Work in Progress: Systematic Derivation of Accurate Analytic Markov Channel Models for Industrial Control

Amal Alrish, Yuriy Zacchia Lun†, Alessandro D'Innocenzo, Fortunato Santucci

Department of Information Engineering, Computer Science and Mathematics
University of L'Aquila, L'Aquila, Italy
amal.alrish@graduate.univaq.it, {alessandro.dinnocenzo;fortunato.santucci}@univaq.it

†*IMT School for Advanced Studies Lucca*, Lucca, Italy
yuriy.zacchialun@imtlucca.it

***Abstract*—The motivation of this work is to systematically derive an accurate Markov channel model suitable to represent any industrial communication protocol. This model accounts for both channel and control dynamics. Our analytic model is derived by taking into account multiple interferers and physical phenomena characterizing a communication link. Our finite-state Markov channel model matches both average packet error probability and worst case bursty behavior of the accurate analytic model of the channel.**

***Index Terms*—WNCS, Markov channel, WirelessHART, MJLS**

I. Introduction

Wireless networked control systems (WNCSs) are receiving ever growing attention from both researchers and practitioners thanks to the introduction and wide spreading of the concepts of the IoT (Internet of things) and 5G (fifth generation of cellular mobile communications). Typical WNCSs consist of sensors, actuators and computational units that communicate over shared wireless channels [1]. These channels are prone to time varying fading and interference which may affect the control performance of the system. This deficiency makes it challenging for WNCSs to meet the stringent reliable and low latency constraints of industrial control applications especially in the case of multi-hop communication over mesh networks. Packet loss, varying transmission delays and sampling intervals are some of the imperfections which lead to unreliable communication and might cause even instability [2]. The design of WNCSs is a challenging task since it must take into account these imperfections by integrating wireless networks models and control algorithms thus implementing the cyber-physical co-design approach [3]. The lack of analytic methods for achieving real-time performance in WNCSs hinders their adoption in control systems [3]. Our work aims to fill this gap by deriving an accurate analytic communication channel model accounting for the aforementioned imperfections. As a first step of our work we focused on packet losses. In WNCSs literature, the packet dropouts have been modeled either as deterministic and stochastic models [4]. The proposed deterministic models specify packet losses in terms of time averages or in terms of worst case bounds on the number of consecutive dropouts (see e.g. [2]). For what concern the stochastic models, in wireless networked control community most of analytic results are derived under the assumption that packet losses are realization of Bernoulli process. In this model the probability of packet loss event is given by the expected value of the packet error rate (PER) associated to the communication channel. However, Bernoulli model is not well suitable to model the stochastic properties of the packet error bursts, since it neglects higher order statistics of the process governing packet losses. The works on WNCSs that account for the bursty behavior normally use finite state stationary Markov jump linear systems (MJLSs, see [5]–[7]), where a transition probability matrix (TPM) of a stationary Markov chain is used to describe the stochastic process that rules packet dropouts. However, all these later works except [7] tackle the problem of the stationary continuous state estimation, so they assume the instantaneous availability of the jump variable. This assumption does not hold for the networked control problem, where the operational modes are observed by controller via acknowledgments. Since the actual success of the transmission is not known in advance, these acknowledgments are only available after the current decision on the control gain to apply. The remaining work [7] solves the problem of the optimal linear quadratic regulation of MJLSs with one time-step delayed mode observations, but does not consider the aspects of stabilizability of the controlled system in the presented setting. As a final remark, it is worth noting that the cyber-physical systems co-design approach is difficult to apply directly in this context since on one hand, none of the MJLS models used in WNCS literature consider explicitly the characteristics of the communication channel in deriving their Markov chains, while on the other hand, to the best of our knowledge, also the number of Markov channel

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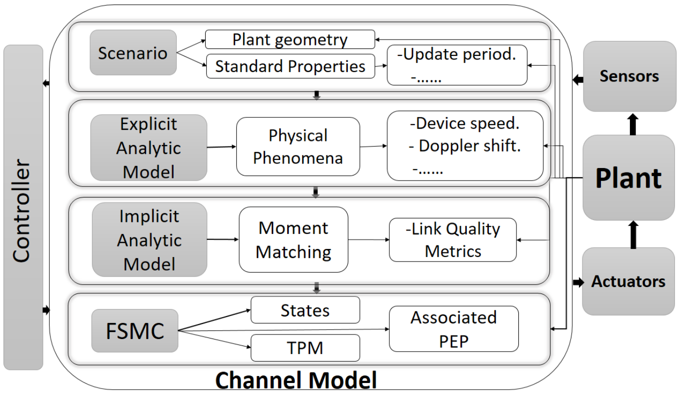

Fig. 1. The block diagram of the channel model in a WNCS

models that take into account the physical characteristics of the channel is still limited. Moreover, the related works assume just some of the physical phenomena which affect the signal transmitted in the channel (i.e. only a small subset of path loss, shadow fading, multipath fading, interference and power residual control is considered).

