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Overview of Wireless Networked Control Systems over Mobile Ad-hoc Network

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***Abstract*—Wireless Networked Control Systems (WNCS), specially, WNCS over Mobile Ad-hoc Network (MANET) have become an interesting area in research community. However, designing a successful WNCS over MANET brings new challenges to the researchers. The motivations of this paper are to identify the design issues, highlighting recent researches for the issues, to establish guidelines for successful implementation of WNCS over MANET. The paper also reviews some simulation tools for such systems.**

Keywords- Wireless Networked Control Systems (WNCS), Mobile Ad-hoc Network (MANET), Optimised Network Engineering Tool (OPNET), Network Simulator Version 2 (NS2), TrueTime.

I. INTRODUCTION

Networked Control Systems (NCS) are now being implemented over wireless networks because of the need for node mobility in many applications. These systems are known as Wireless Networked Control Systems (WNCS). The simplest WNCS includes a plant and a controller with point to point wireless communication between them [1], [2], [3]. An advanced version of WNCS applies the control mechanism over multi-hop Mobile Ad-hoc Networks (MANET) that are self-organising and can be easily deployed without any infrastructure [4]. Furthermore, it can recover or re-configure after failure. WNCS over MANET can be applied in many applications, for instance, military use, rescue operation, assembling space structures, exploring hazardous environment, executing tele-surgery [5], test bed engine monitoring, online aircraft monitoring [6], entertainment, e.g., robot playing games, mobile robots working in a factory plant etc.

However, designing a successful WNCS over MANET brings new challenges to the researchers because of MANET's unpredictable aspects such as topology change, node mobility, delay, jitter etc. Many of these are responsible for performance degradation and even system instability [7], [8]. The motivations of this paper are to identify the design issues, highlighting recent researches for the issues and to establish guidelines for successful implementation of WNCS over MANET. The paper also reviews some simulation tools for such systems. The rest of the paper is organised as follows; section II focuses on co-design problem and recent works, sections III, IV and V and discuss the design issues, section VI highlights co-simulation tools. Finally section VII draws conclusions and points to some future works.

II. RELEVANT WORKS AND WNCS CO-DESIGN PROBLEM

Research papers such as [9], [10], [11], [12], [1], [13] etc. present a brief survey and discussion of design issues for NCS. Various design issues, such as network packet delay and drop, control tasks scheduling and optimisation etc. are discussed in [11]. Several problems, for instance, security, energy supply, signal path loss, transceiver operation mode etc. are explored in [14] for implementation of wireless networks in industrial applications.Co-design approaches, e.g., hard/soft real time systems, tools, e.g., trueTime, jitterbug etc., future research directions of control and task scheduling co-design problem have been highlighted in [1]. Simple models of the fundamental network on design issues of NCS such as network delay packet, drops etc. can be found in [9], [15], [13]. The importance of control and real time task scheduling co-design is explored in [16]. The effect of sampling period, communication delay, jitter, scheduling, blocking of real time tasks on the performance have been investigated in [17]. An integrated model based on NCS and congestion control has been proposed in [5]. Its major limitations are that it models packet drop only from sensor to controller and neglects network delays. A network delay compensation technique using buffer at the actuator and state estimator at the controller is discussed in [18]. Depending on the actual total delay an appropriate control is applied to the plant from the buffer. The investigation of WNCS performance for the inverted pendulum and tracking problem can be found in [2], [3], [19] etc. Paper [19] implemented Rayleigh fading in the simulation to have a realistic wireless signal propagation model with time driven sampling and event driven control-actuation. A co-simulation of control and network, implemented in MATLAB/SIMULINK, is presented in [6] which investigated NCS performance for various data rates, traffic, loads etc. Two Matlab-Simulink based toolboxes: Jitterbug to analyse delay-jitter impact and TrueTime to analyse control-task scheduling impact are discussed in [20] and [21]. An investigation of network delay for WNCS over MANET has been carried out in [22], [23]. The interface for co-simulation between MATLAB and OPNET has been considered in [24], [25], [26]. WNCS over MANET needs careful co-design of the three C fields: Communication, Control and Computing. In the following sections, the design issues are organised in the three areas.

III. Design issues: Communication network

The design issues from the area of communication network are discussed in the following sub-sections.

A. Wireless Communication Standards

1) IEEE 802.11

Most WNCS researches are based on mainly IEEE 802.11 standards and support data rates 1, 2, 11, 54 Mbps. IEEE 802.11 uses Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) as Medium Access Control (MAC) protocol [27]. However, contention based protocols, e.g., CSMA/CA, are not appropriate for real time communication as they require handshaking among the nodes [28] and do not guarantee bounded packet delay.

