MANET–Issues and their Effects on Control Applications

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Abstract

This article presents a case-study on the utilization of the Mobile Ad-Hoc Networks (MANETs) relying on the IEEE 802.15.4 protocol in control applications. The effects of the: a) adopted routing protocol of the network, b) number of communication nodes, c) network geographical topology, d) latency time, and e) the loss of packets and packet reordering, on the stability and performance of a prototype control process is investigated. Furthermore, the multi-hopping capabilities of these MANETs suffer in the case where a large number of nodes are operational, triggering a deterioration in the system's performance. Extensive simulation studies indicate a need to adaptively adjust the gains of the used static controller caused by the packet-latency variations and the excessive packet losses.

1 Introduction

The areas of MANETs [1–5] and WiNCS have received considerable attention in recent years. From a control application point of view the need to exchange information through a wireless communication channel implies time varying delays in the control loop that can affect the performance of the closed loop system and even drive it to instability [6–8]. The characteristics of the communication channel therefore play an important role in the modelling procedure of the controlled system and in the selection of an appropriate controller.

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WiNCS [9, 10] operating under a MANET infrastructure is a rapidly evolving technological area. Recent technological advances have resulted in small, integrated sensing devices, capable of running a complete protocol stack. These devices have been optimized for communication with limited resources (transmission power, memory, no support for floating point calculations). The ease of deploying networks using such sensor nodes, the low prices and the small size of the nodes have made such networks very popular. Thus embedded sensor networks have found support from a number of companies and new communication standards have been developed to support them, like the 802.15.4 [11] and the encapsulating ZigBee Alliance [12].

WiNCS in general and Wireless Mesh Networks (WMN) in particular pose additional problems for the control designer, caused by the mobility of the nodes, which often leads to structural changes in the topology of the network.

In the research effort reported in this paper the main objective is to utilize the technology and the characteristics of a WMN network based on the IEEE 802.15.4 protocol in order to construct and study a client–centric control application. In the standard Client-Server WiNCS [13, 14] architecture, shown in Figure 1, the client computes the control command $u(t)$ and transmits it via a wireless link to a server. The server receives the data–packet after a certain delay Δ_L^1, transfers it to the plant $G(s)$, samples the plant's output $y(t)$ and transmits the measurement back to the client through the same sensor network. The client receives the output after some more delay Δ_L^2 and repeats the process. The main difficulty with the design of such a control loop is the presence of the sensing and actuation delays introduced by the communication network. Unlike in conventional time delay systems, the delays introduced by the network are time varying [15, 16], since they depend on the current traffic on the network. For wireless communication channels, the problem is further compli-

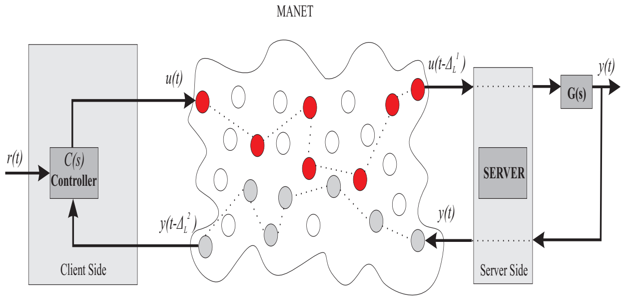

Figure 1. Client–Server Architecture based on a WMN-topology

cated by the mobility of the nodes, which induces structural changes in the routing. Subsequently the number of hops that are deemed necessary for the packets originating from one node to reach the other end varies significantly over time. These changes will be reflected by the jumping–nature of the delay introduced by the network.

In control applications where static controllers are encountered in the feedback path, the utilization of the MANETs as the communication structure between the process and the controller deteriorates the performance and reduces the stability margins of the system. In these cases the advantages offered by the MANET–deployment procedures and the decreasing of the costs should be counterbalanced with the resulting performance of the system.

The effects from the utilization of MANETs under various topological and traffic load conditions, over the IEEE standard 802.15.4 protocol, in feedback loops with classical static controllers, is the main scope of this article.

This research effort is presented in the ensuing structure. In Section 2 the characteristics of the IEEE 802.15.4–based MANETs are presented while in Section 3 the effects of the utilization of MANETs in control applications are presented and coupled with the stability issues examined via the the LMI theory. In Section 4 simulation results are presented from the application of various MANETs architectures to a typical control application. Finally in the last Section 5 the conclusions are drawn.

