This paper presents a novel multiple orthogonal subcarrier modulation based UHF band RFID communication system. In tag-to-reader communication, the demonstration system can deliver 1.6 Mbps through four subcarriers. To improve data rate while suppressing increase in circuit complexity, tag employs square-waves as the subcarriers and uses individual load modulators for each subcarrier. By using multiple orthogonal subcarrier based modulation, proposed communication system can be operated under existing UHF band RFID regulation. In reader, an OFDM demodulator is used. Since the tag backscatters the reader’s CW carrier, carrier frequency offset compensation is not necessary in reader demodulator. Experimental results show that the demonstration system achieves a bit error rate of 10^-5 at an Eb/N0 of 10.8 dB.

**Keywords**: UHF RFID, Passive tag, OFDM, Load modulation, FFT

**I. Introduction**

Passive radio frequency identification (RFID) is gaining a greater market share because passive RFID technology has advantages over barcodes, including non-line-of-sight (NLOS) communication, increased data speed, and a longer read range. In [1][2], RFID technologies was introduced. In [4]-[7], [10], applications of UHF RFID were presented. In [3], [8], [9], performance / function enhancement technologies for UHF RFID were presented. However, as passive RFID technology is used to read a large amount of data from a tag, an improvement in the data rate is required. In particular, aerospace companies require high-speed and high-performance passive RFID technology. In some previous studies, high data rate RFID technology has been studied.[11]-[14] In [11], an
impulse radio ultrawide bandwidth (IR-UWB) technology was used. The uplink (tag-reader) data rate is increased up to 1 Mbps. However, since an IR-UWB signal occupies several GHz, the spectrum efficiency is very low. In [12], a conventional inverse fast Fourier transform (IFFT)-based orthogonal frequency division multiplexing (OFDM) technology was used in a tag. In addition, conventional analog and RF circuits, such as a digital-to-analog converter (DAC), a frequency synthesizer, and a RF up converter, are used in the tag. Hence, the tag consumes more power and is very complex and expensive. In [13], it was shown that the uplink (tag-reader) data rate can be increased up to 5 Mbps using existing UHF RFID tag communication. In [14], a complex backscatter based quadrature phase-shift keying (QPSK) was used to improve spectrum efficiency. However, since the backscattered power is the same as that of existing UHF RFID tag, the signal-to-noise ratio (SNR) is degraded due to the reduced minimum constellation spacing. In addition, since the semi-passive RFID techniques is used in the developed system, battery is used for complex backscattering. This paper presents a multiple orthogonal subcarrier modulation based UHF band RFID communication system. In tag-to-reader communication, the demonstration system can deliver 1.6 Mbps through four subcarriers. For tag-to-reader communication, proposed system uses a multiple orthogonal subcarrier modulation to improve data rate while enabling the operation under existing UHF band RFID regulation. In the proposed system, square-wave subcarriers are used instead of complex exponentials as the subcarriers. By using square-waves as the subcarriers and individual load modulators for each subcarrier, complexity of tag integrated circuit is almost the same as that of existing tag because DAC and memory for subcarrier are not necessary.

II. Square-wave subcarrier OFDM

An OFDM signal can generally be written as

\[
s(t) = \sum_{s=-N_s/2}^{N_s/2-1} \sum_{k=-N_k/2}^{N_k/2-1} s_{n,k}\exp \left( j2\pi \frac{k}{T_s} (t - nT_s) \right)
\]  

(1)

where \( s_{n,k} \) denotes the symbol modulated by the \( k \)-th subcarrier during the symbol time of index \( n \), \( T_s \) represents the symbol duration, and \( N_s \) denotes the number of subcarriers. As shown in (1), it is worth noting that complex exponential functions are used for OFDM subcarriers. Using Euler’s formula, a complex exponential is expressed in terms of the sine and cosine. Hence, DACs are necessary for OFDM transmission. However, passive RFID tags must not use DACs owing to a power limitation and cost constraint. This means that a complex exponential subcarrier-based OFDM technology cannot be used for passive RFID tags. In the proposed square-wave subcarrier-based OFDM technology, a square wave can be represented as

\[
p(t) = \sum_{n=-\infty}^{\infty} u[t - (n - T/4)] - u[t - (n + T/4)]
\]  

(2)

where \( T \) denotes the period of a square wave, and \( u(t) \) is the unit step function. In the proposed method, \( p(t) \) is used as the subcarriers, the same as complex exponential functions in (1). As shown in (2), the square wave represents a binary value (high or low). When square waves with different frequencies are superposed, the resulting signal has multiple amplitudes such that DACs are necessary. If a DAC is used, DAC output controls the impedance of a load modulator. However, since the impedance is dependent on process or device, the signal quality may be degraded. To remove the DACs, each square-wave subcarrier signal uses its own load modulator. In addition, subcarrier signals are superposed in the channel. The proposed tag communicates with reader in line-of-sight (LoS) environments. It means that the isolation between antennas has little influence on the communication performance. As shown in (1), the subcarriers of a conventional OFDM are spaced at equal frequency intervals of \( 1/T_s \). However, a square wave has every
### Table 1. Allowed subcarriers for the proposed method.

