EXPERIMENTAL TD-CDMA SYSTEM FOR CITY LIFELINE MONITORING

T. Fujiwara, A. Ikeda\textsuperscript{††}, Y. Shimazaki\textsuperscript{††}, H. Toyoshima\textsuperscript{††}, M. Sugiura, S. Ito, M. Atsumi, A. Adachi, T. Watanabe\textsuperscript{†}, and S. Mizushina

TAO Hamamatsu Lifeline Research Center
619-4 Irino-cho, Hamamatsu, Shizuoka 432-8061, Japan

\textsuperscript{†}Department of Information Science, Shizuoka University
3-5-1 Johoku, Hamamatsu, Shizuoka 432-8011, Japan

\textsuperscript{††}Oki Electric Industry Co., Ltd.
4-10-3, Shibaura, Minato-ku, Tokyo 108-8551, Japan

Abstract – A dedicated data collection system using CDMA technique for fixed stations is considered to monitor and control city lifelines. Radio transmission model was studied on an experimental TD-CDMA system set up in the field. A feasibility study was carried out on the system operating in the ISM band. The possible problem of interference from a wireless LAN as one of the ISM band sources was investigated. The results showed that it was satisfactorily feasible to operate the experimental system when the interference was below –113dBm.

I. Introduction

A dedicated wireless data collection for monitoring and control of city lifelines during- and post-earthquake periods has been proposed and investigated experimentally at the TAO Hamamatsu Lifeline Research Center (HLRC) since April 1998. The basic concept of the data collection system is depicted in Fig.1. One center station, 1024 relay station, and 256 household terminals (HT) connected to each relay station constitute a two-layered network to cover a total of 260k household terminals. The two-layered network is to be operated in an asynchronous polling mode (1) to achieve a high data collection speed and (2) to eliminate the possibility of communication congestion in emergency situation. Performance tests have been conducted on an experimental system that employs 2.1GHz and 430MHz radio system for the upper- and lower-polling layer, respectively. Results have shown that the upper layer system was capable of collecting 5120B data (= 20B/HT x 256HT) from 1024 cells in about 7 minutes, but the lower layer system took about 24 minutes to collect 20B from 256HTs, as reported in [1].

Fig.1 A model of wireless lifeline data collection and control system for 256k household terminals with a 1024×256 configuration.

To improve the data collection speed, an application of the CDMA technique to lifeline data acquisition system has been considered. In addition, the CDMA offers the capability of protecting subscribers’ privacy. An experimental investigation involving CDMA in a fixed-station system operating at 2.4GHz has been started in April 1999. Preliminary results have shown that the system was capable of collecting 256B lifeline data from 256 HTs in 10.24 seconds and the frame error rate was about 1.8×10\textsuperscript{-3}. 
on average [2].

This paper (1) describes the system design at some length, (2) investigates the radio transmission model, and (3) reports results of experiments on the problem of interference by other ISM (Industrial, Scientific, and Medical) band sources, on the basis of (1) and (2) above.

II. Experimental System

(1) System Configuration

The experimental lifeline data collection system consists of two-layered wireless system. The upper layer consists of one center station and one relay station (RS). The lower layer consists of the RS and 128 household terminals (HT). The experimental setup is depicted in Fig.2. The parameters of the radio system of the upper- and the lower-layer are shown in Table 1.

The center station collects lifeline data from the RS via a 2.1GHz-radio system (upper layer), and stores the data in a database system. The collected lifeline data is analyzed and displayed on the GIS (Geographical Information System) in the center station.

The RS collects and stores the data from the lower layer, and sends it to the upper layer. It consists of a 2.1GHz-radio equipment, a personal computer (PC), and a CDMA base station (BS). The BS gathers lifeline data from 128 HTs via the lower layer, where the 2.4GHz CDMA channels were used in conjunction with polling technique. Hence, the system is called TD-CDMA, as will be described later. The 2.1GHz-radio system transmits the collected data to the center station. A PC in the RS serves for two purposes: communication control and processing-and-storage of gathered lifeline data in the database.

In a HT, an interface unit (IF-U) is connected to liquefied petroleum gas (LPG) meter, natural gas (NG) meter, water meter, and input ports for additional signals, with wired serial communication. The IF-U gathers and transmits lifeline data from the lifeline units to the CDMA terminal. The CDMA terminal transmits the data to the BS via CDMA channels.

In the experimental system, 112 HTs of the 128 HTs were installed in a neighborhood. Each HT was within the 300m-range from the BS with unobstructed propagation path. The HTs were used for lifeline performance monitoring experiment. Remaining 16 HTs were set up in HLRC for gas-valve shut off and monitoring experiments.

