Analysis of Information Transmission with Parallel Pilot Signal for Multipath Estimation Based on Kronecker Product with DFT

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Abstract: The authors have been proposed a method of very efficient wireless frequency usage. It is based on the measurement of multipath property for each timeslot, and the coherent addition of multipath signals. The method has been implemented an LSI chip. We have been proved the effectiveness of this multipath estimation method under the multipath environment quantitatively using by simulation model. In this paper, we investigate about robustness of this method. The frequency different problem between transmitter and receiver is considered. For this purpose, we considered frequency offset problem. This problem is well known as PLL offset. In short time length, the Doppler shift problem can be similar problem as a frequency offset problem. The simulation results showed this method has a strong robustness to the frequency different problem.

Key–Words: 4G mobile communication, sequence design, ZCZ-CDMA, wireless frequency usage efficiency, high-rate wireless communication, frequency offset

1 Introduction

We have proposed a very efficient frequency usage system based on multipath estimation and spread time signals based on the signal design of zero correlation zone (ZCZ) signals using complete complementary codes. [1][2][6]. The method has been implemented as a baseband LSI chip[4].

And we have proposed other new zero cross-correlation zone (ZCCZ) signals based on periodic sequence set without crosscorrelation[3] is applied on the method of reference[1] [2]. The system uses the pilot signal for measuring the multipath properties by time shift delay as the complex value. The pilot signal and the data transmission signals can be used independently in the same time and the same frequency band without crosscorrelation nor interference. The system can get the current multipath properties and use them to detect the transmitted data by adding the multipath signals coherently.

And we have proposed a method to make sparse ZCCZ signals[5], so that the transmitted signal doesn’t have the problem of amplifier dynamic range. we have been prove the effectiveness of this multipath estimation method[5] under the multipath environment quantitatively using by simulation model[7].

In this paper, we investigate about robustness of this method. The frequency different problem between transmitter and receiver is considered. For this purpose, we considered frequency offset problem. This problem is well known as PLL offset. In short time length, the Doppler shift problem can be similar problem as a frequency offset problem. The simulation results showed this method has a strong robustness to the frequency different problem.

2 Information Theoretical View Point

In information theory, the channel capacity is defined based on the S/N ratio. However, what is the noise power? Usually, unuseful multipath signal energy is regarded as noise energy. But when we can estimate all of the multipath time delay, all of the multipath energy can be used by gathering the energy coherently. In fact, the amplitude and the phase for each time slot is enough to use the multipath signal energy as useful signal energy. In this case, the signal power is increased and the noise power is decreased, so the channel capacity is increased.

In current mobile communication technology, only several large power multipath signals are regarded as useful multipath signals, and other multipath signals are regarded as noise, and sometimes the estimation of the large multipath signal is difficult by many reason. On the other hand, our method can al-
most always estimate the multipath properties of each time slot, and increase the channel capacity significantly.

The remained problem was that the dynamic range of transmitter amplifier is sometimes not enough. So, we have proposed the new method[5] that sparse signals can also be used, and have enough property of very efficient wireless frequency usage.

3 Sequence Set without Periodic Crosscorrelation

In this section, we review the new method to make sequence sets without periodic crosscorrelation[3].

Let $F_N$ be the $N$-point DFT matrix as:

$$
\sqrt{N} F_N = \begin{bmatrix}
W_N^0 & W_N^0 & \ldots & W_N^0 \\
W_N^0 & W_N^{-1} & \ldots & W_N^{-(N-1)} \\
\vdots & \vdots & \ddots & \vdots \\
W_N^0 & W_N^{-(N-1)} & \ldots & W_N^{-(N-1)(N-1)}
\end{bmatrix}
$$

$$
= \sqrt{N} \begin{bmatrix}
f_0 \\
f_1 \\
\vdots \\
f_{N-1}
\end{bmatrix}
$$

where $W_N = \exp \left( \frac{2\pi j}{N} \right)$.

