Wireless network effect on PI and type-2 fuzzy logic controller

Michal Blaho, Martin Urban, Peter Fodrek, Martin Foltin

***Abstract*—**With usage of data networks in control new area of research known as networked control systems was presented. Many communication medias and protocols can provide new possibilities in practical implementation. Professional solutions like PROFINET or IWLAN are followed with cheaper and popular networks like ZigBee or CAN bus. Recently, much attention has been paid to the wireless networks. ZigBee wireless networks are very popular for many advantages. Multiple control methodologies and practical applications have been developed for this kind of network. Applications must deal with negative effect of ZigBee network like network overload or packet dropout. In this paper we threated network disadvantages as uncertainty and we reduced them with type-2 fuzzy logic controller. We compared results with PI controller using Matlab and TrueTime environments.

***Keywords*—**Networked control systems, network overload, TrueTime, Type-2 fuzzy controller, packet dropout, uncertainties, Zigbee.

I. Introduction

Networked Control Systems (NCSs) are one type of distributed control systems where sensors, actuators, and controllers are interconnected by communication networks [1, 2]. The use of communication networks offers many advantages in terms of low cost, reduced weight, simple installation and maintenance, and high reliability. In recent years, communication and control co-design for NCS is studied widely [3, 4].

Despite the fact that traditional networks are still used new possibilities of modern data networks (cable or wireless) occurred in control area. The most used industrial cable network are CAN bus, PROFINET and most used wireless based network are IWLAN and ZigBee. CAN bus is reliable, fast and cost effective for multi master and real time applications [5]. PROFINET is the innovative open standard for Industrial Ethernet. PROFINET enables solutions to be developed for factory automation, process automation, safety applications, and the entire range of drive technology including isochronous motion control applications. IWLAN is a technology that means WLAN is applied to industrial environment. It is used in situations, where difficult to realize wired connection between devices in some environment, as well as not allow or expect wired connection in the view of technology [6]. ZigBee is another very popular wireless network with many benefits like low-cost and low-power consumption.

With many advantages in networked control systems also new problems occurred. Random packet looses is one of the key issues. Packet dropout can be caused by many different reasons such as signal degradation, channel congestions or distance between transmitter and receiver. Varying transmission delays is another important issue in networked control systems, which has to be dealt. Delays occur during transmitting information between nodes of network. This delay, either constant or time varying, can degrade the performance of control systems designed without considering the delay and can even destabilize the system [7].

The NCSs issues mentioned above have to be solved using better NCSs models which help to understand the effect of network-induced delay or packet dropouts on system performance. However, implementing networks into control systems especially wireless NCSs means complicated analysis and modeling of control systems. For instance, Markov chains often realize modeling control systems with consideration of random delays. The paper [8, 9, 10] presents methods for the analysis of the wireless NCS using predictive approach, adaptive algorithms are described in [11] and PID controller design is presented in [12].

Fuzzy logic has long history in implementation in various control areas. For its structure and benefits found fuzzy logic usage also in networked control systems. Fuzzy controllers for nonlinear systems, packet dropouts were presented [13, 14]. Real world implementation for remote fuzzy logic controller via Profibus-DP was presented in [15].

The concept of type-2 fuzzy sets was introduced by Zadeh as an extension of the concept of an ordinary fuzzy set, i.e., a type-1 fuzzy set. Type-2 fuzzy sets have grades of membership that are themselves fuzzy [16, 17]. Type-2 fuzzy logic can better model and minimize effect of different kinds of uncertainties. Type-2 fuzzy logic controllers were used for example in modeling for a heat exchange [18] or very popular

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sliding mode [19, 20]. NCS also contain different types of uncertainties like before mentioned transport delays or packet dropouts. Therefor usage of type-2 fuzzy systems in NCS can be beneficial. Unfortunately not many paper deals with usage of type-2 fuzzy controllers in networked control systems.

In this paper we focused on ZigBee wireless network. Standard PI controller and type-2 fuzzy controller were designed for control of process without network. Next we compared performance of controllers under negative effects of network like network overload and packet dropout. Controllers were evaluated through performance indices. The paper is divided into few sections. In the second section we briefly describe networked control systems. The third section is about ZigBee networks. In the fourth section we describe type-2 fuzzy logic and systems. In the fifth section we show our simulation environment. The sixth section shows simulation results.