2 802.15.4–based MANETs

MANETs are networks that operate without a fixed infrastructure. They are characterized by a collection of mobile nodes, that communicate over wireless links. Their key–features are located at the rapid deployment of the network, the node's autonomy and the dynamical topology. Such a network exhibits stochastic behavior, and due to its distributed philosophy, the nodes ought to have self–adaptation to traffic and mobility patterns abilities. Moreover, due to the lack of a centralized topology the nodes ought to have self–healing properties [17, 18].

It is obvious that the design and control of such networks is a complex issue. The challenges are numerous and primary located at the correspondence of the aforementioned MANET characteristics. The power–constraints introduces energy–related considerations in the design of distributed, robust protocols that ensure the reliable data transmission over a wireless link, with a completely decentralized philosophy. Furthermore, in a topology where the network diameter exceeds the node's transmission range, the design of routing policies that operate on a multi–hopping basis [19] and can effectively react on the randomly generated alterations in the nodes geographical position, is essential.

2.1 IEEE LR–WPAN

The IEEE 802.15.4 communication protocol [11] is a novel standard dedicated to Low–Rate Wireless Personal Area Networks (LR–WPAN). A LR–WPAN is a communication network that allows wireless connectivity among nodes with limited power capabilities and relaxed throughput requirements. Such a network targets to ease in installation, low–cost, reliable data transfer, and short–range operation. The basic component of a 802.15.4 link is the Device. In the 802.15.4 link two types of Devices are met; Full–Function Devices (FFD) and Reduced–Function Devices (RFD). A FFD can operate as a *PAN Coordinator*, or as a *Coordinator* or simply as a Device. On the other hand, a RFD is implemented in extremely simple applications, in cases where the recourses and the memory capacity are required to be minimal.

The 802.15.4 LR–WPAN can operate at two network topologies, depending on the application; the star, and the peer–to–peer topology. In the former case, the PAN coordinator is the central controlled responsible for the initialization, termination or route communication around the network. The remaining nodes (FFDs or RFDs) have an associated application, and are the initial or the terminal point of a data exchange. In a peer–to–peer topology, the communication philosophy becomes completely distributed. Each node can communicate with each other within its coverage area. The existence of a PAN coordinator remains as a requirement, but its responsibilities are limited to processes, such as to be the first node transferring data over the link.

Peer–to–peer topologies are met in complex networks formations. Such an architecture combines all the features of a MANET; self–organizing, ad–hoc and self–healing properties.

The IEEE Standard for LR–WPAN covers the lower levels, including the Physical Layer (PHY) and the Medium Access Control (MAC) Sub-Layer of the OSI model. The PHY Layer is responsible for the interaction between the physical radio channel and the MAC Sub–Layer. The data transmission/reception is carried out with modulation and spreading techniques, which are differentiated for each one the three ISM bands. The MAC Sub–Layer utilizes the typical for the IEEE com-

patible wireless–link case Carrier Sense Multiple Access with Collision Avoidance (CSMA\CA) protocol. However, due to the low–rates for the data transmission, the 802.15.4 does not adopt the Clear–to–Send/Request–to–Send (CTS/RTS) handshaking signals. Finally with the establishment of two operational modes, namely *non–beacon* and *beacon* the standard provides a unique opportunity of utilizing Guaranteed Time Slots for the communication between in a Device and the Coordinator where needed.
The performance evaluation outlined in [20] verifies the efficiency of the non–enabled beacon mode IEEE 802.15.4 compared with the classical IEEE 802.11, in terms of overhead and power consumption, while it yields a low hop average delay. In the beacon enabled case the IEEE LR–WPAN can accomplish various MANETs requirements, such as link failure self–recovery and low duty cycle.