Let $X$ and $Y$ also be $X = (x_0, x_1, \ldots, x_{L-1})$ and $Y = (y_0, y_1, \ldots, y_{L-1})$. Then, we can obtain $\sqrt{N} f_k \otimes X$ and $\sqrt{N} f_l \otimes Y$ as:

$$
\sqrt{N} f_k \otimes X
= (W_N^0 x_0, W_N^0 x_1, \ldots, W_N^0 x_{L-1})
= (W_N^{-k} x_0, W_N^{-k} x_1, \ldots, W_N^{-k} x_{L-1})
= (W_N^{-k(N-1)} x_0, W_N^{-k(N-1)} x_1, \ldots, W_N^{-k(N-1)} x_{L-1}),
$$

$$
\sqrt{N} f_l \otimes Y
= (W_N^0 y_0, W_N^0 y_1, \ldots, W_N^0 y_{L-1})
= (W_N^{-l} y_0, W_N^{-l} y_1, \ldots, W_N^{-l} y_{L-1})
= (W_N^{-l(N-1)} y_0, W_N^{-l(N-1)} y_1, \ldots, W_N^{-l(N-1)} y_{L-1}),
$$

where $\otimes$ is the Kronecker product.

The length of each of $\sqrt{N} f_k \otimes X$ and $\sqrt{N} f_l \otimes Y$ is $NL$. When we investigate $F_{NL}(\sqrt{N} f_k \otimes X)$, we know that the spectrum has non-zero terms only at the $k$(mod$N$)$'$th terms. So, it is obvious that when $k \neq l$, the periodic crosscorrelation function between $\sqrt{N} f_k \otimes X$ and $\sqrt{N} f_l \otimes Y$ is zero at every term.

4 Very Efficient Usage of Wireless Frequency

In this section we propose a new method to use the wireless frequency very efficiently. The method is based on a method to measure the multipath properties and a method to use multipath signals by the coherent addition using a linear equation.

The method is explained by using a small example.

Let $\{A, B, C, D\}$ be a set of periodic sequence, where

$$
A = (1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1) \\
B = (1, j, -1, -1) \\
C = (1, -1, 1, -1) \\
D = (1, -j, 1, j)
$$

4.1 measurement of Multipath Properties

In this example, we define ‘a multipath vector’ $P = (p_0, p_1, p_2, p_3)$, where each of $p_0, p_1, p_2$ and $p_3$ denotes the complex multipath factor of each time slot, so each of $p_0 \ldots p_3$ is a complex number. Note that $p_0$ denotes the direct path, so we can suppose $p_0 = 1$.

We can see from the formula (1)

$$
A = (1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1)
$$

Let $A'$ be a finite length pseudo-periodic sequence of pseudo-period 16.

$$
A' = (1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1, 1)
$$

The length of $A'$ is $4 + 16 + 4 = 24$. We can regard $A'$ is obtained by cutting a sequence of length 24 from the infinite length sequence ($\ldots A A A A \ldots$).

In this example, we use another pseudo-periodic signal $(A', 1)$ of length 25, so that the length of the signal is exactly fittable to the method.

When we input the signal $(A', 1)$ into the matched filter for $A$, we obtain the output signal

$$
(A', 1) * A = 16(x, x, x, x, x, 1, 0, 0, 0, 1, 0, 0, 1, 0, 0, x, x, \ldots, x, x)
$$

where each $x$ denotes some value.
Because the multipath property is \( P = (p_0, p_1, p_2, p_3) \), the receiver should receive the signal
\[
A'' = p_0(A', 1, 0, 0, 0) + p_1(0, A', 1, 0, 0) + p_2(0, 0, A', 1, 0) + p_3(0, 0, 0, A', 1). \tag{3}
\]

When this received signal is input to the matched filter for \( A \), the filter outputs:
\[
A'' \ast A = 16(x, x, x, \ldots, x, x, x, x, p_3, p_0, p_1, p_2, p_3, p_0, p_1, x, x, x, \ldots, x, x). \tag{4}
\]

So, when transmit the signal \((A', 1)\) under the multipath environment of \( P = (p_0, p_1, p_2, p_3) \), and receive the signal by the matched filter for \( A \), we can obtain the multipath property \((p_0, p_1, p_2, p_3)\) as the output of the filter matched for \( A \).

Figure 1 shows conceptual figure of equation (2) and of equation (4).

![Figure 1: Filter out put under no multipath and under multipath environment.](image)

### 4.2 Signal for Information Transmission

From the formulae (1), we can also see
\[
B = (1, 0, 0, 0, j, 0, 0, 0, -1, 0, 0, 0, -j, 0, 0, 0).
\]

Let \( B' \) also be a finite length pseudo-periodic sequence of pseudo-period 16:
\[
B' = (-j, 0, 0, 0, B, 1, 0, 0, 0).
\]

The length of \( B' \) is \( 4 + 16 + 4 = 24 \). We can regard \( B' \) is also obtained by cutting a sequence of length 24 from the infinite sequence \((\ldots BBBB\ldots)\).