II. Networked control systems

Computer data networks have a long history. Lots of new communications media and protocols have been developed and improved for many years. This led to many benefits as remote data transfers and data exchanges, reduce wiring, costs of medias and easier maintenance. Considering this benefits data networks became popular in control systems [1].

Multiple sensors and actuators are connected to a centralized controller via shared communication medium in a NCS. Controller, sensors and actuators transmit information and control signal via network as you can see on figure 1.

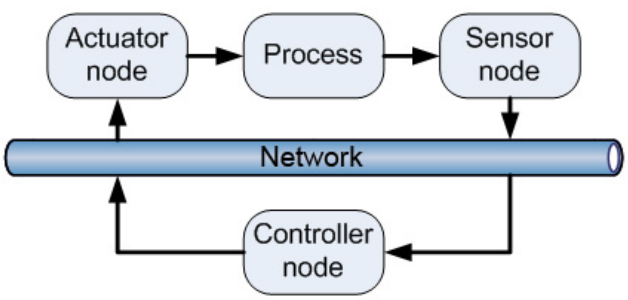

Fig.1 NCS block diagram [2]

Multiple sensors and actuators are connected to a centralized controller via shared communication medium in a NCS. Controller, sensors and actuators transmit information and control signal via network as you can see on figure 1 [2].

There are different networks suitable for NCS in industrial applications. Data can be transferred through cable network (e.g. CAN, EtherCAT, PROFINET) or wireless network (e.g. ZigBee, IWLAN). We focused on ZigBee network in this paper.

III. ZigBee

ZigBee is the only standards-based wireless 802.15.4 technology designed to address the unique needs of low-cost, low-power wireless sensor and control networks. The ZigBee standard employs 64 bit (IEEE) and short 16 bit addresses. The short address supports over 65 535 nodes per network. ZigBee is a multiple access network with CSMA/CA access method where the preferred topologies are the mesh and star. Mesh topology enables flexible network configuration and provides redundancy in the available routes. The star topology is necessary for RF (Reduced Function) devices, as they are not capable of routing.

ZigBee is designed for applications that need to transmit small amounts of data while being battery powered so the architecture of the protocols and the hardware is optimized for low power consumptions of the end device. It provides long battery life. [21] The ZigBee security architecture includes security mechanisms to protect transmitting data. This technology in the security is specifically expressed in the following features: providing sequential freshness, frame integrity checking function, entity authentication service and data encryption. [22]

The number of publications devoted to the study of ZigBee technology and their implementation in real applications. In [23] constructing the Zigbee-based WSAN (A Wireless Sensor and Actuator Network) is discussed in connection with implementation of ZigBee protocol for the application of lights automation. ZigBee wireless technology is also tending to medical applications. How to implement this technology to medical environment deal this papers [24, 25]. To summarize, ZigBee found usage in many applications like building automation, remote control, health care, home automation and many others [26, 27, 28].

IV. Type-2 fuzzy logic

Zadeh has introduced fuzzy sets in 1965. Ten years later he presented concept of type-2 fuzzy sets. Since classical (type-1) sets have been used with success in many fields but not many researchers focused on type-2 fuzzy sets. Mendel returned to the concept of type-2 fuzzy sets and for the last ten years with other researchers has extended this theory [29].

Type-1 fuzzy sets have limited capabilities to directly handle data uncertainties, where handle means to model and minimize the effect of uncertainties. Type-2 fuzzy sets have grades of membership that are fuzzy, so it could be called a "fuzzy-fuzzy set".

A type-2 fuzzy set in the universal set X is denoted as $\tilde{A}$, which is characterized by a type-2 membership function $\mu_{\tilde{A}}(x)$ in (1). The $\mu_{\tilde{A}}(x)$ can be referred as a secondary membership function (MF) or also referred as secondary set, which is a type-1 set in [0, 1]. In (1) $f_x(u)$ is a secondary grade, which is the amplitude of a secondary MF; i.e. $0 \leq f_x(u) \leq 1$. The domain of a secondary MF is called the primary membership of x. In (1), J_x is the primary membership of x, where $u \in J_x \subseteq [0,1]$ for $\forall x \in X$; u is a fuzzy set in [0,1], rather than a crisp point in [0,1]. [30]

$$\tilde{A} = \int_{x\in X} u_{\tilde{A}}(x)/x = \\ = \int_{x\in X} \left[\int_{u\in J_x} f_x(u)/u\right]/x, \ \ J_x \subseteq [0,1] \quad (1)$$

