Power Supply Overlaid Communication and Common Clock Delivery for Cooperative Motion Control

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MST: Master
SLV: Slave

Command
Power
Common Clock

(DC)-PLC for Reduction of Wires
Communication of the Control Signal

- Multi-Carrier Modulation
  - Down-Link: OFDM, Up-Link: OFDMA

(DC)-PLC for Reduction of Wires

- MST: Master
- SLV: Slave

Common Clock for Synchronized motions

- Delivery of a high quality common clock signal to each slave to inform the starting time of actions

Spread Spectrum (SS)
- Continuous transmission
- High resolution (<1 us)
Reception of the Common

RX for Common Clock at the slaves

- MF
- Threshold
- Master Clock

Common Clock

MF Output

High energy

$T_f$

High resolution

Master Clock

Objective

Communication over the **DC Power lines** inside the Robot.

- Command/Response between a Master & Slaves
- Delivery of Common Clock for Cooperative Motion

Master Clock to Cue Slaves to Start

Control signal $\Delta_t$: Interval of Command

- Command(OFDM)#0
- Response(OFDMA)#0
- Command(OFDM)#1

Down-Link

Up-Link

Start the action of Command #0

Start the action of Command #0

Crystal Oscillator

Action start time

Interval of Command

Action start time

Start the action of Command #0

Channel characteristics

- Band Limited (<35MHz)
- Frequency Selective

**AMPLITUDE**

**PHASE**

Gain [dB]

Phase [deg.]

0 10 20 30

0 180

-10 -20 -30

0 10 20 30

0 180

-720 -540 -360

0 10 20 30
Spectra of Signals

Control signal (OFDM(A)): \( L = 105 \) subcarriers

Common clock signal

Challenge:
cohabitation of control signal and clock

Down-Link

- SS \( \rightarrow \) OFDMA @Slaves
- OFDMA \( \rightarrow \) SS @Slaves

Same Channel for SS & OFDM: Flat Interference

Solution of Mutual Interference

- OFDM(A) \( \rightarrow \) SS: Process Gain of SS
- SS \( \rightarrow \) OFDM(A): Interference Cancellation

Different Channel for SS & OFDM: Colored Interference
Reduction of Influence of SS to OFDM(A)

System Parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of Slaves $K$</td>
<td>3</td>
</tr>
<tr>
<td>Channel</td>
<td>Measured</td>
</tr>
<tr>
<td>Noise</td>
<td>None</td>
</tr>
</tbody>
</table>

**Common Clock Signal**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>15 MHz</td>
</tr>
<tr>
<td>Chip Interval</td>
<td>0.1 $\mu$s</td>
</tr>
<tr>
<td>PN Sequence (Interval $N$)</td>
<td>$M$ sequences + 0 padding $(2048=2^{11})$ [bit]</td>
</tr>
</tbody>
</table>

**Control Signal**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>The Lowest Carrier Frequency</td>
<td>2.19 MHz</td>
</tr>
<tr>
<td>Symbol duration Time</td>
<td>3.2 $\mu$s</td>
</tr>
<tr>
<td>The number of Subcarriers /Allocation</td>
<td>106/Slave with High Gain</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK</td>
</tr>
</tbody>
</table>

System Requirement

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Working Hours a year</td>
<td>$1.0512 \times 10^7$ s $(8h/day \times 365)$</td>
</tr>
<tr>
<td>Accuracy of Self-Running OSC</td>
<td>$\pm 100ppm$</td>
</tr>
</tbody>
</table>

- a pair losses of two successive command packets < once a year
- a misdetection of a start cue < once a year
- cue with timing error more than 1us < once a year

Requirements for Communication Part

[Reception performance]

**Common Clock Signal (SS)** : Prob. of False Alarm
Control Signal (OFDM(A)) : Symbol Error Rate (SER)

Required Conditions for Reception Performance

<table>
<thead>
<tr>
<th>Probability Type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Prob. of False Alarm $\varepsilon_f$</td>
<td>$2.1 \times 10^{-7}$</td>
</tr>
<tr>
<td>Prob. of Miss Detection $\varepsilon_m$</td>
<td>$3.2 \times 10^{-1}$</td>
</tr>
<tr>
<td>SER for Control Signal $\varepsilon_S$</td>
<td>$3.19 \times 10^{-6}$</td>
</tr>
</tbody>
</table>
Down-Link