<table>
<thead>
<tr>
<th>Table 1. Air interface parameters of the experimental system in the upper and the lower layers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency</td>
</tr>
<tr>
<td>-----------</td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
</tr>
<tr>
<td>Output power</td>
</tr>
<tr>
<td>Modulation</td>
</tr>
<tr>
<td>Modulation</td>
</tr>
<tr>
<td>Access control</td>
</tr>
<tr>
<td>Data rate</td>
</tr>
<tr>
<td></td>
</tr>
</tbody>
</table>

Note: Fw--- Forward-link, Rv--- Reverse-link

(2) Lifeline Data Collection

Lifeline data in this experimental system consists of the data collected from lifeline units, such as meter reading, alarm signals, identification codes and other
additional signals. This experiment refers to meter reading and alarm signals as core lifeline data.

As shown in Fig.2, 42B lifeline data from LPG meter, 46B from NG, and 44B from water are collected by the IF-U. A total of 62B are extracted as core lifeline data from the entire lifeline data. IF-U also gathers additional data of 188B from meters or additional input ports, when demanded. A total of 261B data is transmitted from the IF-U to the CDMA terminal by adding 8B header and 3B meter status signals to the 250B (=62B+188B) of gathered data.

To collect lifeline data from CDMA terminals to the BS, the BS sends polling command via the forward-link of the CDMA channels. The size of the polling data is 156B: 150B polling command and 6B header. In response to the polling, the CDMA terminal transmits 256B data, by adding 3B header and 3B meter status signals to 250B lifeline data to the BS via the reverse-link.

(3) CDMA Channels

The lower layer of the experimental system involving CDMA channels was allowed to use two radio frequency bands at 2.402GHz and 2.482GHz with a bandwidth of 1.5MHz by authorities, as shown in Table 1. The output power was 10mW or less. Communications with eight terminals were multiplexed using CDMA technique.

The structure of the CDMA channels in the system is shown in Fig.3. The channels of the forward-link (Fw-link) consist of a control channel and a data channel. In the CDMA base station, the data in the channel is modulated by DBPSK (Differential Binary Phase Shift Keying) and further spread with the codes generated by the Orthogonal Gold Sequences (OGS) for the direct sequence CDMA (DS-CDMA) [3]. The spread data is transmitted to the CDMA terminal via 2.4GHz radio system. The received data is despread with the same codes, and is demodulated by DBPSK. In the reverse-link (Rv-link), on the other hand, the CDMA channels consist of 2 data channels. The data is modulated by DQPSK (Differential Quadri-phase Shift Keying), and is spread with OGS codes in the CDMA terminal. It is transmitted to the BS, despread with OGS codes, and demodulated by DQPSK.

The Fw-link has 4 channels: (control and data channels)×(I- and Q-channels). To multiplex these 4 channels, 4 unique OGS codes were used. For the Rv-link, the total of 32 unique OGS codes was used to multiplex 8 terminals each having 4 channels: (2 data channels)×(I and Q). The generating polynomials of the OGS are given by:

\[ G_f(x) = x^6 + x^5 + x^4 + x + 1 \]  
\[ G_r(x) = x^7 + x^5 + x^2 + x + 1 \]

for the Fw- and Rv-link, respectively. The spreading code length of 64 was for the Fw-link, and 128 for the Rv-link.

Referring to Fig.4(a), pilot signals, power control signals, and synchronous word are transmitted in the control channel of the Fw-link. The pilot and the power control signals are inserted in the 1st through the 4th frame. The synchronous word is added only in the 4th frame. The pilot and the power control signals of 8 terminals are arranged in a power control group. The power control group is allocated in every 2.5ms in a 320ms-frame.

The pilot signals provide the forward CDMA channels with a function for timing acquisition and phase reference. The synchronous word is used to synchronize the frames of the channel [4]. The synchronous word is generated by an M-sequence with a period of 31. The generating polynomial is

\[ G_{\text{sync}}(x) = x^5 + x^3 + 1 \]  

Preamble signal and synchronous word are incorporated in the first frame (control frame) of the data channel in Rv-link, as shown in Fig.4(c). They provide the reverse CDMA channels with the spreading codes and frame timings. The polynomial of the synchronous word is the same as for the Fw-link.