We can view examples of type-2 fuzzy sets in three-dimensional figures. In next figure you can see example of type-2 Gaussian membership function. A Gaussian type-2 fuzzy set is one in which the membership grade of every domain point is a Gaussian type-1 set contained in [0,1]. [31]

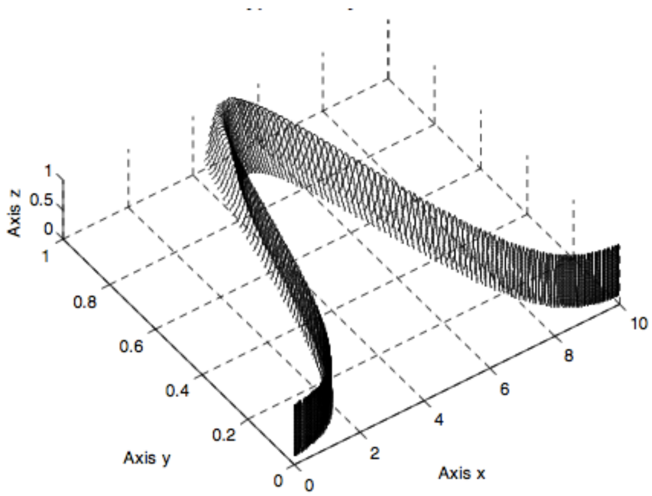

Fig. 2 Three-dimensional view of a type-2 membership function [31]

When $f_x(u) = 1, \forall u \in J_x \subseteq [0,1]$, then the secondary MFs are interval sets such that $\mu_{\tilde{A}}(x)$ in (1) can be called an interval type-2 MF [17]. Therefore, type-2 fuzzy set $\tilde{A}$ can be rewritten as

$$\tilde{A} = \int_{x\in X} \left[\int_{u\in J_x} 1/u\right]/x, \ \ J_x \subseteq [0,1] \quad (2)$$

An example of interval type-2 fuzzy set that is often used (we also used it in our computation) is Gaussian membership function with uncertain mean and fixed standard deviation (3). This function is in the figure 3.

$$\mu_{\tilde{A}}(x) = exp\left[-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right], \ \ m \in [m_1, m_2] \quad (3)$$

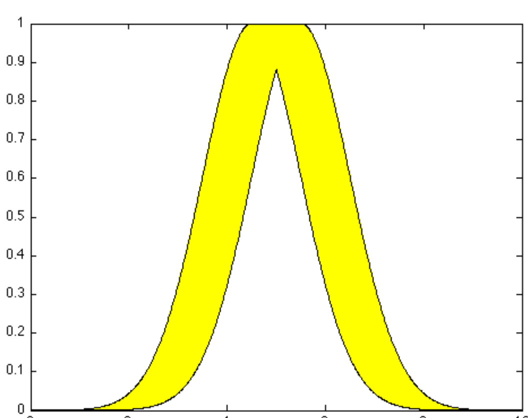

Fig. 3 Gaussian MF with uncertain mean (3)

Other popular example of interval type-2 fuzzy set that is often used Gaussian membership function with uncertain standard deviation (4). This function is in the figure 4.

$$\mu_{\tilde{A}}(x) = exp\left[-\frac{1}{2}\left(\frac{x-m}{\sigma}\right)^2\right], \ \ \sigma \in [\sigma_1, \sigma_2] \quad (4)$$

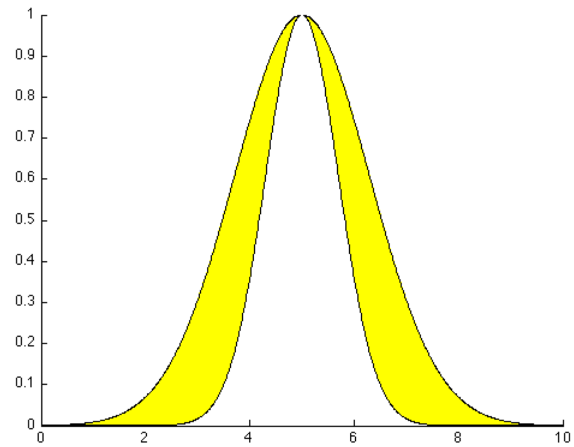

Fig. 4 Gaussian MF with standard deviation (4)

As you can see in figure 3 and figure 4 region of the Gaussian MF with uncertain mean can be bounded by upper $\overline{\mu}_{\tilde{A}}(x)$ and lower $\underline{\mu}_{\tilde{A}}(x)$ MF and it is called footprint of uncertainty (FOU).

