Wireless Sensor Gateway for Industrial Networks Connection

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Abstract: The main objective of this paper is to show new possibilities of wireless communication for mobile industrial sensors in the real-time. The network topology, signal modulations and industrial Ethernet protocol are discussed here. We have been focusing our research on real time communication of wireless sensors. Distance of sensors could be more than 30 meters and there is possibility to communication on different frequencies. The presented communication gateway is a one part of the whole wireless sensors network. The gateway provides communication by various industrial protocols common communication language. Furthermore we based our wireless communication system on 2x2 MIMO design. This solution offers significant increases in data throughput and link range without additional bandwidth or transmit power. The network communication nodes with multiple inputs and multiple outputs are designed as embedded mobile devices. With regard to real time data transfer communication, there is presented signal modulations (BFSK, QPSK, 16QAM, 64QAM) and protocol (PROFINET). The communication gateway software is implemented under QNX Neutrino RTOS and it includes PROFINET RT/IRT communication stack.

Keywords: Gateway, Industrial Network, Modulation, BFSK, QPSK, QAM.

1. INTRODUCTION
This paper shows design of the communication gateway for the wireless sensors network based on industrial Ethernet. The objective of our research is to ensure communication between wire and wireless network so that we are able to satisfy conditions for real-time control (time response of all devices has to be less then 1ms). The communication gateway can be used on PC (using PCI communication boards) or on embedded devices. The gateway solution is implemented under real time operating system – QNX Neutrino RTOS but is able to run under Linux RTAI as well. As demo industrial communication protocol PROFINET RT/IRT was chosen. The wireless communication was established by WiMAX modules (PCI or SDIO interface) based on standard 802.16e for mobile devices. The consequent proposed communication module has to be reduced enough in order to be embedded into the sensor-based industrial systems with small dimensions. In the present time the development of the wireless network is on the prototype level. The communication module and PCI board was set up by hardware that is a powerful and flexible Mobile WiMAX solution and that enables the manufacture of the smallest of mobile devices. This communication chips contain 2x2 MIMO design plus all MAC and PHY features required for WiMAX Forum™ Wave 2 certification. There are presented examples of the digital signal modulations (BFSK, QPSK, 16QAM, 64QAM) based on algorithms. These algorithms are tested in Matlab software.

2. GATEWAY AND NETWORK ARCHITECTURE
The software gateway has to enable communication between controllers and devices in the industrial network with different communication protocols (Profinis, PROFINET IO, CanOpen, EtherCAT, PowerLink, Modbus) and wireless sensors network with real time communication requirements according industrial protocol specifications. Only PROFINET solution is discussed in this paper. [6,7]

Gateway consists of PROFINET driver and gateway configuration tools that are able to set up wireless network fit to real time demands. Application software represents PROFINET device controller for RT or IRT communication with network coordinator properties. [4,5]

Architecture is based on parallel communication data processing that using MIMO system communication. For this purpose was used special embedded communication module with quad core DSP processor. Industrial Ethernet communication (based on PROFINET IO standard) is implemented using ERTEC400 PCI board and PROFINET communication IO stack. [3,8]

The DSP processor contains a special instruction set and hardware components for the fast signal processing. Sophisticate algorithms are implemented to DSP processor for the signal modulation, the signal translation, the signal protocol transformation, ect.
Fig. 1. Gateway module
The presented network has a one coordinator node and set of switches (routers) and the end points. The coordinator node has to take care about consistency of wireless network topology. The coordinate node has a gateway function between wire and wireless network as well. The coordinate node maps the network structure for each node.

Fig. 2. Network architecture of the transceiver module
The network remapping is possible only when the new node map pass the deadline test coordinator utility over the all network devices. Deadline test network utility was proposed by RT UML and has to ensure that the longest way will be under deadline limit in case that one or more nodes are out of order.

3. WIRELESS COMMUNICATION SYSTEM
The wireless communication system is based on WiMAX standard 802.16e for mobile devices. The transceiver node makes use of 2x2 MIMO communication chip and each device has 4 transceiver nodes. Transceiver node is connected with gateway via PCI or SDIO interface. The systems with multiple inputs and multiple outputs (MIMO) have transmitters that send multiple streams by multiple transmit antennas. The transmit streams go through a matrix channel which consists of multiple paths between multiple transmit antennas at the transmitter and multiple receive antennas at the receiver. Then, the receiver gets the received signal vectors by the multiple receive antennas and decodes the received signal vectors into the original information. The switched wireless network based on model of the MIMO systems is shown on Figure 2.