2) IEEE 802.15.4/ZigBee

The theme of 802.15 standards is to support short distances (less than 10m). It offers two versions. High Rate-WPAN (802.15.3) supports high data rate and quality-of-Service (QoS) constraints for multimedia applications and suitable for ad hoc mode. Low Rate-WPAN (802.15.4) offers low cost and low power consumption in ad hoc mode but low data rate and relaxed performance requirements. Supported data rates are 250, 40 and 20 Kbps [27].

3) IEEE 802.15.1/Bluetooth

Bluetooth offers low cost and low power requirement with a high degree of versatility. It has been used in some industrial applications such as sensor devices for monitoring, driver hands-free calling etc. [27].

B. Packet delay

Network packet delay can degrade the NCS performance significantly and even destabilise the entire system [5], [6], [29], [18], [30]. The total closed loop delay τ_{total} is given in (1) where τ_{sc} is sensor-to-controller, τ_c is controller computation and τ_{ca} is controller-to-actuator delay, respectively.

$$\tau = \tau_{sc} + \tau_c + \tau_{ca} \tag{1}$$

For simplicity, the controller delay τ_c is ignored or treated as a part of the controller-to-actuator delay since it is negligible and almost constant compared to the delays τ_{sc} and τ_{ca} [9], [2]. Therefore the total delay can be obtained by (2) [29], [15].

$$\tau \approx \tau_{sc} + \tau_{ca} \tag{2}$$

Control mechanisms based on constant time delay are not suitable for NCS, since network delay is usually time varying [29]. When τ is less than the sampling period T, the stability condition of the NCS can be found by computing the upper bound of delay between any two successive sensor messages [15], [31]. On the other hand, when τ is larger than the sampling period, some delay compensation technique must be employed. Various delay compensation techniques can be found in [32], [30], [18]. Networks with constant and independent delays have been developed in [32]. Controller design with constant and random time delay have been discussed in [30].

C. Packet drop/loss

Wireless networks can suffer from packet drop/loss that can cause instability of the NCS. Re-transmission will generate obsolete packets and it will simply produce more traffic in the network. As NCS carries real-time traffic; it might be beneficial to drop a packet that can not be transmitted immediately. The tolerable packet drop rate must be analysed to maintain guaranteed desired system stability [15]. NCS with packet drop can be modelled as two-state switch θ, where $\theta \in \{0,1\}$ is called *receiving sequence* that indicates reception ($\theta=1$) or loss ($\theta=0$). If the current state of the plant is missing because of the packet drop, the previous state buffered at the controller is used. Therefore, the dynamical model can be expressed by (3) [5]. Modern NCS can tolerate packet drop up to some extent and can still maintain stability [3], [15]. Modelling of NCS with packet drop can be found in [18], [5], [13] etc.

$$\begin{aligned} x(k+1) &= Ax(k) + Bu(k) \\ \bar{x}(k) &= \theta_{sc} x(k) + (1-\theta_{sc})\bar{x}(k-1) \end{aligned} \tag{3}$$

D. MANET routing protocol

Routing protocol determines how routes are established in wireless network and can be classified into the two following main categories.

1) Proactive protocols

A proactive protocol keeps up-to-date routing table by constantly requesting update information and sharing routing tables. The disadvantage of this strategy is that it produces huge traffic in the network [11]. Destination Sequenced Distance Vector routing (DSDV) [33] is an example of proactive protocol for ad hoc networks.

2) Reactive (on demand) protocols

Reactive protocol attempts to establish a route when a node wishes to send a packet and there is no valid route in the route table. Routes are maintained until the destination becomes unreachable or the route is no longer required. The advantage is that less traffic is generated in the network. However, they have the disadvantages such as there is a delay in sending the packet and existing routes can become invalid without the node being made aware of it [11]. Ad hoc On-demand Distance Vector (AODV) [34] and Dynamic Source Routing (DSR) [35] are the examples of reactive protocol.

E. End to end connection type

Communication over wireless network can be performed using either *Transmission Control Protocol (TCP)* or *User Datagram Protocol (UDP)*. TCP/IP is not suitable for MANET as it uses connection oriented packet transfer [36]. On the other hand, UDP offers low overheads as it does not maintain connections and discards obsolete or lost packets. Therefore, it is preferable for networked control applications [3].