2.2 Dynamic Source Routing

The Dynamic Source Routing (DSR) protocol [21] is a reactive routing protocol; its "on–demand" behavior contributes to the alleviation from the routing overhead packets presented in proactive routing algorithms, while allows the automatic scaling of the routing overhead according to the changes of the network topology. Its key feature that distinguishes it from the other reactive routing policies for MANETs is the utilization of source routing; the sender knows the complete hop–by–hop route to the destination. The source route is carried in the packet header of each packet. The DSR utilizes the Route Discovery mechanism for destinations that the routing path is undefined. Moreover, a mechanism for the detection of broken or damaged links, is also supported. Other important features met in DSR are *salvaging*, *gratuitous route repair* and *promiscuous listening*. Referring to salvaging, with DSR routing policies, an intermediate node can use an alternate route from its own cache when a data packet meets a damaged link on its source route. With the gratuitous route repair mechanism a source node receiving a Route Error packet forwards the error information to the Route Request packets. The result is the effective cleaning up of the route caches of the intermediate nodes in the network that may keep stored the failed link. Finally, the promiscuous listening permits to each node overhearing a packet not addressed to itself, examine whether has a more optimal route to the destination. If so, that node transmits a *gratuitous* Route Reply to the source node, with the new optimal route.

2.3 Ad-hoc On-demand Distance Vector

Ad–hoc On–demand Distance Vector (AODV) [22] is a combination of Dynamic Source Routing (DSR) and Destination Sequence Distance Vector (DSDV) [23] routing policies. It operates on demand like the DSR, but borrows the hop–by–hop routing and sequence number utilized in the proactive DSDV algorithm. AODV has been proposed for best–effort routing in mobile ad–hoc networks [24]. The basic mechanism of the AODV policy is summarized in Figure 2. The state created in each node along the path

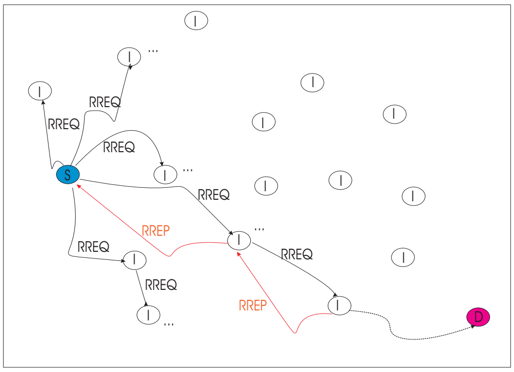

Figure 2. Routing Mechanism based on AODV

is a hop–by–hop state. In this framework each node remembers only the next hop and not the entire route. For the maintenance of a route, this routing policy utilizes the routing tables; for each destination there exists only one entry. Another important feature of AODV is that it exploits timer–based states in each node; if a routing table entry that is not used within a specific time period expires and is discarded from the routing table.

2.4 AODV Versus DSR

AODV and DSR share similar policies for the discovery of a path. Moreover, their on–demand philosophy is advantageous for networks with dynamical topology and power constraints. Thus, are quite often preferred from the proactive routing algorithms, like DSDV, as the latter wastes too much wireless resources, especially for large, highly–mobile networks. However, AODV and DSR have many essential differences focused on the routing mechanism, that affect differently on the overall network's performance outlined analytically in [25]. In general DSR due to source routing and promiscuous listening introduces less routing overhead. However, the impression gained from the aforementioned contribution is that DSR behaves better in environments with small number of nodes, low traffic load and limited observed mobility. On the other hand, AODV outperforms in more competitive, "crowded" networks, in terms of traffic and mobility. In [26, 27] it is claimed that the above differences in performance, are a consequence of the differing impact of mobility on the mechanisms of these protocols, while a framework for a systematic evaluation of the aforementioned impact on MANET routing protocols is presented.

2.5 Wireless–NCS Simulation

The network scenarios are tested with the NS–2 [28] simulator for the physical, MAC and network layers of

Table 1. Simulation Parameters

Network Characteristics	Values
Simulation Time (sec)	800
Number of nodes (N)	20–60
Number of Active Connections (L)	25
Maximum N_O of Packets Transmitted per Connection	10000
UDP Packet Size (B)	8
UDP Transmission Interval per Connection(sec) (T_S)	0.1–2
Maximum Speed per Node (m/sec)	20
Coverage Area ($M \times M$)	50x50–500x500
Agent Type	UDP
Routing Protocol	AODV

each node. In order to evaluate the performance of a MANET–type network, the NS–2 is extended for the IEEE LR–WPAN Standard case [29]. Providing a variety of networking protocols, several scenarios can be simulated, based on the cases examined.