There is important to define single parts and equipments by requirements for the complex real time network composition. The parts and equipments definition is based on their parameters and implemented algorithms inside. Developed wireless gateway system is designed for real time communication with deadline limits. Therefore, we studied principles and we tested data communication speed by simulations of sophisticated types of digital modulations. This software part of gateway is based on signal modulation package that was implemented in mathematical software Matlab and consequently it is implemented in Gateway solution. Following chapters are devoted to digital modulated signaling package what is a key for safety wireless communication network in physical layer.

4. MODULATED BANDPASS SIGNALING
Modulations are useful algorithms and methods for wireless data communication through air medium. Analog modulations transform analog baseband signals to high wireless frequencies. Digital modulations are the base of digital signal transformation to high bandpass frequency spectrum.

The modulated bandpass signal \( v(t) \) is modulated by amplitude waveform \( R(t) \) and phase waveform \( \theta(t) \) of the complex envelope \( g(t) \). These variables contain basic information about digital data signal in basic frequency spectrum.

\[
v(t) = R(t) \cos(\omega_c t + \theta(t)), \tag{1}
\]

where \( \omega_c = 2\pi f_c \) and \( f_c \) is free carrier frequency 2.4GHz.

Modulated bandpass signal is defined by a real part of multiply of complex envelope and high frequency part. There is possibility to describe mathematical formula by Cartesian variables:
where complex envelope is baseband part of signal modulation:

\[ g(t) = x(t) + jy(t) = |g(t)| e^{j\theta(t)} \]

Modulated bandpass signal \( v(t) \) is transform by Fourier transformation from time domain to frequency domain of the signal.

\[ V(f) = \frac{1}{2} G(f - f_c) + \frac{1}{2} G(- f - f_c) \]

There is \( V(f) \) transformed bandpass signal in frequency domain and transformed shifted complex envelope \( G(f - f_c) \) in frequency domain.

These characteristic digital modulations are examples of the most common ones for wireless communication:

- BFSK
- QPSK
- 16QAM
- 64QAM

A spectral efficiency \( \eta \) of digital modulations depends on data transfer capability in defined time. The spectral efficiency \( \eta \) is described by mathematical formula:

\[ \eta = \frac{R}{B_T} \]

where \( R \) [bits / s] is data capability and \( B_T \) [Hz] is spectrum rate. There is dependency of the theoretical spectral efficiency \( \eta \) for digital modulations types with null-to-null bandwidth:

- BFSK \( \ldots \eta = 0.5 \)
- QPSK \( \ldots \eta = 1 \)
- 16QAM \( \ldots \eta = 2 \)
- 64QAM \( \ldots \eta = 3 \)

There is description and mathematical formulas and simulation of digital modulations in this article. The simulations of the modulated signals and its characteristics are designed and computed by the sophisticated mathematical programming environment MATLAB 7.1. [1, 2]

5. BANDPASS MODULATION BFSK

FSK modulation is nonlinear digital modulation without memory with multilevel states of the digital signal. Modulated bandpass signal \( v(t) \) is modulated by phase waveform \( \theta(t) \), which changes frequency of the signal. Amplitude waveform \( R(t) \) of the complex envelope \( g(t) \) is constant. The modulation BFSK is binary frequency shift keying digital modulation with two possible states 0 and 1 of baseband information signal.
The example for simulation of the data communication system by BFSK modulation is defined by these basic parameters:

Amplitude waveform:
\[ R(t) = 5 \]  \hspace{1cm} (6)

Phase waveform:
\[ \Theta(t) = D_f \cdot \int_{-\infty}^{t} m(\tau) \cdot d\tau \]  \hspace{1cm} (7)
\[ D_f = 5 \]

The modulated bandpass signal \( v(t) \) is described by formula:
\[ v(t) = 5 \cdot \cos \left[ 2 \cdot \pi \cdot 2,4 \cdot 10^6 \cdot t + 5 \cdot \int_{-\infty}^{t} m(\tau) \cdot d\tau \right] \]  \hspace{1cm} (8)

where binary data sequence is represented by information signal \( m(\tau) = 1011011100 \). Simulation of BFSK modulation is shown on Figure 3 and Figure 4.

6. BANDPASS MODULATION QPSK

QPSK modulation is Quadrature Phase-Shift Keying signal processing. Modulated bandpass signal \( v(t) \) is modulated by phase waveform \( \Theta(t) \), which changes discretely phase angles \( \Theta \) of the signal. Amplitude waveform \( R(t) \) of the complex envelope \( g(t) \) is constant. This digital modulation contains four levels digital signal.