F. Delay jitter

In general, jitter is defined as deviation of an instant in the signal from its actual position in time or standard deviation of the measured delays of network packet. This problem can be caused by some or all of the following: clock drift of a transmitter-receiver, congestion, routing algorithm in communication systems, scheduling of real-time tasks in computer systems, number of hops on the path etc. [10], [37], [38]. It can be expressed by (4) where u_i is the time between *i*-th and (*i+1*)-th packet arrival and v_i is the time between *i*-th and (*i+1*)-th packet departure. In this case, negative jitter represent clustering of packets that can cause buffer overflow and positive jitter correspond to dispersion of packets that can cause excessive delay [39].

$$\varepsilon_i = v_i - u_i, \forall i \quad (4)$$

The motive of delay jitter control is to ensure that the packet delays are kept between predefined maximum and minimum delays and to minimise the difference between packet delays [10], [40]. This problem can be easily removed by using buffers at the receiver [39]. Besides buffers, delay jitter problem can also be minimised or avoided by synchronising the NCS plant and controller nodes periodically [15].

G. MANET model

MANET simulation study presents mainly two challenges: radio signal propagation and node mobility models [36].

1) Radio signal propagation model

Simpler propagation models assume symmetric wireless links, independence from ground height etc. that might produce impractical results. Furthermore, simulation of the same network in different simulation packages might produce different results. This can be explained by the physical layer considered in the package [36]. Simulation works on wireless networks usually consider the following three signal propagation models.

- Ideal or free space model: The transmission range is treated as a complete circle with the transmitter at the centre [41].
- Path loss or two-ray-ground reflection model: The transmission area is considered a complete circle but the radius depends on the medium type, environment, e.g., open field etc. [41].
- Path loss-fading or shadowing model: It considers the path loss model and treats the reception at the boundary as statistical behaviour [41].

A comparison between computer simulation and real world wireless network experiments [42], [43], [44] revealed that the *shadowing model* exhibited the closest behaviour to the real world experiment [42].

2) Node mobility model

This difference in movement can produce misleading results [36]. For movement, *random way-point model* can be used. In this model, nodes move from one point to another random point at a constant speed chosen from a specified range. It then waits at the new point for some time and then another random destination point is chosen. This movement model provides continuous node movement so that MANET routing algorithms can be evaluated [43], [44].

H. Security

Wireless networks inherently suffer from security problems as signals are broadcast to all receivers. Two types of security issues can be identified.

1) Signal integrity

The concern of signal integrity comes from the interference from other radio transmitters. This problem can be crucial for IEEE 802.11 and Bluetooth technology as they both use the unlicensed ISM 2.4 GHz band. However, the spread spectrum techniques implemented by the standards can mitigate the interference in most cases [27].

2) Authentication

As radio signals can be received by all nearby receivers, unauthorised users can exploit the resources of WNCS. The IEEE 802.11 standard offers a WLAN authentication mechanism called Wired Equivalent Privacy (WEP) from the MAC layer. However, the security provided is not adequate. On the other hand, current Bluetooth technology specifies security in link layer and application developers have to choose the required security method. Again, Bluetooth security is not strong enough to exchange sensitive data [27].

IV. Design Issues: Computing

Today's almost all NCS controllers are executed as one or more real time tasks in a distributed computing environment [8]. The following sections explore the issues that are crucial for smart combination of computer and control tasks for WNCS.

A. Control task scheduling algorithm

The computer must ensure that the control tasks are scheduled in an efficient way to improve the overall system performance [16]. Some frequently used real time task scheduling algorithms are discussed below.

1) Fixed Priority (FP)

A fixed priority is assigned to each task before execution and the policy is pre-emptive [45]. It is the most common scheduling strategy and widely used in commercial real time operating systems [16]. However, this scheduling policy generates irregular delay patterns and the CPU is not utilised properly [16], [8], [45].

2) Rate Monotonic (RM)

Task is assigned priority based on its period. Shorter period tasks have higher priorities and it is pre-emptive [45], [46]. Rate Monotonic scheduling is optimal in the sense that if there exists any static priority assignment algorithm that satisfies the deadlines of a task set, then RM also satisfies the deadlines of that task set [16], [46].

3) Earliest Deadline First (EDF)

Tasks are prioritised based on their deadline and task with the earliest deadline is assigned the highest priority [16]. The priorities are dynamic and task period can vary [47]. If it is possible to schedule a task set using pre-emption then EDF generated schedule will also meet the deadlines of the task set [48].

FP and RM are considered to be static and EDF is a dynamic strategy. Upper bound of processor utilisation for hard real time pre-emptive tasks and the rule for optimum FP scheduling can be found in [45] . The task model also assumes that they are independent, periodic with fixed priorities and fixed execution time. On the other hand, dynamic schemes can achieve full utilisation by assigning priorities based on their current deadlines [45].

B. Control task invocation method

Tasks at plant and at the controller sites are generally invoked in the following ways.

- Clock/time driven: The task is initiated at predefined time instants [32], [18]. Generally, sampling is clock or time driven.
- Event driven: The task is invoked when an event occurs, for instance, when an information packet is received from another node through the network [32], [1], [18]. In general, control and actuation tasks are event driven.
- Clock-Event driven: In some cases, actuators can receive control packet on events and then refresh the signals during sampling time [18].