The parameters that have been utilized for our test case are outlined in Table 1. In this case study a number of nodes N move randomly in a square area $M \times M$ meters. At each instant L–connections are active; each node of these connections attempts to transmit every T_s a short packet of KB using UDP and AODV as its routing protocol. In control applications the number of bytes is small (i.e. 8 bytes), while the sampling period is desired to be as small as possible. In our case T_s is fixed with its value between 0.1 and 2 seconds. The coverage area of each node is 50 meters, while several cases are examined w.r.t the topology of the network ($M = 50 \ldots 500$) and the number of nodes present in this topology ($N = 20, 60$).

In this research effort we are interested in a noisy, mobile ad–hoc wireless network, focusing on the relationship between the transmission delay of a UDP frame that is produced from the multi–hoping mechanisms of the network and the characteristics of the route that the latter follows until it reaches it destination.

Due to the nodes' mobility, routing is not fixed. Therefore, the number of hops, and consequently the delay during the transmission of a packet alters as the node moves from one position to another. Moreover due to the connectionless services provided by the transport layer, other interesting phenomena are also observed; for example a packet that fails to reach its destination or an intermediate node, may be dropped or sent back to its source node. The retroactivity mentioned above as a UDP characteristic, is becoming even more dominant as delay factor as the network conditions become more congested. Some of the observed events are described in the cases that are presented in Figure 3.

After the simulation of a variety of scenarios simulated, certain observations are inferred relating the network's performance to the: a) number of nodes, b) traffic load, and c) topology area. The metrics utilized in the present work are the round–trip delay and the ratio of the successfully received packets. In Figures 4 and 5 the results of the MANET scenarios simulated are outlined.

The recorded results indicate the mean value of round–trip delay $d = \Delta_L^1 + \Delta_L^2$ and received packets successful ratio R for light (UDP Transmission Interval per Connection equal to 2 sec) and heavy (UDP Transmission Interval

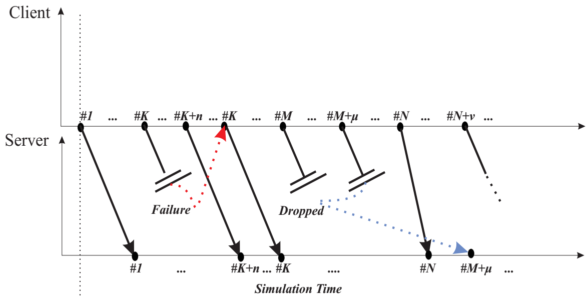

Figure 3. Phenomena observed during a UDP Data Transmission from Client to Server

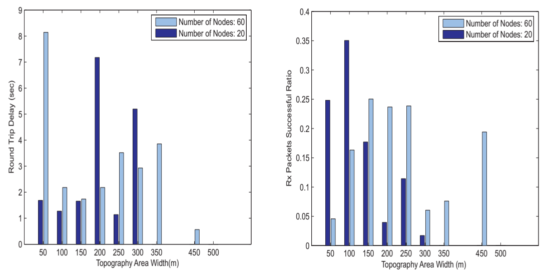

Figure 4. d, R (mean value) for Congested Traffic Conditions ($T_s = 0.1sec$)

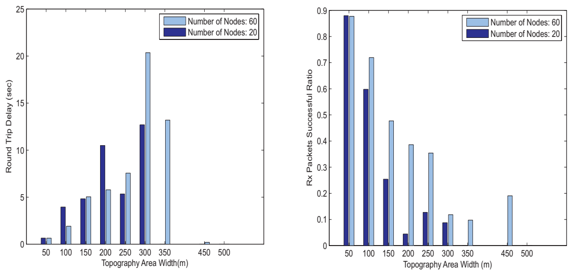

Figure 5. d, R (mean value) for Light Traffic Conditions ($T_s = 2sec$)

per Connection equal to 0.1 sec) traffic conditions *only* for the node–pair of our interest.

It is obvious that in the case of light traffic conditions, as the number of nodes N increases, this results in an improvement of R, and d for small geographical areas only, verifying that with the aforementioned increase the multi–hopping routing policy acts more efficient. In middle–sized areas (200m–300m area width), there exist no clear conclusions for the round–trip delay and for wider geographical areas (>300m), the reception of even a small amount of information in the case of 60 nodes/network compared to the nilpotent ratio of the 20 nodes–case is quite advantageous.

When the traffic load becomes heavier and the number of nodes is increased, the congested conditions in small areas are not alleviated. However, the amount of information successfully received becomes more significant as the area widens, and the number of nodes increases.