When we input the pseudo-periodic signal \((B', j)\) of length 25 and pseudo-period 16 into the matched filter for \( A \), we obtain the output signal
\[
(B', j) \ast A = (x, x, \ldots, x, x, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, x, x, \ldots, x, x).
\]

When we input the signal \((A', 1)\) of length 25 into the matched filter for \( B \), we obtain the output signal
\[
(A', 1) \ast B = (x, x, \ldots, x, x, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, 0, x).\]

So, the signals \((A', 1)\) and \((B', j)\) can be used independently at the simultaneous.

Figure 2 shows the different output with ZCZ(zero correlation zone) in different sequence input.

![Figure 2: Conceptual figure of the filter output between different sequence.](image)

Now, we should consider the multipath environment.

When the signal \((B', j)\) is transmitted under the multipath environment \( P \), the receiver receives the signal:
\[
B'' = p_0(B', j, 0, 0, 0, -p_1(0, B', j, 0, 0) + p_2(0, 0, B', j, 0) + p_3(0, 0, 0, B', j). \tag{5}
\]

When the received signal \(A''\) of the formula (3) is input to the matched filter for \( B \), the output signal is:
\[
A'' \ast B = (x, x, \ldots, x, x, 0, 0, 0, 0, 0, 0, 0, 0, 0, x, x, \ldots, x, x).
\]
Similarly, when the received signal $B''$ of the formula (5) is input to the matched filter for $A$, the output signal is:

$$B'' \ast A = (x, x, \ldots, x, x, 0, 0, 0, 0, 0, 0, 0, x, x, \ldots, x, x).$$

So, the pseudo-periodic signals $(A', 1)$ and $(B', j)$ can be used independently without crosscorrelation even under the multipath environment $P$. Thus, we can use $(A', 1)$ as a pilot signal to measure the multipath property and use $(B', j)$ as an information transmission signal.

When $(B', j)$ is input to the matched filter for $B$, the output signal is:

$$(B', j) \ast B = (x, x, \ldots, x, -4j, 0, 0, 0, 4j, 0, 0, 0, -4, x, \ldots, x).$$

So, when the received signal of the formula (5) is input to the matched filter for $B$, the output signal is:

$$(B'' \ast B) = 4(x, x, \ldots, x, x),$$

$$\begin{bmatrix}
-jp_0 & -jp_1 & -jp_2 & -jp_3 \\
 p_0 & p_1 & p_2 & p_3 \\
 jp_0 & jp_1 & jp_2 & jp_3 \\
 x, x, \ldots, x
\end{bmatrix}.$$  \hspace{1cm} (6)

**4.3 Information Transmission Method**

When the multipath problem is solved, the signals $(B', j, 0)$ and $(0, B', j)$ are recognized as the different signals. So, both signals can carry the different data.

In this example, the data $(b_0, b_1, b_2, b_3, b_4, b_5)$ is carried by the chip-shifted signals $(B', j, 0, 0, 0, 0, 0), (0, B', j, 0, 0, 0, 0), (0, 0, B', j, 0, 0, 0), \ldots$, and $(0, 0, 0, 0, 0, B', j)$.

So, the transmitted signal should be:

$$b_0(B', j, 0, 0, 0, 0, 0) + b_1(0, B', j, 0, 0, 0, 0) + b_2(0, 0, B', j, 0, 0, 0) + b_3(0, 0, 0, 0, 0, B', j).$$

When this signal is transmitted under the multipath environment $P$, and the received signal is input to the matched filter for $B$, the output signal is:

$$(x, x, \ldots, x, x, x, x, q_0, q_1, q_2, q_3, q_4, q_5, q_6, x, x, \ldots, x, x),$$

where

$$\begin{bmatrix}
q_0 \\
q_1 \\
q_2 \\
q_3 \\
q_4 \\
q_5 \\
p_0 & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\
p_0 & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\
p_0 & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\
p_0 & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\
p_0 & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\
p_0 & p_1 & p_2 & p_3 & p_4 & p_5 & p_6 \\
q_0 & q_1 & q_2 & q_3 & q_4 & q_5 & q_6
\end{bmatrix}.$$  \hspace{1cm} (7)

Thus, we got a system of 7 linear equations in 6 unknowns, where $b_0, b_1, b_2, \ldots$ and $b_5$ are unknowns. Because $p_0, p_1, p_2, p_3$ are obtained as the output of the matched filter for $A$, and $q_0, q_1, q_2, \ldots$ and $q_6$ are obtained as the output of the filter, the linear equation system can be solved easily. So, the transmitted data $(b_0, b_1, b_2, b_3, b_4, b_5)$ are detected even under the multipath environment $P$.