Type-2 fuzzy logic system is similar to type-1 fuzzy logic system and is shown in figure 5. This system consists of these five main parts: fuzzifier, rule base, inference engine, type-reducer, and defuzzifier.

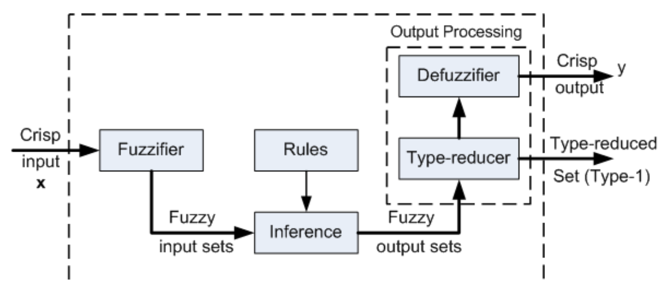

Fig. 5 Type-2 fuzzy logic system

The type-2 fuzzy rule base consists of a collection of IF-THEN rules. With M rules and the rule of a type-2 relation between the input space and the output space can be expressed as:

$$R^l: IF\ x_1\ is\ \tilde{F}_1^l\ and\ \dots\ and\ x_p\ is\ \tilde{F}_p^l, \\ THEN\ y\ is\ \tilde{G}^l, l = 1, \dots, M \quad (5)$$

The inference engine combines rules and gives a mapping from input type-2 fuzzy sets to output type-2 fuzzy sets. The output of inference engine block is a type-2 set. The firing strength F^i for the ith rule can be an interval type-1 set expressed as

$$F^i = \left[\underline{f}^i \ \ \overline{f}^i\right]^T \tag{6}$$

where

$$\underline{f}^i = \underline{\mu}_{\tilde{F}_1^i}(x_1) * \dots * \underline{\mu}_{\tilde{F}_p^i}(x_p)$$
$$\overline{f}^i = \overline{\mu}_{\tilde{F}_1^i}(x_1) * \dots * \overline{\mu}_{\tilde{F}_p^i}(x_p) \tag{7}$$

To reduce type-2 fuzzy set to type-1 fuzzy set we must used type reduction. Many type reductions like centroid, height or modified weight was presented but center-of-sets is common one.

$$Y_{COS}(x) = [y_l \ \ y_r] =$$
$$= \int_{y^1} \cdots \int_{y^M} \int_{f^1} \cdots \int_{f^M} 1 / \frac{\sum_{i=1}^M f^i y^i}{\sum_{i=1}^M f^i} \tag{8}$$

Karnik and Mendel have developed iterative algorithm for computing y_l and y_r [32]:

1. Without loss of generality, assume that the pre-computed y_r^i are arranged in ascending order; i.e., $y_r^1 \leq y_r^2 \leq \cdots \leq y_r^M$.
2. Set $f_r^i = (\underline{f}^i + \overline{f}^i)/2$ for $i = 1, \dots, M$. Compute y_r as $y_r = \sum_{i=1}^M f_r{}^i y_r{}^i \,/\, \sum_{i=1}^M f_r{}^i$. Let $y_r{}' \equiv y_r$.
3. Find R $(1 \leq R \leq M-1)$ such that $y_r^R \leq y_r{}' \leq y_r^{R+1}$.
4. Compute $y_r = \sum_{i=1}^M f_r{}^i y_r{}^i \,/\, \sum_{i=1}^M f_r{}^i$ with $f_r^i = \underline{f}^i$ for $i \leq R$ and $f_r^i = \overline{f}^i$ for $i > R$ and let $y_r{}'' \equiv y_r$.
5. If $y_r{}'' \neq y_r{}'$ go to step 6.
6. Set $y_r{}' \equiv y_r{}''$ and go to step 3.

The procedure for computing y_l is very similar to the one just given for y_r. Just replace y_r^i by y_l^i and in step 3 find L $(1 \leq L \leq M-1)$ such that $y_l^L \leq y_l{}' \leq y_l^{M+1}$. Additionally, in step 2 compute y_l as $y_l = \sum_{i=1}^M f_l{}^i y_l{}^i \,/\, \sum_{i=1}^M f_l{}^i$ by initially setting $f_l^i = (\underline{f}^i + \overline{f}^i)/2$ for $i = 1, \dots, M$ and in step 4 compute y_l as $y_l = \sum_{i=1}^M f_l{}^i y_l{}^i \,/\, \sum_{i=1}^M f_l{}^i$ with $f_l^i = \overline{f}^i$ for $i \leq L$ and $f_l^i = \underline{f}^i$ for $i > L$.