Comparing the traffic conditions for the scenarios simulated, the heavy–loaded case is more demanding in terms of effective routing and buffer capacity than the light–loaded one. Therefore the round–trip delay becomes smaller as the traffic load increases; the routers prefer to forward those packets that they have a route available, and not to keep in their routing buffers packets for which a new route needs to be discover. However, the overall ratio R remains more significant in the case of light–traffic networks.

3 MANET–Control Related Issues

Consider a discrete time MANET in a zero–latency environment, with a transfer function given by:

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ y(k) &= Cx(k) \; . \end{aligned} \tag{1}$$

Let the control loop be formed via the utilization of a static feedback controller of the form $u(k) = Ky(k)$. Upon computation of this controller the resulting closed–loop system has its poles in eig$(A + BKC)$.

However in a Wi–NCS, the actual case corresponds to inserting delays in the loop, as shown in Figure 6. These delays are time–varying and depend on the behavior of the wireless communication channel and the protocols that are used. In this time–delayed case, unlike the anticipated control command $u(k) = KCx(k)$, the actual applied one is delayed and given by:

$$u(k) = K_{r_s} C x(k - r_s(k)), \tag{2}$$

where we assume that the overall delay is time varying, since $r_s(k)$ is a random bounded sequence of integers $r_s(k) \in [0, 1, \ldots, D]$, and D is the upper bound of the delay term.

The closed–loop system, where $r(k) = 0$, is formed by augmenting the state vector to $\tilde{x}(k)$, in order to include all the delayed terms, as

$$\tilde{x} = [x(k)^T, x(k-1)^T \ldots x(k-D)^T]^T \; .$$

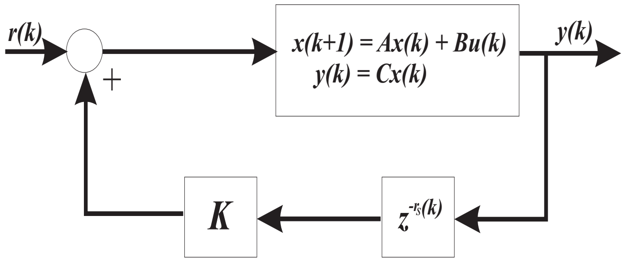

Figure 6. MANET–based equivalent controlled system structure

The dynamics of the open–loop system, at time k, with the augmented state vector take the following form

$$\begin{aligned} \tilde{x}(k+1) &= \tilde{A}\tilde{x}(k) + \tilde{B}u(k) \\ y(k) &= \tilde{C}_{r_s}(k)\tilde{x}(k) \; , \quad \text{where} \end{aligned}$$

$$\begin{aligned} \tilde{A} &= \begin{bmatrix} A & 0 & \ldots & & 0 \\ I & 0 & \ldots & 0 & 0 \\ 0 & I & \ldots & 0 & 0 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 0 & 0 & \ldots & I & 0 \end{bmatrix}, \; \hat{B} = \begin{bmatrix} B \\ 0 \\ 0 \\ \vdots \\ 0 \end{bmatrix}, \\ \tilde{C}_{r_s}(k) &= \begin{bmatrix} 0 & \ldots & 0 & I & 0 & \ldots & 0 \end{bmatrix} , \end{aligned} \tag{3}$$

where the vector $\tilde{C}_{r_s}(k)$ has its elements zeroed, except from the $r_s(k)$–th one whose value corresponds to the unitary matrix.

The closed–loop system is switched [30, 31], since the $r_s(k)$ (and thus the feedback term $K_{r_s}(k)C$) is of time–varying nature. The dynamics of the overall closed loop system are described from:

$$\tilde{x}(k+1) = \tilde{A} + \tilde{B}K_{r_s(k)}\tilde{C}_{r_s(k)}\tilde{x}(k) + \tilde{B}r(k) \; , \tag{4}$$

$$y(k) = \tilde{C}_{r_s}(k)\tilde{x}(k) \tag{5}$$

The closed loop matrix $\tilde{A} + \tilde{B}\; K_{r_s}(k)\; \tilde{C}_{r_s}(k)$ can switch in any of the $D+1$–vertices $A_i = \tilde{A} + \tilde{B}\; K_i\; \tilde{C}_i$, and therefore conditions are sought for the stabilization of the switched system

$$\tilde{x}(k+1) = A_i\tilde{x}(k), \; i = 0, \ldots, D.$$

Under the assumption that at every time instance k the bounds of the latency time $r_s(k)$ can be measured, and therefore the index of the switched–state is known, the system can be described as:

$$x(k+1) = \sum_{i=0}^{D} \xi_i(k) A_i x(k) \; , \tag{6}$$

where $\xi(k) = [\xi_0(k), \ldots, \xi_D(k)]^T$ and $\xi = \{^{1,\text{mode}=A_i}_{0,\text{mode}\neq A_i}$.

