A Theoretical Framework for Control over Wireless Networks

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***Abstract*— The main problem in control over wireless networks is conceiving a joint control algorithm and communication system design to optimize a given cost function. To solve this problem, we propose a theoretical framework derived from the Platform Based Design (PBD) methodology [19]. According to the PBD principles, we first map control specifications to communication network specifications involving a set of values of the communication parameters such as quantization noise, coding, modulation scheme, and power level. Then, a communication scheme is chosen according to the communications specifications so that the control specifications are satisfied. To do so, we use a hybrid system formalism that models the dynamical behavior of the communication scheme to capture the mixed continuous-discrete characteristics of the configuration parameters.**

***Keywords*— Control over wireless networks, Safety Specifications, Hybrid Systems, Platform Based Design.**

I. Introduction

While the design and operations of wireless networks have been addressed during the last two decades to support various communications services and applications, only recently there has been a growing interest in research on the interaction between control and wireless communication, e.g. [11], [20]. In particular, distributed control where the communication infrastructure is offered by wireless networks and the application of control methods for the energy efficient operation of wireless networks are two general topics of research interest. The problem of energy consumption within the modulation optimization problem for a wireless link was addressed with control tools in [5]. In [20], the authors identified a critical domain of error probabilities outside which the optimal controller fails to stabilize a distributed systems where sensor data and control commands are sent via a wireless channel. For the study of the performance of networked control systems, an interesting framework was proposed in [12] and [13]. In the analyzed case, feedback loops are, by assumption, closed over a shared network. In [12], tradeoffs between communication parameters, e.g., data rates and time delays, are illustrated. In [13] the authors compare the performance achieved by the use of different MAC protocols.

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In this paper, we develop a hybrid dynamical model for resource allocation over wireless links, with particular attention to wireless sensor and actuator networks used in control applications. We consider a basic feedback digital control scheme, where the controller and the plant exchange signals by means of a time-varying wireless link. We address the problem of *linear controller synthesis with safety specifications* that arises in many application domains such as automotive control, manufacturing systems, and air traffic management systems. Given a set of "good states" within which the system should evolve, this problem deals with finding the set of all initial states for which there exists a controller such that the closed–loop system never leaves the set. The design problem involves setting control structure and parameters so that the specifications are satisfied. To deal with these issues, we use the principles of Platform Based Design (PBD) (e.g. [19]). In particular, by applying the platform based design methodology, we break the original controller synthesis problem into two main steps:

- We design a controller for the plant to fulfill the specifications, without considering non—idealities due to wireless communication system;
- Then by following an assume-guarantee approach, we select communication system parameters so that the controller synthesized at the earlier step still works in the presence of non–idealities.

Under the mild assumption of asymptotic stabilizability of the plant, a solution to the safety problem is guaranteed to exist, provided that the communication system is capable of maintaining the "size" of the non—idealities bounded in a range given by the safety problem characteristics and by the dynamical properties of the plant. The bounds are obtained by mapping the control system specifications to specifications at the communication-system level. To maintain the operation of the communication scheme within these bounds, we propose an adaptive control approach for the communication channel.

The adaptive approach, in correspondence to a given choice of the parameters in the constraints, checks if the underlying wireless link setup (in terms of capacity and bit error rate) can satisfy the requirements of the control problem. In the case the link set up cannot satisfy the requirements, the supervisor forces the channel to switch to a different setup. Since, for a given bandwidth on the wireless link, a limited set of combinations are allowed, the supervisory design problem can be formulated as a *Hybrid System control problem* where a hybrid system model describes the operations of the feedback control scheme in correspondence of each discrete state (identified by the wireless link setup). The ultimate goal of this approach is to identify the characteristics of the overall feedback loop and to develop algorithms for concurrent design of the control laws and of the supervisor for the wireless channel.

The paper is organized as follows. In Section 2 we set the control scheme and wireless communication scheme. Section 3 illustrates the methodology to solve a safety problem via a wireless communication scheme. Section 4 proposes a hybrid model for characterizing protocol stack dynamic configuration and Section 5 offers some concluding remarks.

II. Safety Problem over Wireless Networks

Problems with safety specifications arise in many application domains such as automotive control, manufacturing systems, and air-traffic management systems. Given a plant P and a set of 'good states' within which the plant should evolve, this problem deals with finding the set of all initial states (known in the literature as the *maximal safe set [6]*) for which there exists a controller such that the closed–loop system never leaves the set. This control problem has been studied in the literature in the past few years both for continuous–time systems (see e.g. [14], [21]) and for discrete–time systems (see e.g. [1], [3], [22], [6]). More recently this problem has been addressed in [7] where the focus is on the particular class of *digital controllers*, and a first step towards the implementation of control algorithms embedded in electronic devices at the physical layer is provided.