To maintain each transmitted signal power from eight multiplexed terminals to the BS at a reference level, a closed-loop power control technique was employed [5]. The power control signal is involved in the control channel as shown in Fig.4(a). The period of the power control is 2.5ms.
The forward error collection (FEC) technique [6] was carried out for the data channels of the Fw- and Rv-link shown in Fig. 4 (b) and (c). The convolutional coding and Viterbi decoding were used for the FEC. The convolutional code rate \( r \) and the constraint length \( k \) are at 1/3 and 9, respectively. The CRC (Cyclic Redundancy Check) code of 8 bits was inserted in each sub-frame of 20ms in the data channels of Fw- and Rv-link.

To suppress burst errors, an interleaving technique was employed [7]. A block interleaver, which is the memory with span:48b and depth:32b is incorporated in the data channels. Encoded data is loaded into the memory along the span and read out along the depth to scramble the bit-array of the data.

The data transmission rate was chosen at 19.2ksps for Fw-link and 9.6ksps for Rv-link, respectively, as shown in Table 2. The chip rate of the CDMA channel was chosen at 1.2288Mcps (chips per second). The processing gain was given as 64 and 128 for Fw-link and Rv-link, respectively.

Table 2. Data transmission parameters of the experimental CDMA system.

<table>
<thead>
<tr>
<th></th>
<th>Fw-link</th>
<th>Rv-link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chip rate</td>
<td>1.2288Mcps</td>
<td>1.2288Mcps</td>
</tr>
<tr>
<td>Data size</td>
<td>156B</td>
<td>256B</td>
</tr>
<tr>
<td>Frame length</td>
<td>320ms</td>
<td>320ms</td>
</tr>
<tr>
<td>Data rate</td>
<td>19.2ksps</td>
<td>9.6ksps</td>
</tr>
<tr>
<td>Processing gain</td>
<td>64</td>
<td>128</td>
</tr>
</tbody>
</table>

Fig. 3 CDMA channel structure of the experimental system

Fig. 4 Structure of the frame for CDMA channels
(4) TD-CDMA Scheme

Requirements set for the experimental data gathering system were: (1) the number of terminals accessed by the BS was 256, and (2) the bit error rate (BER) was $1 \times 10^{-6}$ or less. In order to meet these requirements, a combined technique of CDMA and TDMA has been proposed and implemented. In the CDMA part, 4 orthogonal codes were employed for the Fw-link, and 32 orthogonal codes for the Rv-link, as described in the previous section. To achieve the access to 256 terminals, TDMA technique operated in a polling mode was used in conjunction with the CDMA technique. Hence, the resultant system can be regarded as a TD-CDMA (Time Division and Code Division Multiple Access) data acquisition system.

Fig.5 is a time chart of operation of the experimental TD-CDMA system. The multiplexed CDMA channels were divided into 32 time-slots of 320ms to operate in a polling mode. A group of 8 terminals, say, terminals 1 through 8, was assigned to one of the 32 time-slots. The BS sent a polling command to the group at the designated time-slot. The invoked 8 terminals responded to transmit the data to the BS via CDMA channels. As a result, the BS collected data from 256 ($8 \times 32$) terminals in one polling cycle: 10.24 seconds ($=0.32$ seconds $\times 32$).

III. Experiments and Results

(1) Outline

An allowed frequency band for this experimental system was 2.482GHz, which overlaps with the ISM band used by wireless LAN (W-LAN).

With regard to the propagation characteristics, propagation loss and CR ratio (CRR) were studied considering the Nakagami-Rice distribution model [8], [9]. CRR is the ratio of the dominant component to the randomly fluctuating components. The interference of the W-LAN was investigated by measuring the received power at the CDMA base station (BS). Also, the frame error rate (FER) was measured simultaneously.

(2) Experimental Arrangement

The arrangements used in measurements of propagation characteristics for the Fw-link, such as propagation loss and CRR at CDMA terminals are shown in Figs.6 through 8. Fig.6 shows the arrangement of HTs set up in the field (arrangement-1: Arrng-1). The distances between the antenna of the BS and the terminals are within 15~235 m-range. Fig.7 shows the arrangement of the terminals placed in the room close to the BS (arrangement-2: Arrng-2). P1 is the position with direct line-of-sight path, and P2 with obstructed propagation path by a wall and the roof of the building. Fig.7 (a) and (b) show the side and the top views of the Arrng-2. To experiment on the interference from W-LAN, a W-LAN unit was placed at L1 or L2, in turn, as depicted in Fig.8 (arrangement-3: Arrng-3). L1 and L2 are at the same place as P1 and P2 of Arrng-2.