In our work, we are aiming at addressing this gap by deriving an accurate and analytic model of the communication channel used in industrial control applications that accounts for the listed physical phenomena. Such a model would better represent the channel statistics and help to improve the overall system performance. We already got some preliminary results on this topic. In particular, we developed a finite-state stationary Markov channel model of a WirelessHART channel subject to a persistent interference from a neighboring network. We also defined some general performance metrics that are useful to evaluate and validate the finite-state model of an analytic communication channel.

The rest of the paper is organized as follows: in Section II we describe the scenario, explicit and implicit analytic model for a generic interfered control protocol system, and present some general performance metrics useful to evaluate and validate the finite-state Markov channel model which is derived in Section III. Finally in Section IV we draw conclusions and outline our future plans.

II. The model for an interfered control protocol system

Figure 1 illustrates the block diagram of the process that allows to derive the channel model subject to several physical phenomena due to various neighboring networks. It consists of the following steps/blocks.

A. Scenario

The first step in developing an accurate model of the wireless link consists in a thorough analysis of the communication scenario to be considered. The challenges in analysis and co-design of WNCSs are best explained by considering wireless industrial control protocols. WirelessHART and ISA-100 standards have been used widely for control and monitoring applications adopted in the previous years [8]. As a running example, in this paper we will use the WirelessHART since we already obtained some interesting results for this protocol. WirelessHART is a networking protocol specifically developed for wireless industrial automation [9], [10]. This protocol is based on the physical layer of IEEE 802.15.4-2006 [11] and on a dedicated data link layer that defines a medium access control protocol combining frequency hopping with a time-division multiple access scheme utilizing a centralized a-priori slot allocation mechanism. Since most of the physical systems evolve in a continuous time but are often governed by discrete controllers, it's crucial to transfer to the discrete domain by sampling the dynamics of the system. The samples should be taken in a particular time instants. The update rate, which is how often we may measure the system's variables through sensors and send control commands to actuators, should be proportional to the sampling rate chosen according to the dynamics of the system. However, WirelessHART has limitation on the update rate. WirelessHART uses Publish data messages [10, p. 248] in order to convey the control system data, where the update period is 0.1 s. The smaller is the update rate, the more stringent constraints we have on receiving packets via WirelessHART link. Thus, the update rate is a joint parameter that needs to be set carefully in order to meet both channel and control dynamics' requirements. A realistic scenario in industrial environment must handle the impact of other networks presence at the same ambient, where multiple transmitters and multiple receivers are taken into account. Therefore, one receiver might or might not have one or more interferers depending on the standard and the application. Thus, an accurate analytic model should account for multiple interferers aside from physical phenomena characterizing a communication channel.

B. Explicit analytic model

The second step is to derive an explicit equation that represents the transmitted signal subject to different channel imperfections. In our work, transmitted signals are assumed to be affected by path loss, shadow fading, multipath fading, and interference. Path loss models are used to compute the decrease in the power of a radio signal as it propagates away from the transmitter. Many path loss models have been addressed in the literature such as free-space, two-ray model, simplified path loss model, empirical models etc. For instance, WirelessHART is based on IEEE 802.15.4-2006 standard, which for 2.4 GHz center frequency uses a two segments function with a path loss exponent of 2 for the first 8 m and then a path loss exponent of 3.3 thereafter. Shadow fading could be modeled in different ways. The most common model for random variations due to blockage from objects is log-normal shadowing [12], which has been investigated for indoor environments in [13], [14]. The shadowing correlation properties can be modeled as in [15]. They are described with correlation standard deviation, the typical decay distance, and the device speed. Therefore, the speed of the movement of the parts of the system will affect the channel model. Multipath fading occurs in any environment where there is a multipath propagation and the paths change for some reason. Multipath fading changes not only the strengths of involved signals but also their phases, as the path lengths change. Therefore, when the system (or any of its parts) is moving, its velocity causes a shift in the frequency of the signal transmitted along each signal path making the so called Doppler frequency. Thus, the Doppler frequency is also a collaborative parameter that affects both channel and control dynamics. We underline that in some industrial settings typical for WNCSs applications multipath fading is not an issue since highly absorbing environments often eliminate multipath propagation [16]. Thus, some channel models may neglect it. However, the general wireless channel model must take into account the multipath fading that can be modeled through Rician or Nakagami distribution based on the characteristics of the channel that interconnect the network. In addition, as the useful signal travels along a channel between its source and receiver, it might happen that unwanted signals, whether they are generated by devices using the same communication standard or by coexistence devices (i.e. using different standards), could be added to the useful signal and modify it in a disruptive manner. To address the case of coexistence devices one might use a CCA (clear channel assessment) mechanism, if available and appropriate. In particular, CCA provides an optional coexistence feature targeting other protocols and modulation standards, but it cannot address the case of users of different neighboring networks based on the same protocol. In such a case, even frequency hopping spread spectrum technique can not provide immunity to interference (due to a limited number of available channels). At any given instant, a channel occupied by the signal of interest may or may not be interfered by one or more neighboring devices belonging to other networks. The presence of devices which interfere a certain link can be modeled as a binary random process that represents their activity status (ON-OFF). This time-varying behavior is a distinctive characteristic of the channel affected by multiple intermittent interferences. Such behavior can be encompassed by the signal-to-interference-plus noise ratio (SINR), which is the power of a certain signal of interest divided by the sum of the interference power (from all the other interfering signals) and the power of some background noise. Typically, the bit error rate (BER) is a function of SINR, so following the basic characteristics of the underlying protocol (e.g. the frame length, modulation, symbol rate), SINR and PER could be derived as a function of their features. In particular, the PER is always a function of BER which is in turn a function of SINR. The relation between PER and BER depends on whether any forward error correction (FEC) method is implemented in a protocol or not. FEC improves the reliability by making the transmitter send redundant data which allows the receiver to recognize just the part of the data that contains no errors [17]. As a result, the receiver has the ability to detect a limited number of errors that may occur anywhere in the message, and often to correct these errors at the cost of a fixed, higher forward channel bandwidth. In the case of no FEC, even one erroneous bit leads to a corrupted data packet.