The stability of the switched system [32], in (6) is ensured if $D+1$ positive definite matrices $P_i,\ i=0,\ldots,D$ can be found that satisfy the following LMI:

$$\begin{bmatrix} P_i & A_i^T P_j \\ P_j A_i & P_j \end{bmatrix} > 0, \forall (i,j) \in I \times I, \quad (7)$$
$$P_i > 0, \forall i \in I = \{0,1,\ldots,D\} \quad (8)$$

Based on these P_i–matrices, it is feasible to calculate a positive Lyapunov function of the form $V(k,x(k)) = x(k)^T(\sum_{i=0}^{D} \xi_i(k) P_i)x(k)$ whose difference $\Delta V(k,x(k)) = V(k+1,x(k+1)) - V(k,x(k)))$ is negative for all the $x(k)$–solutions of the switched system, thus ensuring the asymptotic stability of the system.

Henceforth, in a MANET–based controlled system the computation of a feedback controller (equation 2) that preserves stability against the recorded latency times can be tested. Under the assumption of a stable closed–loop system, a gain adaptation mechanism is desired to address the performance issue.

In is article, the focus is on the preservation of stability, against the packet–latency time variations and the extensive packet losses, that are inserted.

4 MANET–based Controlled System Performance

The suggested scheme was applied in a simulated prototype SISO-system with the following transfer function $G(s) = \frac{10^3}{(s+10)^3}$. Assuming a sampling period of $T_s = 1$ second, the discrete equivalent of the continuous system is (accounting for the ZOH)

$$\begin{aligned} x(k+1) &= \begin{bmatrix} 0.001 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix} x(k) + \\ &+ \begin{bmatrix} 1 \\ 0 \\ 0 \end{bmatrix} u(k) \\ y(k) &= \begin{bmatrix} 0.9972 & 0.0026 & 0.000 \end{bmatrix} x(k) \end{aligned}$$

Assume that a discrete and delayed controller $u(k) = K\ y(k - r_s(k))$ is inserted in the loop. From the LMI theory a feedback controller is computed to ensure the stability against delays of 25 seconds. This maximum value (25 sec) was selected on an ad–hoc basis by observing the typical latency time patterns, on a MANET–structure with 20 or 60 operational nodes. The resulting controller had a gain of $K = -0.1$, while the reference input corresponds to a step input.

For the examined case we assume that all the network's nodes "wake up" at the same time instant. The network is restricted in a square area of $50 \times 50m$. While in our test cases each node can exchange information with each other, only two nodes are of our interest; the node that describes the functionality of the plant (server) and the one that controls the remote plant (client). The utilized routing protocol is the Ad–hoc On Demand Distance Vector (AODV) [22], while in transport layer the information exchange is based on User Datagram Protocol (UDP).

In Figure 7 we present the varying latency times in the case where 60 nodes have been utilized while in Figure 8 we present the system's response which is compared with the response obtained from the zero–latency case.

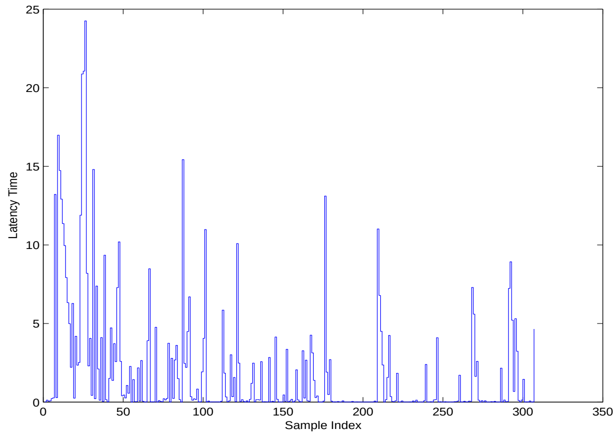

Figure 7. Closed loop latency time (60–nodes case)