In this paper, we consider problems with safety specifications with digital control and we suppose that the plant and the controller share information via a wireless channel. We assume that the communication channel is time–varying and that the controller and the plant may change their mutual position. Since the communication channel is time–varying, the controller is required to adapt its configuration so that the controlled plant satisfies the safety constraints in all possible channel states.

More formally, let P be the plant and C the controller. We assume that P is a continuous–time linear dynamical control system:

$$\begin{array}{l} \dot{x}(t) = Ax(t) + Bu(t) \\ x(t) \in \mathbb{R}^n, u(t) \in \mathbb{R}^m, t \geq 0. \end{array} \qquad (1)$$

We associate to P the corresponding exponential discretization P_T with sampling time $T > 0$ (see e.g. [4]):

$$\begin{array}{l} x(t+1) = A_d x(t) + B_d u(t), \\ x(t) \in \mathbb{R}^n, u(t) \in \mathbb{R}^m, t \geq 0, \end{array}$$

where:

$$A_d = e^{AT}, \quad B_d = \int_0^T e^{A(T-\tau)} B d\tau.$$

The controller C is a digital controller.

The control scheme considered here is shown in Figures 1, 2, where C and P share information via a wireless link; information coming from the controller is at first quantized through a uniform quantizer and then sent via a wireless link; information coming from the plant is at first sampled, then quantized through a uniform quantizer and finally sent via the wireless link to the controller.

The parameters that characterize the communication system are listed below:

1) Sampling time T;
2) Quantization threshold M;
3) Quantization width δ;
4) Modulation scheme mod (e.g. PAM, PSK, FSK);
5) Transmitted power level p;
6) Distance r between the plant and the controller;
7) Disturbance n due to the communication channel.

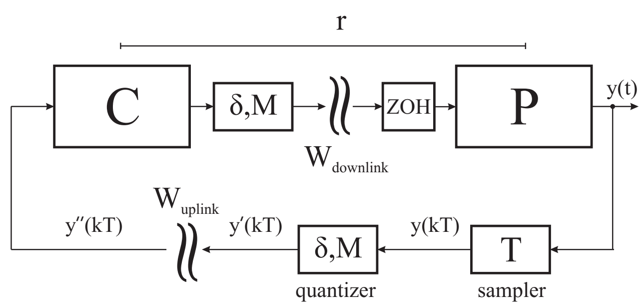

Fig. 1. Communication scheme

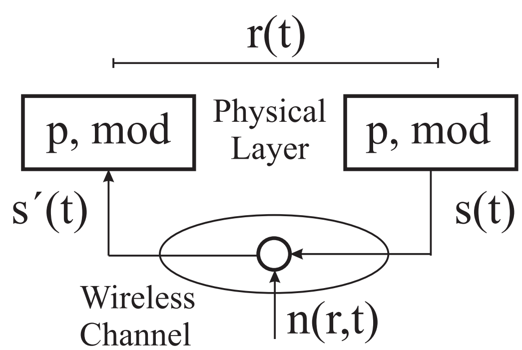

Fig. 2. Wireless channel scheme

The controller synthesis problem that we address in this paper is the design of a digital controller C and of an adaptive communication system such that the safety specifications on the controlled plant P are satisfied. More precisely,

Problem 1: Given a plant P of the form (1) and a set of good states $\Omega \subset \mathbb{R}^n$ within which the state x of the plant P should evolve, find:

- a digital controller C,
- a communication system (as in Figure 1), and
- the set of all initial states in Ω

such that the closed–loop system satisfies the safety requirements, i.e.

$$x(t) \in \Omega, \forall t \geq 0.$$

III. Solving the Safety Problem over Wireless Networks: a Platform Based Design Approach

In this section, we approach the controller synthesis problem formulated in the previous section using the principles of PBD [19]: we consider the synthesis of the controller C subject to bounded disturbances that capture the non–idealities of the communication channels, then we design the communication system so that the disturbance bounds are never violated.