Once y_l and y_r are obtained, they can be used to calculate the crisp output. Since the type-reduced set is an interval type-1 set, the defuzzified output is:

$$y(x) = \frac{y_l + y_r}{2} \tag{9}$$

V. Simulation Environment

For our experiments we used simulation environments. All simulations were realized in Matlab environment using TrueTime simulator.

A. Matlab

The Matlab high-performance language for technical computing integrates computation, visualization in programming in an easy-to-use environment where problems and solutions are expressed in familiar mathematical notation. MATLAB features a family of add-on application- specific solutions called toolboxes. Toolboxes are comprehensive collections of MATLAB functions (M-files) that extend the MATLAB environment to solve particular classes of problems.

B. TrueTime

TrueTime is a Matlab/Simulink-based simulator for simulating networked and embedded real-time control systems. TrueTime facilitates co-simulation of controller task execution in real-time kernels, network transmissions, and continuous plant dynamics. The TrueTime network block simulates medium access and packet transmission in a local area network. Six simple models of networks are supported: CSMA/CD (e.g. Ethernet), CSMA/ AMP (e.g. CAN), Round Robin (e.g. Token Bus), FDMA, TDMA (e.g. TTP), and Switched Ethernet.

The usage of the wireless network block is similar to and works in the same way as the wired one. To also take the path-loss of the radio signals into account, it has x and y inputs to specify the true location of the nodes. Two network protocols are supported at this moment: IEEE 802.11b/g (WLAN) and IEEE 802.15.4 (ZigBee). [33]

NCSs issues have been studying in some papers using TrueTime environment. In [34] influence of the sampling period in the performance of a real-time distributed system was presented. Control system was tested under different jitter conditions with the adaptive controller. Model based predictive networked control systems [35] were used for compensation of random network delay.

C. Simulation schema

Our simulation schema consisted of PI controller, process and wireless network blocks. We used PI controller and transfer function of the process according to Tipsuwan [1]. Mathematical description of process ($G_P(s)$) and controller ($G_C(s)$) are followed:

$$G_P(s) = \frac{2029.826}{(s+26.29)(s+2.296)} \tag{10}$$

$$G_C(s) = \frac{0.1701(s+0.378/0.1701)}{s} \tag{11}$$

For representation of our ZigBee network blocks from TrueTime were used. Basic properties of whole network can be set in TrueTime Wireless Network block. For simulation we set especially Network type, number of nodes, loss probability but the others can be set too. Network nodes are represented by TrueTime Send and TrueTime Receive blocks that provide data exchange. Simulation schema is on the next figure.

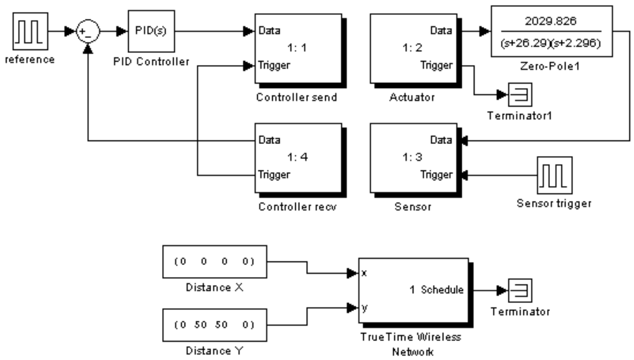

Fig. 6 Simulation schema

Type-2 fuzzy controller was developed based on PI controller equivalent. First we tried to construct type-1 fuzzy controller equivalent of PI controller as:

1. We determined universes for error (-1.5,1.5) and integral for error (-0.15,0.15).
2. Intervals were covered with 7 type-1 membership functions; standard deviation was 0.5 for error and 0.05 for standard deviation.
3. Mean of output membership functions was computed for all combinations of inputs as $Mean_{OUT} = 0.1701Mean_E + 0.378Mean_{IE}$
4. Output of type-1 fuzzy controller was computed with height defuzzification