(3) Propagation Experiments

Since the experimental system was set up in an urban region with direct line-of-sight path condition,
the propagating signals were composed of a dominant component and fluctuating components by fading. Hence, Nakagami-Rice distribution model was applied to the experimental CDMA channels. The signal-plus-fluctuation ensemble is presented by:

$$e(t) = [c + x(t)] \cos 2\pi f_c t + y(t) \sin 2\pi f_c t \quad (4)$$

$$x(t) = r(t) \cos \theta \quad (5)$$

$$y(t) = r(t) \sin \theta \quad (6)$$

where $c$ is the amplitude of the dominant component, $r(t)$ the envelope of the fluctuating components having normal distribution, $\theta$ the phase angle with uniform distribution, and $f_c$ the carrier frequency. The probability density function $q(r)$ is given as:

$$q(r) = \frac{r}{\sigma^2} \exp \left( -\frac{c^2 + r^2}{2\sigma^2} \right) I_0 \left( \frac{cr}{\sigma^2} \right) \quad (7)$$

where $\sigma$ is the variance of the envelope of the received signal, and $I_0$ the modified Bessel function of the first kind and zeroth order [8], [9], [10]. $CRR$ is defined as:

$$CRR = 10 \log_{10} (c / r) \quad (8)$$

The cumulative distribution function in the Fw-link of the experimental system was calculated with parameterized $CRR$ using computer simulation based on the Nakagami-Rice distribution model. The results of the simulation for $CRR=21$, $23$, $26$, $28$, $29$ and $30\text{dB}$ are shown by dashed curves in Fig.9.

The measurement of the Fw-link signal power was taken during 28 seconds at each terminal in the Arrng-1 (Fig.6). The cumulative distribution functions of the received signal power at terminals T1 through T5 are given by the thick solid curves in Fig.9. The $CRR$ values at respective terminals can be found by fitting the experimental curves to simulation results, and the results are summarized in Table 3. $CRR$ was found at $23$~$30\text{dB}$ levels. It is noticed that the propagation mechanism for the Fw-link was of direct type and showed high stability in the field. Therefore, the propagation loss was found by the difference between the output power and the received signal power (Table 3).

To investigate the propagation mechanism around the CDMA base station, the $CRR$ and the propagation
loss of the Fw-link were also measured with the Arrng-2 (Fig.7), in like manner as described in the Arrng-1. Results of the measurement are shown in Table 4. The CRR were 27dB and 15dB at P1 and P2, respectively. The result of P1 showed that the propagation mechanism for the Fw-link was of direct type similar to the Arrng-1. The propagation loss was 81 dB on the average. The result of P2 also showed that the propagation was direct despite the presence of the wall. The propagation loss at P2 was 92 dB on the average. The attenuation through the wall was estimated at about 10dB.

Table 4. The CR ratio and the propagation loss in Arrng-2.

<table>
<thead>
<tr>
<th>No</th>
<th>D (m)</th>
<th>Pt (dBm)</th>
<th>Pr (dBm)</th>
<th>Loss (dB)</th>
<th>CRR (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>P1</td>
<td>14</td>
<td>-71.4</td>
<td>81.4</td>
<td>27</td>
<td></td>
</tr>
<tr>
<td>P2</td>
<td>16</td>
<td>-81.6</td>
<td>91.6</td>
<td>15</td>
<td></td>
</tr>
</tbody>
</table>

Note: D --- Distance between the BS and the HT
Pt --- Output power
Pr --- Received signal power

(4) Interference from W-LAN

In order to experiment the influences of the W-LAN, a W-LAN unit was placed at L1 or L2 in the Arrng-3 (Fig. 8). The parameter of the W-LAN is shown in Table 5.

Table 5. Parameter of W-LAN for the experiment.

<table>
<thead>
<tr>
<th>Frequency</th>
<th>2.471-2.497 GHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bandwidth</td>
<td>26 MHz</td>
</tr>
<tr>
<td>Output power</td>
<td>10 mW/MHz</td>
</tr>
<tr>
<td>Modulation</td>
<td>DS-SS</td>
</tr>
<tr>
<td>Access control</td>
<td>CSMA</td>
</tr>
</tbody>
</table>

In the experiment, both the CDMA system and the W-LAN of another network, (operating in the lower level of the building), were working simultaneously. The communication log including error record was stored in the PC. Results are shown in Tables 6 and 7. The W-LAN was ON and OFF intermittently, as indicated with ON or OFF in Tables 6 and 7.

