Modeling, Analysis and Control of Multi-hop Control Networks*

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Today embedded systems span all aspects of everyday life, from automotive to avionics systems, from white goods to consumer electronics. The architecture of embedded systems has changed over the years as technological advances made it possible to integrate increasingly complex subsystems. In particular, it has become possible to coordinate multi-agent systems performing a common or distributed task, delivering a global emerging behavior. As an example Unmanned Autonomous Vehicles (UAVs) are increasingly used in defense applications, where they are called to fulfill missions that require close collaboration. Monitoring the environment, energy efficient buildings, and industrial plants is today possible with a possibly large number of sensors distributed over a wide region. In these applications, communication is a fundamental feature. Given the task they are called upon to perform and the physical locations where they are deployed, wireless communication is an essential enabling feature. Possibly the most advanced application of networked embedded systems is control. Industrial plant control and autonomous driving in freeways are typical examples of distributed control. Systems in which sensors, actuators and computing elements are connected by means of a shared (wired or wireless) network are commonly indicated as Networked Control Systems (NCSs).

In Section 1, we provide an overview on the state of the art on NCSs explaining how our work is related to it. We first focus on the current research on this emerging class of control systems where different communication constraints are taken into account, including transmission delays, unreliable communication links, limited bandwidth, scheduling, routing and multi-hop wireless communication. Then, in Section 2, we illustrate and motivate the adoption of multi-hop wireless networks in NCSs. Finally, in Section 3, we illustrate the contributions of our line research on modeling, analysis and control of Multi-hop Control Networks, which are based on the scientific publications [3, 16, 39, 4, 15].

* This contribution is an introduction to the line of research developed in the attached collection of the papers [3], [16], [39], [4], [15]. The co-authors of these papers are R. Alur, M.D. Di Benedetto, Alf J. Isaksson, K.H. Johansson, G.J. Pappas, E. Serra, G. Weiss.
1 Networked Control Systems

The interest drawn in recent years around the research area of NCSs is mainly due to development of embedded and networked technologies. Embedded systems are computer systems designed to perform dedicated functions, often with real-time computing constraints. They are embedded as part of a complete device often including hardware and mechanical parts. The last achievements in the field of micro electronics is pushing towards the direction of having embedded systems span all aspects of modern life and there are many examples of their use. Seamlessly, the spreading of these embedded devices in different environments of both social and working life, and the fact that they enclose communication functionalities, has produced the foundations for the development of swarms of networks de facto that consist of embedded systems.

The resulting blend between embedded control devices and communication networks gives birth to a new category of control system where sensors, actuators and computing elements are connected by means of a shared network as shown in Figure 1. In fact, the exploitation of communication networks to collect data from distributed sensor or supply control commands to distributed actuators, expand the control capabilities of both the single actors and of the whole network, enabling new control specifications and requiring novel control constraints. For example, the temperature control features of a building can be broaden by exploiting the temperature sensors embedded in the majority of the common handheld devices owned by the people working in the offices. The data collected by these devices can be used to close the control loop also in uncovered regions where sensors are not available, improving the temperature control of the entire building.

Fig. 1. Abstraction of a networked control system.
Obviously, the interaction of these embedded control devices through networks is characterized by Pros and Cons. Some of the Cons are quite intuitive and are related to intrinsic problems of the communication networks, due both to sharing of hardware and software resources and to mobility of the network agents (e.g. security aspects, limited bandwidth, delays and power efficiency). Some other Cons are related to the network characteristics, but are less intuitive since they are inherent to the topology of the network and to the communication protocol adopted (e.g. coordination and cooperation of a crowd of network actors to achieve a common control task or to perform data fusion).

Classical control theory provides theoretical results to predict behavior and performance of a complex system that consists of the interconnection of simple systems. However these theoretical results are applicable only if it is possible to regard the interconnection as ideal, in the sense that it neither corrupts nor delays data. The development of new communication technologies in control systems has made the assumption of ideal interconnection difficult to justify. The very technologies that enable a wide employment of NCSs impose communication constraints and affect the dynamics of the closed loop networked system. The communication protocol and the operating system of the computer on which control is implemented influence the design of both control and communication policies.

For these reasons the research on NCSs has been intensified recently, see for example [43], [36], [7], [21] and references therein for a general overview. [19] is a recent survey providing a compendium on NCSs and last research trends in the field. The survey focuses on different fields and research arenas including both control over network and control of network. In particular, in research field of control over network, the main issues addressed are:

- network delay and packet drops;
- bandwidth allocation and scheduling;
- fault tolerant control;
- network security;
- component integration.