Clock driven sensing and event driven control-actuation are found in many applications. Clock-driven sampling and an event-driven control-actuation approach have several advantages, for instance, they do not require plant-controller synchronisation, supports multi-rate sampling [2], [3] and power efficient [49].

C. Sampling jitter

The inconsistency of sampling period is called rate/sampling jitter [32]. It is also defined as the difference between the maximum and minimum sampling latencies in all tasks using (5) where L_s is the sampling latency [1]. Sampling jitter can be caused when controller tasks are scheduled based on priority or tasks have non-pre-emptive characteristics [7]. Sampling jitter compensation approaches for control applications can be found in [50].

$$J_s \stackrel{\text{def}}{=} \max_k L_s^k - \min_k L_s^k. \quad (5)$$

D. Power management

Power saving solutions can be put into two categories. Short term solutions consider saving power by optimising physical layer and MAC protocol. On the other hand long term solution attempt to devise low power mode and power saving scheduling / routing / transmission [27].

1) IEEE 802.11

Devices can save power by entering *doze mode*. In this mode, devices suspend all radio activities and wake up periodically to exchange information with other nodes. However, this mode increases the response time of the devices [27].

2) Bluetooth

Devices stop receiving as soon as they find that the packet is destined to another device or receiving signal power is very low. Hence, a device that that is not addressed a valid packet remains active 10% of the time. Bluetooth also offers three power saving modes: *hold*, *sniff* and *park* [27].

V. DESIGN ISSUES: CONTROL

The controller must be chosen properly so that it can take advantage of the network and application type. The following sections the issues from the control area.

A. Sampling period

Typical values can range from hundreds of microseconds to hundreds of milliseconds [27]. One of the rules for choosing sampling period T is given in (6) where ω is the natural frequency of the closed loop system [32], [8].

$$0.2 \leq \omega * T \leq 0.6 \quad (6)$$

Higher sampling rate improves the performance of an NCS [12]. But it increases computational overhead and generates excessive traffic into the network [10]. A trade-off study of sampling period and network traffic can be found in [51].

B. Plant type

Some plants, e.g., temperature control systems are open loop stable and can be categorised as soft real time systems. Such systems suffer only from reduced performance due to delays and remain stable as long as the delay magnitude is not excessively large. On the other hand, open loop instable plants, e.g., inverted pendulum on a cart, are more difficult to control. Such systems are hard real time systems and must execute with a certain deadline. The effect of delay on the performance varies from one system to another [6].

VI. CO-SIMULATION TOOLS

Some co-simulation tools are discussed in the following sections.

A. Optimised Network Engineering Tool (OPNET)

OPNET offers a comprehensive discrete event simulation for different types of network; from LAN to satellite networks. OPNET supports mainly three levels of modelling: network, node and process. OPNET models can be compiled into executable code that can be debugged or simply executed to generate output data [52]. The *terrain modelling module* (TMM) can be used to observe the impact of various environment, e.g., open field, obstacles etc.

B. Network simulator version 2 (NS2)

NS2 [41], [53] is a discrete event network simulator that supports different types of protocols and has support for Ad-Hoc Wireless Network. For analysis purposes, NS2 produces a *trace file* containing individual packet details such as, source node, transmission time, packet size, destination node, received time etc. It can also create a *nam file* for simulation animation. NCS has been implemented as an extension over NS2 that simulates the NCS plant and the controller [54].

C. Truetime

TrueTime [1], [17], [21] is a Matlab-SIMULINK based toolbox that allows performance evaluation of multitasking real time kernel executing various tasks with network support. TrueTime includes support for both wired and wireless (IEEE 802.11b/g, IEEE 802.15.4) network protocols. However, the network blocks have limited support for MANET. Simulation of WNCS using TrueTime can be found in paper [20].

VII. Conclusion

In ad-hoc systems, strict guarantee for topology, delay etc. are not practical. Therefore, a smart integration of communication network, computing and control is required for quality performance of WNCS. This paper presented the network, control and computing co-design issues and discussed co-simulation tools for WNCS. NCS over MANET is a thriving area of research. The following ideas can be used as guidelines for future works.

- Online co-simulation using MATLAB for control/computing and NS2/OPNET for communication networks.
- Investigating the impact of the environment, e.g., experimental area, node movement model etc. on the performance of WNCS.
- Development of co-design theory and co-simulation tools for control, computing and communication.
- Developing deterministic communication protocol to guarantee bounded packet delay.
- Devising security protocols for WNCS.
- Currently, Bluetooth technology is getting popularity among the people using mobile devices. A WNCS using Bluetooth can be suitable for a small area such as an office room.

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