This steps leads to type-1 fuzzy controller equivalent of PI controller. This is also type-2 fuzzy controller equivalent with one mean value according to (3). Next we designed type-2 fuzzy controller:

1. We determined again universes for error (-1.5,1.5) and integral for error (-0.15,0.15).
2. Intervals were covered with 7 type-1 membership functions; standard deviation was 0.5 for error and 0.05 for standard deviation. Delta about mean value for error was set as ± 0.65 and delta about mean value for integral of error was set to ± 0.065
3. Mean of output membership functions was computed for all combinations of inputs as $Mean_{OUT} = 0.1701Mean_E + 0.378Mean_{IE}$ without deltas. Intervals for output membership functions were set with deltas after this computation with delta set to ± 0.2
4. Output of type-2 fuzzy controller was type-reduced and defuzzification as in (8) and (9).

To prove that out controller were equivalent we have made simulation without TrueTime network. Type-2 fuzzy logic controller was equivalent to PI controller without uncertainties and also with our uncertainties around mean values as you can see in the next figure.

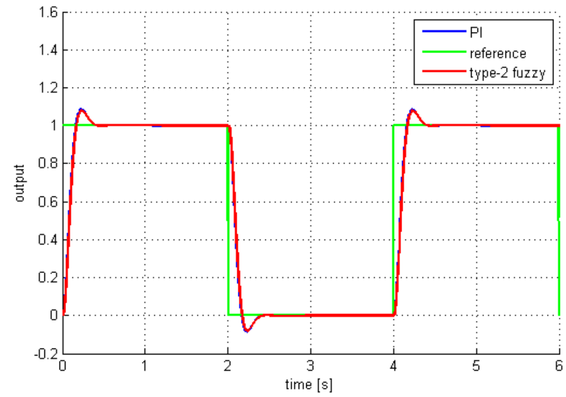

Fig. 7 Equivalency test

VI. Simulation Results

With simulation schema on figure 6 we did three experiments to compare PI controller and type-2 fuzzy controller performance within networked control system. All three settings can influence network or control system properties. For evaluation of the performance we have used three steps (in 0s, 2s and 4s) and focused on network overshoot (η) and settling time (t_{reg} – 2.5% error band) for each of the steps. We have also evaluated performance indices IAE and ITAE for whole simulation defined as

$$IAE = \int_0^t |e(t)| dt \quad (12)$$

$$ITAE = \int_0^t t|e(t)| dt \quad (13)$$

A. Sampling period

In networked control system sensors usually sample process values in periodic times. Different sampling times are suitable for different dynamics of systems. Usually more samples lead to much better control of the system. This is not always productive for networked control systems. Many sampling values can overload network communication. This could lead to network delays that could affect stability of whole system. In our first simulation we changed sampling periods against simulation of the figure 7 from 0.005s to 0.00285 and you can see results on the next figure.

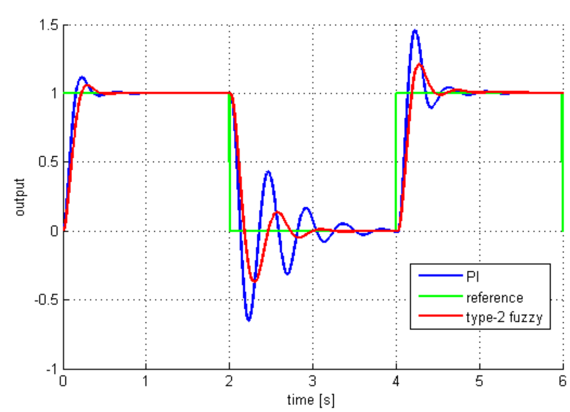

Fig. 8 System with 0.00285s sampling time

Many samples overloaded network therefor oscillations occurred. PI controller couldn't deal with this situation. On the other side type-2 fuzzy logic controller could suppress situation on the network with half of the overshoot and faster settling time also. Performance indices were also better for type-2 fuzzy logic controller as you can see in table 1.

Tab.1 Comparison of controllers – sampling time

		PI controller	Type-2 fuzzy
Step1	η (%)	11.7	5.8
	t_{reg} (s)	0.331	0.380
Step 2	η (%)	65.4	36.7
	t_{reg} (s)	3.634	2.924
Step 3	η (%)	45.9	20.9
	t_{reg} (s)	4.705	4.436
Performance	IAE	0.7152	0.5829
	ITAE	1.8476	1.4070

B. Node numbers

There would be no reason for networked control if we want to control one system over network. Multiple systems are interconnected through network nodes. Just like with sampling period more nodes can overload network communication, especially with some network protocols. We added multiple network nodes with different sampling periods. This caused that more than one node wanted to transmit data at the same time at some point of simulation.