- SS → OFDMA @Slaves
- OFDMA → SS @Slaves

Same Channel for SS & OFDM: Flat Interference

Common Clock Signal

Receiver of Common Clock Signal (RX_c)

Control Signal +
Common Clock Signal

MF Output

\[ \Theta : \text{Threshold for detection} \]

\[ T_0, T_0 + N T t \]

PDF

Prob. of False Alarm

Prob. of Miss Detection

Reception Performance of the Common Clock Signal (Down-Link)

\[ \theta : \text{Threshold of common clock} \]

\[ 10^{-7} \]

\[ 5 \]

\[ 4 \]

\[ 3 \]

\[ 2 \]

\[ 1 \]

\[ 0 \]

\[ 0.1 \]

\[ 0.2 \]

\[ 0.32 \]

\[ 0.4 \]

\[ 0.5 \]

Prob. Miss detection \( \varepsilon_m \)

\[ \theta : \text{small} \]

\[ \theta : 41.7 \]

\[ \theta : 45.0 \]

\[ \theta : \text{large} \]

\[ \gamma_d = 14.5 \text{dB} \]

\[ \gamma_d = \text{Control signal power (OFDM)} \]

\[ \gamma_d = \text{Common clock signal power (SS)} \]

Requirement

\[ \gamma_d < 14.5 \text{ dB} \]
Reception Performance of the Control Signal (Down-Link)

- In the case of using IC, at the $\gamma_d = 14.5\,[\text{dB}]$, $\text{SER} < 10^{-8}$ (required SER = $3 \times 10^{-8}$)

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Reception Performance of the Common Clock Signal (Up-Link)

- **Required Condition** $\gamma_u < 15\,[\text{dB}]$

- **Threshold of common clock** $\Theta$:
  - $\Theta: \text{small}$
  - $\Theta: \text{large}$

- **Slave** $0,1,2$ ($\gamma_u = 15\,[\text{dB}]$)

- **Requirement** $\gamma_u < 15\,[\text{dB}]$

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Reception Performance of the Control Signal (Up-Link)

- In the case of using IC, at the $\gamma_d = 15\,[\text{dB}]$, $\text{SER} < 10^{-8}$ (required SER = $3 \times 10^{-8}$)
Conclusions

Propose
- A multiple servo control communication system in which the power supply overlaid communications
- Delivery of a common clock for cooperative motion control

Result
- Control signals and master clock can coexist in actually channel.

Cooperative Motion Control System

- Cooperative motion: Multiple machines work at the same time with each other.
- Robot group control
- Assembly lines
- Partner robots
- Control of moving machines
- Relocation of machines
- Saving of space

Performance of Wireless Cooperative Control

- Packet errors
- Control performance of each machine (stability, etc.)
- Synchronization of all machines

New measurement of performance is "the synchronization of all machines".

A Wireless Cooperative Motion Control System with Mutual Use of Control Signals

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Conventional Control Signal Transmission

Conventional method
- One input and one output.

Mutual Use of Control Signals

Conventional method
- One input and one output
- The nature of wireless

Proposed method
- Multiple input and one output
- We consider to use the control signals of the other machines.

Purpose

A wireless control method for a cooperative motion system
- Mutual use of the control signals
  - Improvement of control performance and synchronization
- New measurement of performance
  - Synchronization of all machines

Rotary Inverted Pendulum

The pendulums are controlled to make their arm angles \( \phi[k] \) follow the target value while keeping the pendulums in an upright position \( (\theta[k] = 0) \).

Basic model
- Bipedal walking robot
- Crane
- Rocket launching pad

Underactuated system
- One actuator for two degrees of freedom

\[ u[k] : \text{Control information (torque)} \]
\[ x[k] : \text{State information} \]
\[ x[k] = [\theta[k] \ \dot{\theta}[k] \ \phi[k] \ \dot{\phi}[k]] \]