<table>
<thead>
<tr>
<th>Frequencies of null subcarriers ( (1/T_s) )</th>
<th>Allowed frequencies of subcarriers ( (1/T_s) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1, 2, 4, 8, 11, 13, 16</td>
</tr>
<tr>
<td>1</td>
<td>2, 3, 4, 5, 7, 8, 11, 13, 16</td>
</tr>
<tr>
<td>1,2</td>
<td>3, 4, 5, 6, 7, 8, 10, 11, 13, 14, 16</td>
</tr>
<tr>
<td>1,2,3</td>
<td>4, 5, 6, 7, 8, 9, 10, 11, 13, 14, 15, 16</td>
</tr>
</tbody>
</table>

Odd harmonic of the fundamental frequency. Hence, the frequency of the subcarriers must be assigned to avoid an overlapping with the harmonics of other subcarrier signals while maintaining the orthogonality of the subcarriers. For example, if a subcarrier with a frequency of \( 1/T_s \) is used, subcarriers with frequencies of \( 3/T_s \), \( 5/T_s \), \( (2k+1)/T_s \) must not be used. Table 1 shows the allowed subcarriers for some cases of the null subcarriers. For example, as shown in 1st row in Table 1, if the DC is not used, the frequency of \( 1/T_s \) can be used as a subcarrier. Since the square wave with a frequency of \( 1/T_s \) has every odd harmonic of \( 1/T_s \), square waves with frequencies of \( 3/T_s \), \( 5/T_s \), \( (2k+1)/T_s \) must not be used. And, the frequency of \( 2/T_s \) can be used as a subcarrier because it is not a odd harmonic of \( 1/T_s \).

### Table 2. Specifications of the tag-to-reader demonstration system.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency band</td>
<td>917-923.5 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>1.6 Mbps</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>4</td>
</tr>
<tr>
<td>Subcarrier frequency spacing</td>
<td>Integer multiples of 400 kHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>ASK</td>
</tr>
</tbody>
</table>

Since the square wave with a frequency of \( 2/T_s \) has every odd harmonic of \( 2/T_s \), square waves with frequencies of \( 3\times2/T_s \), \( 5\times2/T_s \), \( (2k+1)\times2/T_s \) must not be used. And, the frequency of \( 4/T_s \) can be used as a subcarrier because it is not a odd harmonic of \( 1/T_s \) nor that of \( 2/T_s \).

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* In Table 1, allowed subcarriers up to a frequency of \( 16/T_s \) are shown as an example.
III. System Architecture and Function Blocks

Fig. 1 and Table 2 show a block diagram and the specifications of the proposed tag system, respectively. The proposed system uses backscattering technique for tag-to-reader communication. Tag transmitter consists of four subcarrier modulators, four load modulators, and four antennas. As shown in Fig. 1, each load modulator uses its own load antenna. The load modulator is implemented using an Agilent HSMP 3822 PIN diode. In the demonstration system, the transmission bit rate of each subcarrier modulator is equal to 400 kbps. Frequencies of the subcarriers are 800 kHz, 1,200 kHz, 1,600 kHz, and 3,200 kHz, respectively.** The tag receiver consists of envelope detector and digital demodulator and is the same as existing UHF RFID tag receiver.

Fig. 2 shows a block diagram of the reader. Reader transmitter consists of digital modulator, DAC and direct RF up-converter. The resolution and sampling rate of the DAC are 12 bits and 5.12 MS/s, respectively. A modulator upconverts the baseband signals to 900 MHz RF band. Dielectric resonator type band-pass filter (BPF) is used to remove the harmonics of the mixer output. The insertion loss of the BPF is less than 3 dB. Driver amplifier (DA) and power amplifier are used to transmit a continuous wave (CW) power level of 1W (30dBm). Lowpass type band selection filter is used to reject out-of-band interferers. The insertion loss of the band selection filter is about 0.5 dB in frequency band of 902 MHz to 928 MHz. The maximum output power of the power amplifier is 2 W (33 dBm).***

The RF receiver uses a direct-conversion receiver architecture. The band selection filter removes signals outside the 917 MHz to 923.5 MHz band. To prevent the saturation, the gain of LNA is set to 16 dB and the input P1dB of mixer is set to 13.2 dBm. Attenuator is used to maximize the analog-to-digital converter (ADC) dynamic range while avoiding clipping. The mixer output is amplified by a linearized one-stage differential amplifier to provide gain before the channel selection filter. In addition, the channel selection filter output is amplified to use the full dynamic range of the ADC. The resolution and sampling rate of the ADC are 8 bits and 40.96 MS/s, respectively. Table 3 summarizes the performance characteristics of the reader RF transceiver.