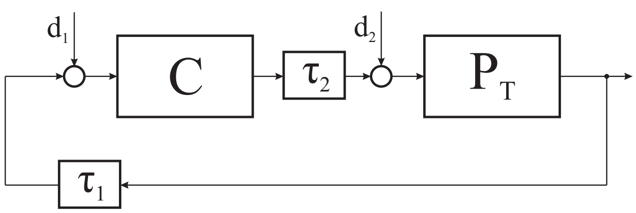

Fig. 3. Control scheme

Non–idealities coming from the communication system can be modeled as additive continuous disturbances d_1 and d_2, while τ_1 and τ_2 model delay components in data transmission in the two wireless links, as shown in Figure 3. We assume that:

$$d_1 \in D_1, \quad d_2 \in D_2, \quad \tau_1 \in [0, \tau_{1,max}], \quad \tau_2 \in [0, \tau_{2,max}], \tag{2}$$

where $D_1 \subset \mathbb{R}^m$ and $D_2 \subset \mathbb{R}^n$ are compact sets and $0 \in D_1$ and $0 \in D_2$. Since D_1 and D_2 depend on the parameters chosen in the communication system, we will make explicit the dependence of these sets on the communication system parameters:

$$(T, M, \delta, mod, p, r, n).$$

In [20] the transmission on a communication channel is affected by an error due to packet loss characterized by a given probability that a packet be discarded (if corrupted). In our approach, we assume that a *corrupted packet is not discarded*, and we model the generated error by means of the additive disturbance signals d_1 and d_2 and delays τ_1 and τ_2.

In the following, we only carry out our analysis for the uplink wireless communication branch, since the downlink branch may be treated similarly. Moreover, we neglect the delays τ_1, τ_2, since we assume that the transmission time required to deliver a sample is such that

$$(\tau_1 < \tau_{1,max}) \wedge (\tau_2 < \tau_{2,max}).$$

For controller synthesis problems with time delays the reader is referred to [15] and the references therein.

The presence of continuous disturbances in the control scheme of Figure 3 has to be taken into account when designing the controller C to satisfy safety requirements. In this scenario, a controller solving the safety problem must be *robust* with respect to the disturbances. In the following we refer to this last controller synthesis problem as the *robust safety problem*. Robust safety problems are in general a hard task to solve and a complete theory is still missing. Some preliminary results are available e.g. in [6], [17], and the references therein. Here we view this controller synthesis problem from a slightly different perspective: our approach is based on an *assume-guarantee* reasoning, frequently used in the formal verification of reactive and timed systems. First we synthesize a controller for the control scheme as in Figure 3, where we assume:

$$D_1 = \{0\}, \quad D_2 = \{0\}, \quad \tau_{1,max} = 0, \quad \tau_{2,max} = 0. \tag{3}$$

Then we verify that the obtained controller solves the robust safety problem with constraints (2).

¿From now on, we suppose that a controller C has been synthesized using e.g. the results in [6] or [3] for satisfying safety requirements on the plant system P, under constraints (3). This controller in general is not a solution to the robust safety problem. However, according to [6], [8]), if the plant is *asymptotically stabilizable*, there always exists a real $\mu \in (0, 1)$ for which a solution to the robust safety problem with disturbances sets μD_1 and μD_2 can be found. Since sets D_1 and D_2 depend on the communication scheme parameters, the robust safety problem translates into finding suitable communication system parameters for which the robust safety problem can be solved.

We now show how to map the set D_1 on the space W_{uplink} generated by the parameters $(T, M, \delta, mod, p, r, n)$ of the communication scheme. We want to associate the set D_1 to the set $\Phi(D_1) \subset W_{uplink}$, i.e. we want to define, for a given set of disturbances D_1 that may be taken by d_1, the set of communication parameters $(T, M, \delta, mod, p, r, n)$ that guarantee $d_1 \in D_1$.

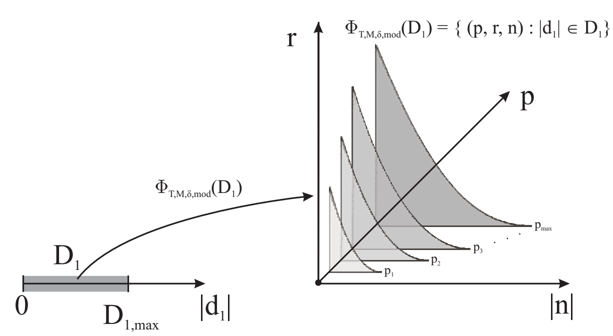

Fig. 4. Specifications on d_1 mapped to specifications on the communication parameters

For the sake of simplicity, we assume here that:

- variables T, M are fixed *a priori*;
- variables δ, mod can have a finite set of values;
- $D_1 = [0, D_{1,max}]$ is mono-dimensional.

Then, we need to define a function $\Phi_{T,M,\delta,mod}$ from D_1 to the space generated by the triple (p, r, n) (see Figure 4) for each combination of the parameters T, M, δ, mod. Note that the number of these combinations is finite.

The function Φ maps the set of allowed disturbance values $d_1 \in D_1$ to a subset of W_{uplink} that includes allowed communication parameters. Note that in Figure 4 the range of $\Phi_{T,M,\delta,mod}(D_1)$ is a projection of $\Phi(D_1)$ for fixed parameters T, M, δ, mod on the 3-dimensional space with coordinates (p, r, n).

