T, corresponding to the first and second bit of the transmitted symbols, the received data sequence is decoded. Fig. 2(g) shows that polarization inversion of the circularly polarized signal indeed does not affect the demodulation due to the chosen coding of the data sequence.

Fig. 2. Down-link and up-link communication scheme (ex.: ASCII code for character ‘M’).

In the following the interrogation of the tag is described. Back-scatter modulation is applied to read data from the tag. An active modulator is used on the tag to perform a circular polarization modulation of the back-scattered waves. Compared to a passive reflex modulator an active modulator shows conversion gain which converts into an increase of transmission distance. As shown in Fig. 3 the active modulator consists of an RF amplifier and two SPDT switches.

For reading or interrogating the tag a linear polarized unmodulated RF carrier is emitted by the interrogator and is received by the tag antenna where it is split equally to the mutually isolated antenna ports connected to the input and output ports of the active modulator as depicted in Fig. 3. Two single-pole, double throw switches controlled by the tag microprocessor according to the modulating data switch the RF amplifier either in forward or backward direction. By amplifying the incident RF power appearing at the left-hand circularly polarized antenna port as right-hand circularly polarized wave, or vice versa, a circular polarization modulation is performed. A coding equal to that used for communication from the interrogator to the tag has been chosen to be insensitive to bit-inversions (Fig. 2(b)). For power saving the power supply for the active modulator is only turned on by a battery switch when the
tag is read. To ensure a stable operation the crosspolarization isolation of the circularly polarized tag antenna has to be higher than the gain of the active modulator as no further means have been taken to decouple its input and output ports.

At the interrogator, where enough supply power is available, a homodyne detection can be used for the demodulation. However, it is known that the use of one homodyne detector can cause a cancellation of the received signal for critical distances between the interrogator and the tag. To prevent this phenomenon, single-sideband (SSB) down-converters are used at the demodulation path of the left-hand and right-hand circularly polarized signals. The intermediate frequency signal of the SSB mixers is led to the input ports of a comparator whose output signal is sampled by a microcontroller. Further demodulation and decoding is performed in the same way as already described at the tag (Fig. 2(f), 2(g)).

III. SYSTEM EXTENSION FOR FREQUENCY HOPPING TECHNIQUE

Microwave tagging systems used for managing production lines and manufacturing processes are operated in environments where channel fading occurs due to multipath propagation. Excess delay spreads up to more than 1 µs are possible in different factory environments. This results in a frequency selective slow fading channel. Spread spectrum techniques may be used to achieve high immunity against multipath phenomena. Additionally in multiple reader environments the main jamming threat occurs from RF carriers of other reader units located at the same place. By randomizing the carrier frequency of each reader using frequency hopping (FH) methods, signal destructive fading and jamming can be reduced to short time intervals. In synchronous FH systems jamming can even be avoided completely. Due to the packet oriented transmissions the frequency hopping rate must be relatively fast, 1 hop/byte for example. Therefore, the combination of circular polarization modulation and frequency hopping technique is very promising for multiple tag and multiple reader environments. The implementation of the FH technique for the presented microwave tagging system requires some modifications at the reader side (interrogator). The RF front end of the tag and the tag itself remain unchanged, which is important with respect to power consumption and price.

Fig. 4 shows the block diagram of the interrogator extended for frequency hopping technique. Compared to Fig.1 the main modification concerns the RF generator which consists of a low cost, fast hopping synthesizer which covers the whole 2.4 GHz ISM band. This synthesizer is composed of three sub units. First a direct digital synthesizer (DDS) generates the narrow frequency spacing (fine grid) in the hopping pattern, but over a limited frequency range. Second a voltage controlled oscillator (VCO) controlled by a phase locked loop (PLL) circuitry generates the broad frequency spacing (coarse grid) in the order of several MHz. Third a single sideband (SSB) up-converter with carrier suppression combines the two RF-signals to the transmit signal. The mixed use of DDS and PLL technique allows to extend the frequency range to several times the span of the DDS without reduction of switching speed or phase noise performance. This is due to the fact that DDS allows for instant frequency switching with arbitrary fine frequency spacing but over a limited frequency range of several MHz. The PLL has to cover only a coarse frequency grid corresponding to the DDS frequency span and therefore can be operated with a large loop bandwidth. This combination allows FH-bandwidths over 100 MHz with any channel resolution and switching speeds of less than 50 µs. Hopping speeds up to 10 khop/s have been achieved in a prototype system.

The approach is superior to synthesizers which multiply the output of a DDS through the action of the PLL loop. As those designs use the DDS as reference in the PLL, all DDS related spurs occurring inside the loop are multiplied the same way as the reference frequency and lead to unacceptable phase noise. Small loop bandwidths in the PLL on the other hand result in slow switching speeds.