If we can use the complex number sequences, we can use large scale DFT matrices. So, in future, this method will give us very efficient wireless communication method. Note that if we use wider frequency band, the time slot should be narrower, and the resolution of multipath become better. The resolution of multipath means the addition of plural multipath signals is divided into plural signals.

**5 Simulations**

**5.1 Scheme of the transmission system using kronecker product with DFT for simulation**

We employed here 8-point DFT matrix. As we mentioned in previous section 3, we can apply this method to any length of data. So, we determine the length of data is 89 in this simulation. So, the chip length is $8 \times 89 = 712$. Then we add 64 chips both edge of these chips for making pseudo-periodic signal. So, the total chip length is 840. As we mentioned previous sections, there are 8 orthogonal sequences in the case.
of 8-point DFT matrix. One of 8 DFT rows is using as a pilot signal, so we put the orthogonal sequences as a data in order to make a clear main pulse with matched filter. Then we can get a code gain for pilot signal. Another 7 sequences of DFT rows are using for the data transmission, so we can transmit \(7 \times 89\) data at the same time. These each data can be complex number, so we applied 64QAM for each data. So, the total transmitted information are \(7 \times 89 \times 6 = 3738\) bits. The transmission rate is \(3738/840 = 4.45\) bits/chip.

I’d like to point up again, the pilot signal and the data signals are sent simultaneously. So, the multipath effect is the same between the pilot and the data signals. It means that the accuracy of multipath estimation is very good in the time axis.

5.2 The structure of transmitter and receiver model

The structure of transmitter and receiver model is as Figure 3. This simulation is based on the equivalent low-pass system model. In order to this, each chips are composed by 4 samples. Band width is limited by the root nyquist filter. We assumed the sampling for receiver is exactly fit to chip synchronization.

![Figure 3: Transmitter and receiver model.](image)

5.3 Effectiveness of the multimath estimation method

There are some assumptions for the fading environment. Receiver dose not move so quickly. Chip rate is \(1 \mu\) sec,1 MHz. The carrier frequency band is 1 GHz. For the relative power of relative delay time to main pulse, the carrier delay profile is assumed as COST207(monotony dropped by 30 dB in 7 \(\mu\) sec delay). Carrier for each time slot is reached as a rayleigh fading. As a result of the fading with this delay profile, the multipath fading power is 43 % of original total signals power.

Figure 4 shows a comparison of the results between the ordinary 64QAM which has not multipath estimation and the dft-kronkecker product system with multipath estimation. The bit error rate for the ordinary 64QAM is very bad even in a small power of fading environment. On the other hand, the dft-kronkecker product system has a good property under the fading environment. When no fading, the dft-kronkecker product system seems to be slightly bad compare with the ordinary 64QAM. That is cause to the accuracy of a pilot signal estimation. If there was not the estimation error, this bit error rate line assumed to be just fit to the line of the ordinary 64QAM.

5.4 Influence of Different Frequency between Transmitter and Receiver

In the mobile communication situation, Doppler shift occurs. Then the received carrier frequency is moved. we investigate about robustness in the frequency different problem between transmitter and receiver. For this purpose, we considered frequency offset problem. This problem is well known as PLL offset. In short time length, the Doppler shift problem can be similar problem as a frequency offset problem. We assumed the frequency offset as 10,20,30 Hertz.

Figure 5 shows the comparison of the influence of frequency offset between the ordinary 64QAM which has not multipath estimation and dft-kronkecker product system with multipath estimation under the no multipath environment. The results shows the dft-kronkecker product system with multipath estimation is more strong for the frequency offset problem than the ordinary 64QAM system.

Figure 6 shows the results of the dft-kronkecker
product system with multipath estimation under the multipath environment and also under the no multipath environment. The result shows the dft-kronecker product system with multipath estimation is effective and strong to the frequency offset problem even in the multipath environment.

Figure 5: Comparison of the influence of frequency offset between the ordinary 64QAM which has not multipath estimation and dft-kronecker product system with multipath estimation under no multipath environment

Figure 6: BER for the dft-kronecker product system with multipath estimation under the multipath and also under the no multipath environment

6 Conclusion

We investigated the robustness in the frequency different problem between transmitter and the receiver for the dft-kronecker product system with multipath estimation. The simulation results showed this dft-kronecker product system with multipath estimation has a strong robustness to the frequency different problem.

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