In Table 6, the frame error rate (FER) exceeded 50% during ON periods, and nearly no-error during OFF periods. In Table 7, on the other hand, the FER was below 0.2% during both ON and OFF periods. Since the results of FER in the previous experiments was about 0.2% on the average, Table 7 show that the influence of the W-LAN was negligible at L2 in the Arrng-3.

Table 6. Frame Error Rate and power level for Rv-link, when W-LAN was operating at L1 in Arrng-3.

<table>
<thead>
<tr>
<th>Elapsed Time (sec)</th>
<th>Output of W-LAN</th>
<th>FER [%]</th>
<th>Power level (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 90</td>
<td>OFF</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>90 – 300</td>
<td>ON</td>
<td>70.1</td>
<td>-100</td>
</tr>
<tr>
<td>300 – 360</td>
<td>OFF</td>
<td>1.7</td>
<td>-100</td>
</tr>
<tr>
<td>360 – 420</td>
<td>ON</td>
<td>57.5</td>
<td>-100</td>
</tr>
<tr>
<td>420 – 480</td>
<td>OFF</td>
<td>1.6</td>
<td>-100</td>
</tr>
<tr>
<td>480 – 540</td>
<td>ON</td>
<td>59.7</td>
<td>-100</td>
</tr>
<tr>
<td>540 – 600</td>
<td>OFF</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>600 – 660</td>
<td>ON</td>
<td>84.9</td>
<td>-100</td>
</tr>
<tr>
<td>660 – 720</td>
<td>OFF</td>
<td>3.5</td>
<td>-100</td>
</tr>
<tr>
<td>720 – 780</td>
<td>ON</td>
<td>88.8</td>
<td>-100</td>
</tr>
<tr>
<td>780 – 960</td>
<td>OFF</td>
<td>0.32</td>
<td>-100</td>
</tr>
</tbody>
</table>

Table 7. Frame Error Rate and power level for Rv-link, when W-LAN was operating at L2 in Arrng-3.

<table>
<thead>
<tr>
<th>Elapsed Time (sec)</th>
<th>Output of W-LAN</th>
<th>FER [%]</th>
<th>Power level (dBm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0 – 60</td>
<td>OFF</td>
<td>0</td>
<td>-100</td>
</tr>
<tr>
<td>60 – 300</td>
<td>ON</td>
<td>0.16</td>
<td>-100</td>
</tr>
<tr>
<td>300 – 960</td>
<td>OFF</td>
<td>0</td>
<td>-100</td>
</tr>
</tbody>
</table>

During W-LAN ON and OFF intermittent at L1 or L2, the power level at the input of the BS receiver was measured for 16 minutes. As the signal came in 320ms per every 640ms, the signal and the noise level were both included in the data. The data was decimated and rearranged by extracting maximum and minimum value for every 0.8 seconds. The power level at L1 is presented in Fig.10. The averages of the power for the ON or OFF period in L1 are shown in Table 6. The corresponding results for L2 are in Fig.11 and Table 7.

Transmitted signal power from each terminal was controlled so that power level was maintained at –100dBm. The noise level was –127dBm, when W-LAN was OFF at both L1 and L2 (Figs.10 and 11). In case of ON at L1, the noise level became –107dBm (Fig.10), and the FER jumped to a 50%-level.
At L2, on the other hand, the noise level was –113 dBm, even when W-LAN was ON. The \textit{FER} was at 0.2\% or less. That is, the operation of the experimental CDMA system was found adequate enough in the presence of the W-LAN, when the power level of the interference was kept below –113 dBm. It is suggested from the result at L2 that the interference was reduced by 10dB attenuation through the wall.

A close observation of Fig. 10 shows spikes above the –100dBm level when the interference was above –107dBm. Since the power control employed in the Fw-link transmission was supposed to maintain the input level at –100dBm, the presence of the spikes suggests that the interference disturbs the power control operation and induces communication errors. Further study on this problem is currently under way.

IV. Conclusion

The propagation characteristics of an experimental TD-CDMA system is studied. The effects of the interference due to a W-LAN were investigated. Results have shown that the \textit{CRR} was at the 23dB level or more. The propagation mechanism of the setup was of a steady direct type. It was shown that the operation of the TD-CDMA system was adequate, when the W-LAN interference was kept below –113dBm for a –100dBm signal. When the interference exceeded –107dBm, the communications failed by at least 50\%. Further study is under way to investigate the influence of a microwave oven operating near household terminals.

Acknowledgement

This work was conducted in a project run by the TAO and was funded by the Ministry of Posts and Telecommunications, Japan.

References