C. Implicit Analytic Model

The next step is to find a tractable representation of the explicit analytic model. To this aim, it's possible to approximate it with another random process, (e.g. log-normal process) and then apply moment matching approach to get the signal statistics. Thus, starting from the expression of SINR, in our case, and given the properties of the random process involved in it, SINR can be seen as a weighted sum of randomly correlated log-normal processes. Following the same reasoning as in [18], the mean, variance and autocovariance can be derived based on applying matching between the first and second order moments of SINR. It can be seen that PER and BER are continuous monotonically non increasing functions defined on the range of SINR. Thus we can derive also the stochastic characteristics of the PER. As a consequence, we obtain the stochastic characteristics of the channel that permit us to describe the inherit imperfections of the communication link by defining some important quality metrics such as the packet error probability (PEP), the PER's variance, and the maximum number of consecutive dropouts with non negligible probability of occurrence. In practical applications, the PER is considered negligible when it is smaller than a specified threshold which might be as small as the *machine epsilon*. Knowing this threshold with the stochastic characteristics of the channel, the highest number of consecutive packet losses can be derived. Therefore, the implicit analytic model of the protocol can be characterized by the outlined link quality metrics. These metrics should be compared with the link quality metrics of the finite-state abstractions of the analytic model, in order to validate those abstractions and provide guidelines on the choice of parameters defining the aforementioned abstractions. Practically, the analytic model of the channel is defined on continuous state-space. However, using a finite number of channel states can be more beneficial in several application scenarios (e.g. modeling channel error bursts, decoding in channels with memory, adaptive transmission). Such abstraction of the analytic model is depicted in the next section.

III. Markov Channel

This section describes the procedure to design a general finite-state Markov channel (FSMC, that is represented by the lower block of the channel model in Figure 1) explaining the behavior of the underlying protocol communication link. The suitability of FSMC model for the fading channel has been thoroughly discussed in the literature like in [19]. The binary symmetric channel is associated with each state of an ergodic and stationary discrete-time Markov chain [20] describing the temporal evolution of the fading wireless channel. However, as we have seen in the previous section, in the case of multiple intermittent interferers, the parameters of the analytic model are varying in time due to stochastic ON-OFF status of each interferer. Thus, also the Markov chain of the finite-state channel is time varying. In order to characterize each state of the Markov chain, the range to SINR is divided into several consecutive intervals. There are many ways of doing such a partitioning [21], and the communication channel is said to be in a state s_i of the Markov channel if the value of SINR is included in the interval between two related consecutive thresholds of SINR, that are defined by the choice of the partitioning method. These thresholds allow to compute the PER associated to the state. It is worth saying that in most of the cases we would like to minimize the number of states representing the channel. Based on link quality metrics (i.e. the expected value of the PER, the PER's variance, and the maximum number of consecutive dropouts) of the analytic channel, one could choose the most suitable partitioning method for any given number of states, since the link quality metrics can be computed also for the Markov channel abstraction. In particular, we can apply the method addressed in [22] to obtain the highest number of consecutive dropouts under the considered Markov channel with non negligible probability of occurrence. The maximum number of consecutive packet losses obtained from both the analytic channel model and the finite-state Markov channel must coincide in order to have the same worst case bursty behavior. The average lossy behavior of both previous models coincide by construction since they have the same average PER. As a consequence, the aforesaid abstraction of the analytic channel would be useful for solving networked control problems, e.g. stability. We already showed the importance of this model for the WNCSs by deriving, on the basis of our model, a stationary MJLS model closed over a WirelessHART link. We got some preliminary results showing that our modeling framework permits to design a controller that guarantees stability and improves control performance of the closed-loop system.

IV. CONCLUSION AND FUTURE PLANS

In this paper we described the late developments of our research on cyber-physical systems co-design for industrial applications. It considerably extends our previous results on advanced control over a WirelessHART network subject to interferences. Our goal is to finalize the accurate Markov channel model simultaneously accounting for path loss, shadow fading, multipath fading, interference and power residual control and test its applicability on different protocols. The presented framework may be useful for the emerging scenarios e.g. URLLC (ultra reliable and low latency communications).

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