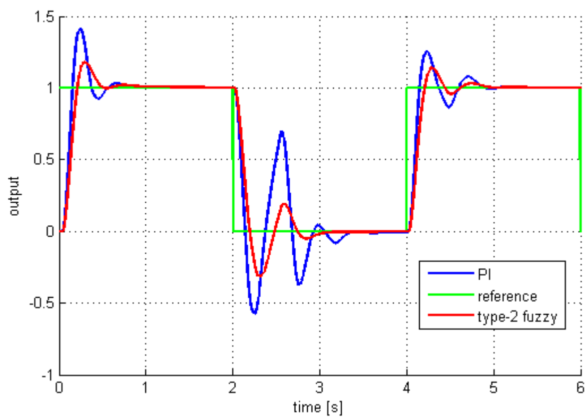

Fig. 9 System with 14 nodes

When multiple nodes wanted to transmit at the same time protocol had to decided which node could send his data. Network was overloaded again. Controller or sensor had to waited for free network therefor oscillations occurred again. Performance of type-2 fuzzy logic controller was also better as in first simulation. You can find evaluation of the simulation parameters in table 2.

Tab.2 Comparison of controllers – nodes

		PI controller	Type-2 fuzzy
Step1	η (%)	41.3	17.9
	t_{reg} (s)	0.72	0.461
Step 2	η (%)	70.3	31.3
	t_{reg} (s)	3.3	2.96
Step 3	η (%)	25.2	14.2
	t_{reg} (s)	4.83	4.82
Performance	IAE	0.7601	0.6079
	ITAE	1.6974	1.2888

C. Packet dropout

With long distance between nodes some information could lose. In wireless networks signal loss and disturbance can occur often. When packet is lost retransmission of data is possible when the sampling period is not too small. Many times last received sample is used again for computation. Next figure show simulation of packet dropout without retry limit.

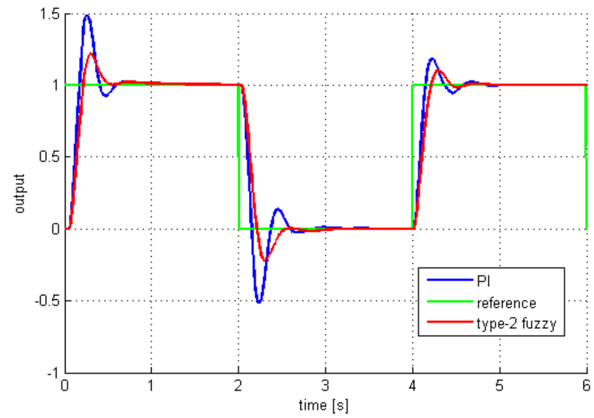

Fig. 10 System with 15% packet dropout

Fast sampling period caused that network control system could deal with small percentage of packet dropouts. For higher packet dropout performance of system degrades. PI controller showed bigger overshoots than type-2 fuzzy controller and settling time was also better. You can find evaluation of the simulation parameters for packet dropouts in table 3.

Tab.3 Comparison of controllers – dropout

		PI controller	Type-2 fuzzy
Step1	η (%)	48.7	21.7
	t_{reg} (s)	0.556	0.471
Step 2	η (%)	51.6	22.1
	t_{reg} (s)	2.568	2.485
Step 3	η (%)	18.1	10.1
	t_{reg} (s)	4.532	4.413
Performance	IAE	0.5844	0.5505
	ITAE	1.0990	1.0697

VII. Conclusion

Recently, the progress in network technology over the past decade is bringing an advancing trend to control system, where communication networks replace point-to-point cables. This paper has introduced the fundamental characteristics of NCSs and communication network ZigBee.

In Matlab environment using TrueTime tool we simulated control loop with PI and type-2 fuzzy controller. Our goal was comparing performance of designed control systems. We focused on three problems of NCSs that are sampling period, network overload and packet dropout.

With PI controller each of this three issues decrease quality of control. In this case system had oscillating character. With type-2 fuzzy controller system also decrease control performance but compared to PI controller we obtained less overshoot and faster settle time. It is because type-2 fuzzy controller works with our issues as uncertainties.

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