In the transmit mode the output signal of the frequency hopping synthesizer is fed to the circular polarization modulator and radiated from the antenna. In the receive mode the FH signal is supplied to the linear polarized antenna that transmits the RF power carrier used for the back-scatter modulation on the tag. The FH signal is also fed over a power splitter to the local oscillator ports of the down-converters in the demodulation paths. As depicted in Fig. 4 the frequency hopping process is removed from the received signals of the circular polarized antenna and also converted to the base band. The down-converted signals are sampled after filtering by an analog-to-digital (A/D) converter. Further demodulation is performed by digital signal processors. This allows for more complex demodulation algorithms and corrections of errors due to non-ideal hardware influences.

Although the power carrier of the circular polarization modulated waves is FH modulated, no synchronization of a
A despreading code is needed on the tag. Therefore, only a broadband impedance match of the tag front end is required. An aperture coupled antenna is used for the tag. By optimizing the parameters (relative permittivity, substrate thickness) of the patch layer, the bandwidth requirements for the operation in the 2.4-GHz ISM band can be fulfilled (4% relative bandwidth at 2.44-GHz corresponding to a voltage standing wave ratio (VSWR) lower than two). The input impedance match of the passive RF detector is mainly limiting the bandwidth of the tag front end. For a VSWR of two a relative bandwidth of only 3% may be achieved with a high dielectric substrate (ε \textsubscript{r} >10). A high dielectric substrate is preferred for further miniaturization of the tag as the dimensions of the RF front end on the feed layer of the aperture-coupled tag antenna scale down with increasing relative permittivity. Thus, the frequency range of the FH signal is finally limited by the bandwidth of the RF detector on the tag to about 75 MHz for the 2.4 GHz ISM band.

IV. EXPERIMENTAL RESULTS

First, an aperture-coupled patch antenna with switchable polarization sense[5] depicted in Fig. 5 has been built for a prototype tag (Fig.11). The patch antenna is dual polarized and uses a quadrature hybrid to feed the orthogonal slot apertures with the required 90 degree phase-shift. To ensure a good radiating efficiency, a 3.18 mm thick substrate with a low relative permittivity of ε \textsubscript{r} = 2.33 has been chosen for the upper layer containing the patch. The feed layer consists of 0.508 mm (20 mil) thick substrate of ε \textsubscript{r} = 2.22.

Far field measurements in an anechoic chamber have been performed to determine the antenna gain and radiation patterns (Fig. 7 and 8). The axial ratio and the crosspolarization isolation, i.e. the isolation between RHCP and LHCP waves, have been measured with an automated electromechanical positioner. The antenna gain is 7 dBi at 2.45 GHz and the measured crosspolarization isolation is better than 20 dB. Also an axial ratio lower than 1 dB has been measured.
As the axial ratio and the crosspolarization isolation of the tag antenna determine the performance of the whole tagging system, the circular polarization has been characterized by means of an automated E-field scanner [7], (Fig. 8). The ellipticity defined as ratio of semiminor and semimajor axis is about 0.95 in the middle of the patch. The measurement of the magnitude of orthogonal E-field vectors has been performed at a distance of 0.1m above the patch surface. Due to the radiation characteristic the ellipticity increases by a factor of two at a distance of about two wavelengths from the patch edges for this measurement distance.

The simulation of the antenna was performed by a planar EM solver using the method of moments [6]. Fig. 9 shows the comparison between measured and simulated VSWR at the LHCP and RHCP antenna ports. It has been found that an additional crossed-slot (Fig. 6) blocking the surface currents that flow across the direction of the resonant components increases the crosspolarization isolation.

In order to demonstrate the superior performance of aperture coupled antennas used for microwave tags, a fully operational prototype tag (Fig. 10) has been built. Aperture coupled patch antennas are the preferable antenna type because they allow to separate the feed layer from the radiating patch resulting in a high front-to-back ratio. All RF front end electronics is placed on the rear side of the patch on the feed layer.

The RF front end of the prototype tag consists of an aperture-coupled antenna with switchable polarization sense, RF detectors and off-the-shelf components for the RF switches ($P_{dc} < 70 \, \mu W$) and the comparator ($P_{dc} < 10 \, \mu W$). For the two identical RF detectors located in the demodulation paths on the tag, low-barrier zero-bias Schottky diodes have been used showing a voltage sensitivity of 30 mV/\mu W at 2.45 GHz for a narrowband match. A low noise amplifier (LNA) has been used as active device for the active modulator on the tag. The current consumption of the LNA is 3 mA at a supply voltage of 3 V.

A prototype hand-held interrogator (Fig. 11) using commercial components for the RF amplifier, frequency synthesizer and RF switches has also been built for setting-up a demonstrator tagging system based on the basic specifications summarized in Table I and Table II.
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