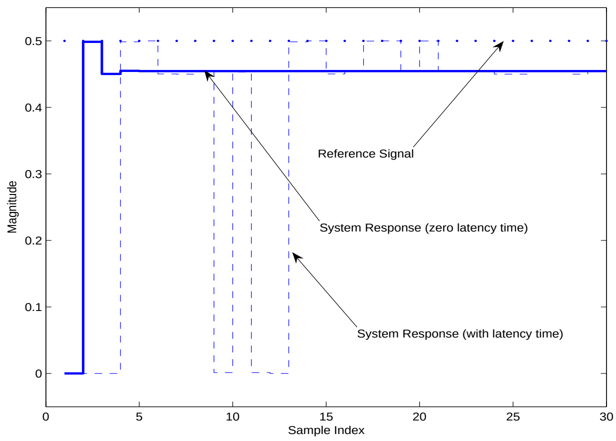

Figure 8. Effect of delay in System Response (60–nodes case)

In Figures 9 and 10 we present again the latency times and the system response (latency and zero–latency case) for the case where 20 nodes have been utilized.

In both simulation results, the inserted delays from the network are degrading the performance of the controlled system and push the later to instability. The number of nodes directly affects the performance as an increase in the number of the nodes results in an increase in the latency time and the data–packets losses. In the case of the 60–nodes the mean delay time is 1.8172sec while in

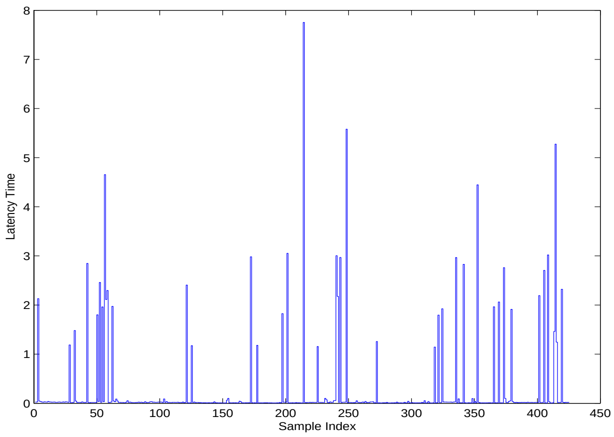

Figure 9. Closed loop latency time (20–nodes case)

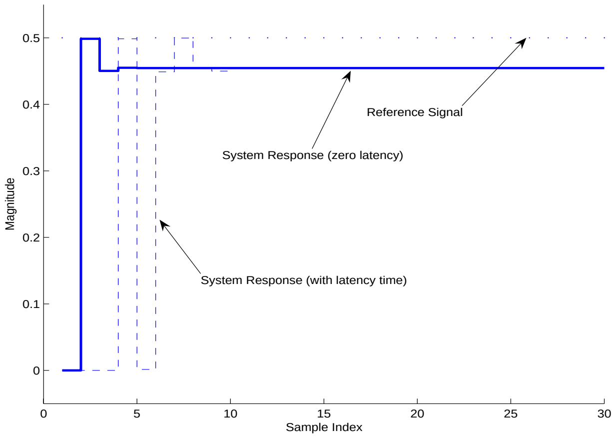

Figure 10. Effect of delay in System Response (20–nodes case)

the case of 20–nodes the mean delay time was 0.295sec. Moreover the maximum latency time that was observed was 24.2527 (7.7536)sec in the case of 60 (20) nodes.

The effect of the geographical span of the nodes is intense as for the studied case the geographical bounds combined with the frequency of the traffic generation, result in highly congested network conditions. Therefore, the increase of the number of the nodes participating in the network results in an increase in latency times, and consequently in degradation of the controlled system's performance.

5 Conclusions

In this article a case–study on the utilization of the MANETs relying on the IEEE 802.15.4 protocol in control applications has been presented. The usage of MANETs in cases where systems are controlled with static feedback, result in degradation of the system's performance while pushing the overall controlled system close to instability. In these cases gain scheduling approaches based on LMI–criteria, that satisfy the stability of the controlled system over certain delays, should be employed. Simulation results have been presented to cover this case study.

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