Data are represented by permitted values of complex envelope defined by this algorithm:
\[ g(t) = x(t) + jy(t) = A_C \cdot e^{j\Theta(t)} \]  \hspace{1cm} (9)

Signal constellation describes complex envelope with four points of complex numbers for each of four-level digital signal.
\[ x_i = A_C \cdot \cos(\theta_i) \]
\[ y_i = A_C \cdot \sin(\theta_i) \]  \hspace{1cm} (10)

![QPSK constellation diagram of complex envelope g(t)](image)

Fig. 6. Simulation of the digital data sequence \((23130D)\) modulated by QPSK bandpass signal in constellation diagram.

The example for simulation of the data communication system by QPSK modulation is defined by these parameters:

Amplitude waveform:
\[ R(t) = 5 \]  \hspace{1cm} (11)

Phase waveform:
\[ \Theta(t) = 45^\circ \ldots m(t) = 0 \]
\[ \Theta(t) = 135^\circ \ldots m(t) = 1 \]
\[ \Theta(t) = 225^\circ \ldots m(t) = 2 \]
\[ \Theta(t) = 315^\circ \ldots m(t) = 3 \]  \hspace{1cm} (12)

The modulated bandpass signal \( v(t) \) for chosen information signal \( m(t) = 0 \) is described by formula:
\[ v_0(t) = 5 \cdot \cos \left[ 2 \cdot \pi \cdot 2,4 \cdot 10^6 \cdot t + \pi \left( \frac{3}{4} \right) \right] \]  \hspace{1cm} (13)

, where digital data sequence is represented by information signal \( m(t) = 23130D \). Simulation of QPSK modulation is shown on Figure 5 and Figure 6.

![Simulation of the digital data sequence (23130D) modulated by QPSK bandpass signal in time domain.](image)
7. BANDPASS MODULATION QAM

QAM modulation is Quadrature Amplitude Modulation signal processing. Modulated bandpass signal \( v(t) \) is modulated by phase waveform \( \theta(t) \), which changes discretely phase angles \( \Phi \) of the signal and discretely amplitude \( R_i \) changes of the complex envelope \( g(t) \). The digital modulation 16QAM (64QAM) contains 16 (64) levels digital signal. Data are represented by permitted values of complex envelope defined by this algorithm:

\[
\begin{align*}
  g(t) &= x(t) + jy(t) = R(t) \cdot e^{j\theta(t)} \\
  x_i &= R_i \cdot \cos(\theta_i) \\
  y_i &= R_i \cdot \sin(\theta_i)
\end{align*}
\]

(14)

(15)

Signal constellation describes complex envelope with 16 (64) points of complex numbers for each of multilevel digital signal.

\[
y_i(t) = 3 \ldots m(t) = 0 \\
y_i(t) = 1 \ldots m(t) = 6 \\
\vdots
\]

(17)

The modulated bandpass signal \( v(t) \) for chosen information signals is described by formula:

\[
\begin{align*}
  v_0(t) &= -3 \cdot \cos\left(2 \cdot \pi \cdot 2,4 \cdot 10^6 \cdot t\right) - 3 \cdot \sin\left(2 \cdot \pi \cdot 1 \cdot 10^6 \cdot t\right) \\
  v_6(t) &= 1 \cdot \cos\left(2 \cdot \pi \cdot 2,4 \cdot 10^6 \cdot t\right) - 1 \cdot \sin\left(2 \cdot \pi \cdot 1 \cdot 10^6 \cdot t\right) \\
  \vdots
\end{align*}
\]

where digital data sequence is represented by information signal. Simulation of 16QAM modulation is shown on Figure 7 and Figure 8. Simulation of 64QAM modulation is shown on Figure 9 and Figure 10.

![16QAM constellation diagram of complex envelope g(t)](image)

Fig. 8. Simulation of the digital data sequence (0-15) modulated by 16QAM bandpass signal in constellation diagram.

8. CONCLUSIONS

The main goal of this paper is to show options of the wireless network gateway design based on MIMO systems. The whole designed gateway system consists of individual embedded devices with the separate nodes of real-time wireless network. The design of the wireless network gateway fulfills parameters of the industrial network PROFINET. The signal modulation methods are described here. The methods are usable for the wireless communication network gateway. The digital modulation methods are GFSK (Gaussian Frequency-Shift Keying), QPSK (Quadrature Phase-Shift Keying), QAM (Quadrature Amplitude Modulation). These modulations are applied for the common transceiver chips, which are usable for a creation of the communication matrix. In this paper, Digital modulations are simulated in time, frequency and constellation domain. The simulations are developed from mathematical formulas, which are implemented for practise using. The next research will be focused to the designed network gateway realization and the signal modulations measuring and analyzing.
Fig. 9. Simulation of the digital data sequence (0-63) modulated by 64QAM bandpass signal in time domain.

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Fig. 10. Simulation of the digital data sequence (0-63) modulated by 64QAM bandpass signal in constellation diagram.