** The subcarrier frequencies are decided according to 2nd row in Table 1.

*** According to local regulation in Korea, 4 W effective isotropic radiated power (EIRP) is allowed.
Fig. 3 presents a block diagram of the digital demodulator in the reader. Based on the fact that the subcarriers in the tag are orthogonal, the digital demodulator is designed utilizing the OFDM demodulator architecture. Since the tag backscatters the reader’s CW carrier, the carrier frequency of a tag is the same as that of a reader. Hence, carrier frequency offset compensation is not necessary in the reader demodulator, as shown in Fig. 3. The proposed tag transmit preamble signals for demodulation in the reader. The preamble uses the subcarrier with frequency of $2/T_s$ because signal with one frequency simplifies the digital demodulator in reader. The preamble consists of three signal sections. The first of these sections consists of four bits $\{1,0,0,1\}$ and is used for signal detection. The number of bits of the first of preamble is decided by environmental conditions in which subcarrier frequency offset can be tolerated up to $0.1/T_s$ and system achieves a bit error rate (BER) of $10^{-3}$ at an $E_b/N_0$ of 10.5 dB.

The second consists of 25 consecutive 0’s is used for a digital automatic gain control (AGC). In addition, the third consists of four bits and is used for start frame delimiter (SFD) detection. The signal detection is achieved using the cross-correlation between the first section of reference preamble and the received signal. The power of the second section of preamble is used for a digital AGC. The SFD detection is accomplished using the cross-correlation between the third section of reference preamble and the received signal. Since the demodulator utilizes an OFDM architecture, FFT is used for the demodulation.

**IV. Experiment Results**

Fig. 4 shows photographs of the developed system. In Fig. 4(a), four SMA connector and four load modulators are shown. In Fig. 4(b), digital MODEM
Fig. 5. Load-modulated signals from the tag with subcarrier of (a) 800 kHz, (b) 1,200 kHz, (c) 1,600 kHz, (d) 3,200 kHz, and (e) all four frequencies.
Table 4. Comparison with representative ultra low-power communication techniques.

<table>
<thead>
<tr>
<th>Year</th>
<th>This work</th>
<th>Helleputte [17]</th>
<th>Thomas [14]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>2010</td>
<td>2012</td>
<td></td>
</tr>
<tr>
<td>Comm. technique</td>
<td>UHF RFID (ASK-OFDM)</td>
<td>IR-UWB</td>
<td>UHF RFID (QPSK)</td>
</tr>
<tr>
<td>Power consumption</td>
<td>9 uW (analog part)</td>
<td>3.3mW</td>
<td>0.12 uW (analog part)</td>
</tr>
<tr>
<td>Frequency</td>
<td>902-928 MHz</td>
<td>0-960 MHz</td>
<td>850-950 MHz</td>
</tr>
<tr>
<td>Data rate</td>
<td>1.6 Mbps</td>
<td>19.5 Mbps</td>
<td>0.4 Mbps</td>
</tr>
<tr>
<td>Req. Eb/No (BER=10^-4)</td>
<td>9.2 dB</td>
<td>–</td>
<td>11.5 dB</td>
</tr>
<tr>
<td>Battery use (analog part)</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>

Fig. 6. PSD of load-modulated signals with four subcarriers.

 hyperspectral subcarrier-based OFDM technology for a tag-to-reader communication link. The tag used multiple load modulators to remove DACs. Each load modulator was modulated with a different square-wave subcarrier signal. The hardware measurement results showed a BER of 10^-5 at an E_b/N_0 of 10.8 dB.

V. Conclusion

This paper presented a square-wave subcarrier-based OFDM technology for a tag-to-reader communication link. The tag used multiple load modulators to remove DACs. Each load modulator was modulated with a different square-wave subcarrier signal. The hardware measurement results showed a BER of 10^-5 at an E_b/N_0 of 10.8 dB.

REFERENCES


*To measure the BER performance, the transmitter, receiver, and AWGN signal generator are connected using a cable, and an adjustable attenuator is used to sweep the receiver input power.*