In [17] a collection of basic results on the control of systems that operate under communication constraints is illustrated. The literature on robust stability of networked control systems (see e.g. [24], [14], [29]) generally addresses stability analysis in the presence of packet loss and variable delays.

In [20] the authors state that the network-induced imperfections and constraints can be categorized in five types:

1. quantization errors in the signals transmitted over the network due to the finite word length of the packets;
2. packet dropouts caused by the unreliability of the network;
3. variable sampling/transmission intervals;
4. variable communication delays;
5. communication constraints caused by the sharing of the network by multiple nodes and the fact that only one node is allowed to transmit its packet per transmission.
According to the authors, much of the available literature on NCSs considers only some of above mentioned types of network phenomena, ignoring the other types. There are, for instance, systematic approaches that analyze stability of NCSs subject to only one of these network-induced imperfections. In [20], the authors develop a novel NCS model incorporating network-induced imperfections of type 3, 4 and 5. Then they present allowable bounds on delays and transmission intervals guaranteeing both stability and performance of the NCS. When relating our work with the current research about the interaction of control networks and communication protocols, most efforts in the literature focus on scheduling message and sampling time assignment for sensors/actuators and controllers interconnected by wired common-bus networks, e.g. [9], [37], [42], [32], [33]. The authors in [41] use model predictive control to stabilize a plant over a multi-hop control network, by only considering the delay introduced by the routing policy.

However, in our opinion, what is needed for modeling and analyzing control protocols on multi-hop control networks is an integrated framework for analysing/co-designing network topology, scheduling, routing, transmission power and control. These aspect have been considered in [6], where a simulative environment of computer nodes and communication networks interacting with the continuous-time dynamics of the real world is presented.

To the best of our knowledge, the first attempt to formally model multi-hop wireless sensor and actuator control networks has been presented in [3, 4].

2 Multi-Hop Networks

Wireless communication is emerging in control applications with main advantages being reduced installation costs and increased flexibility, as well as ease of maintenance, debugging and diagnostics. However, wireless devices are usually battery powered: for this reason, energy efficiency and power minimization is a fundamental issue to be addressed. Control with wireless technologies typically involves multiple communication hops for conveying information from wireless sensor devices to a controller, and from the controller to wireless actuator devices. The challenges in designing and analyzing multi-hop Wireless Control Networks (WCNs) are best explained by considering the recently developed WirelessHART [2], [30] and ISA-100 [1] specifications. These standards allow designers of WCNs to define a communication schedule to all nodes of the network, in order to orchestrate conveyance of sensing information to the controller and of control information to the actuators. In a multi-hop wireless network, there are one or more intermediate nodes along the path that receive and forward packets via wireless links. Multi-hop wireless networks have several benefits [13]:

- compared to single-hop networks (single wireless links), multi-hop wireless networks can extend the coverage of a network and improve connectivity;
- transmission over multiple short links might require less transmission power and energy than that required over long links;
- they enable higher data rates resulting in higher throughput and more efficient use of the wireless medium;
they avoid wide deployment of cables and their use increases the cost-efficiency of the network;

in case of dense multi-hop networks, several paths might become available increasing robustness of the network (possibility of multi-path by data flooding).

Beyond these advantages, there are exist real control applications where the benefits carried out by multi-hop networks are evident. One of these applications is that of control of green buildings.

Buildings consume significant amount of energy: in fact residential and commercial buildings account for approximately 20% of world energy use. In smart buildings, Wireless (and Wired) Sensor and Actuator Networks (WSANs) determine the observable and controllable variables available to the building manager and need to be systematically designed, located and monitored to achieve effective control, diagnosis and reliability at low installation and maintenance costs. Wireless multi-hop networks plays a dual role in the realization of such intelligent buildings since, if sideways they introduce some problems in the design, on the other side they offer an amazing palette of possibilities to the designer. Control algorithms for applications such as fire detection, temperature control, distributed control of air flow in buildings, place several challenges to network design. When wireless sensor networks are deployed, guaranteeing network robustness and reliable communication at reduced power consumption and maintenance costs has become a major concern.

3 Technical Contributions

In this section we illustrate the line of research we started with the papers [3, 4], which addresses the problem of characterizing the effect of multi-hop communication networks in the analysis and control of NCSs.

In the paper [3] we propose a formal model for analyzing the joint dynamics induced in a Multi-hop Control Network by network topology, scheduling, routing, transmission errors and control. Our model allows systematic mathematical design techniques such as sensitivity and compositional analysis, and is related to the growing research body on switched system (see e.g. [35, 23]). We show that a multi-hop control network can be abstracted as a switched system. While generic approaches that ignore the specific structure of the switched system are applicable, we provide a detailed model that identifies the contribution of specific constituents to the dynamics. For example, the elaborated model allows us to apply the approach proposed in [38, 5] for analyzing each control loop separately in a compositional manner. Our model incorporates wireless industrial control protocols, such as WirelessHART and ISA 100, and can be used to co-design control and scheduling. We develop an experimental tool and show that it is possible to resolve design parameters of a controller by representing the dynamics of a multi-hop control network symbolically.
While in the model proposed in [3] perfect communication links are assumed and the focus is on scheduling. In the paper [39] we assume fixed schedules and focus on modeling and analyzing the effects of link failures on the stability of the control loops. We analyze fault tolerance of multi-hop control networks, by proposing a formal model and an analysis tool for verifying stability of the closed loop system in the presence of link failures. We first consider communication errors whose duration is long compared to the speed of the control system, and propose to model them as permanent link failures. We show that the complexity of analyzing such failures is NP-hard, and discuss a way to overcome this limitation using compositional analysis. Then we consider typical packet transmission errors, where links fail for one time slot independently of the past and of other links, and we propose a transient error model. We provide a sufficient condition for stability with probability one in presence of transient link failures, and show how it can be used in typical scenarios. We finally consider failures that have random time span. We identify conditions that allow to reduce the verification of almost sure stability of such systems to the verification of high probability of exponential stability of systems with permanent failures. We focus on practical tools that can scale to large and complex systems. In particular, we analyze the computational complexity of checking the sufficient conditions and propose ways to cope with these complexities be means of over-approximations and compositional analysis. Relating our approach for addressing link failures, we remark that we model multi-hop control systems as switched systems where link failures induce random switching signals. For this reason the theory of Discrete-Time Markov Jump Linear Systems (see e.g. [34]) applies. In particular any sufficient condition for almost sure stability can be used as a sufficient condition for stability of multi-hop control systems. The difference between our results and the general conditions developed in the literature (e.g. [12, 18, 40, 28, 31, 27, 8]) is that we use the specific structure of the switched systems that arises when multi-hop control networks are modeled. Also, our focus is on conditions that can be efficiently checked under assumptions that are reasonable in relevant applications (wireless sensor/actuator networks). Another line of research that is related to our work is complexity analysis of control problems (see e.g. [25, 11]). We establish a new NP-hardness result and discuss ways to walk around computational complexities using compositional analysis and over-approximations.

In the paper [16] we describe how the translation of multi-hop control networks to switched systems can be automated and use it to solve control and networking co-design challenges in some representative examples. In particular, we show that our model allows compositional analysis. We address the problem of designing scalable scheduling and routing policies when closing a considerable number of control loops on the same communication network, and propose an approach based on task-graph abstraction [26, 22, 10]. The main difference between our work and other studies of task-graph abstractions is that we focus on finding the set of all schedules that satisfy the task-graph constraints as a basis for further analysis, while most of the research is focused on finding individual optimal schedules (see e.g. [26]). We apply methods developed in [38, 5] and pro-
pose a scheduling solution in a mineral floatation control problem that can be implemented on a time triggered communication protocol for wireless networks.

In the paper [4] we collect in a unifying framework the contributions of the papers [3, 16, 39].

In the recent paper [15], starting from the mathematical framework developed in [3], we address the novel issue of characterizing controllability and observability of a continuous-time SISO LTI plant embedded in a Multi-hop Control Network that implements scheduling and routing protocols, and where failures of communication links may occur. We motivate the exploitation of redundancy in data communication (i.e. sending sensing and actuation data through multiple paths) with the aim of rendering the system robust with respect to link failures (e.g. when the battery of a node discharges or a communication channel goes down), and to mitigate the effect of packet losses (e.g. transmission errors). We extend the model in [3] to model redundancy, by defining a weight function that specifies how the duplicate information transmitted through the multi-hop network is merged, and by defining a semantics of the redundant data flow through the network. We remark that the differences introduced with respect to the model in [3] do not invalidate compositionality of the framework. As a first result, given a Multi-hop Control Network, we state necessary and sufficient controllability and observability conditions on the plant dynamics and on the scheduling and routing of the communication network. As a second result, given a Multi-hop Control Network and a set of failures configurations of the communication nodes, we state necessary and sufficient conditions on the plant dynamics, on the scheduling and routing of the communication network, and on the set of failures configurations, such that there exists a scheduling and routing configuration that guarantees reachability and observability conditions of the Multi-hop Control Network for each failures configuration. Since we adopt a constructive proof, we provide a methodology to configure scheduling and routing of a Multi-hop Control Network, in order to satisfy controllability and observability of the closed loop system for any fault occurrence in a given set of failures configurations.

References