Assume now that we are using $m - PAM$ modulation, for some $m = 2^1, 2^2, \cdots, 2^{n_{mod}}$. The number of information bits contained in a symbol is given by $\log_2 m$. Furthermore, for a given combination of sampling time T, quantization threshold M and quantization width δ, the number of bits that we have to send within a sampling time interval is given by $\log_2(\frac{2M}{\delta})$. To guarantee a maximum fixed delay in data transmission, we need a transmission bit rate:

$$f_b \geq \frac{\log_2(\frac{2M}{\delta}) + e}{T},$$

where e be the number of bit introduced by channel coding. Since we encode m bits for each symbol, the symbol rate is given by:

$$f_s \geq \frac{\log_2(\frac{2M}{\delta}) + e}{T \log_2 m}.$$

Clearly, the capacity of the channel $\mathcal{C}$ must be larger than f_s. We assume now that Grey Coding is used to map a symbol to a sequence of bits: more precisely, given two symbols m_i and m_{i+1}, $i = 0, 1, ..., m-1$, they are associated to neighbor values of the associated sample. Assume now that the number of bits for sample is a multiple of the number of bits per symbol: in this case, the assumption of using a Grey Coding implies that, if we send a symbol m_i and receive the neighbour symbol m_{i-1} or m_{i+1}, the error on the received value of the measured sample is bounded by:

$$\delta \sum_{i=0}^{\frac{\log_2(\frac{2M}{\delta})}{\log_2 m}} 2^{i \cdot \log_2 m} := \alpha(M, \delta, m).$$

Note that if one symbol is transmitted for each sample, the bound is given by δ. Generalizing, if we send a symbol m_i and receive the symbol m_{i-z} or m_{i+z}, the error on the received value of the measured sample is bounded by $z\alpha(M, \delta, m)$, being z the number of symbol errors. The overall error on the input signal of the controller is given by $d_1 = y(kT) - y''(kT)$ (see Figure 1): in the worst case, it will be given by the maximum quantization error and the maximum symbol decision error. Thus:

$$|d_1(kT)| \leq d_{qe} + d_{se} \leq \frac{\delta}{2} + z\alpha(M, \delta, m) \leq D_{1,max}. \quad (4)$$

¿From equation (4) it is possible to give bounds on the maximum number z of symbol errors such that $|d_1(kT)| \leq D_{1,max}$:

$$z \leq \left\lceil \frac{2D_{1,max} - \delta}{2\alpha(M, \delta, m)} \right\rceil.$$

¿From the value of z, it is possible to define the set of allowed values of $\{(p, n, r)$ such that $|d_1(kT)| \leq D_{1,max}\}$ for the parameters $(T, M, \delta, m - PAM)$.

The reception of a generic signal transmitted via a communication channel [16] is affected by disturbance. In particular we assume that the received signal is expressed by:

$$s' = s + n,$$

where n represents the channel disturbance that is dependent on time and on the distance $r(t)$ between transmitter and receiver, assumed to be time–varying as well. This generic expression can be used to take into account many different noise and interference sources that usually affect a time–varying communication channel.

An $m - PAM$ modulation format is characterized by m symbols generated by a mono-dimensional base space. In particular we recall that the generic PAM signal for a channel that does not require carrier transmission can be expressed as follows:

$$s_i(t) = \alpha_i g(t) \quad \alpha_i = \frac{i}{m} \quad i = 1, \cdots, m,$$

where $g(t)$ is the pulse shape that we assume to be: $g(t) = p \text{ rect}\left(\frac{t - T/2}{T}\right)$. By defining $E_g = \int_0^T |g(t)|^2 dt$ the energy of the rectangular pulse $g(t)$, we obtain, by the Gram-Smith procedure, the orthonormal basis for the waveform set:

$$\chi(t) = \frac{g(t)}{\sqrt{E_g}}.$$

The generic signal vector is thus given by:

$$\alpha_i \sqrt{E_g},$$

where $E_g = p^2 T$. The PAM signal constellation can be represented as in Figure 5.

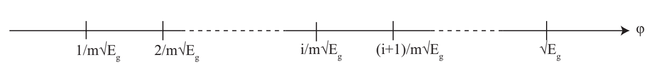

Fig. 5. Signal space diagram for a digital PAM signal

The decision thresholds at the reception of a symbol i are placed at $\frac{p\sqrt{T}(2i \pm 1)}{2m}$. Thus, to guarantee a maximum number z of errors on symbol reception, the following condition must hold:

$$\int_0^T (s_i'(t) - s_i(t))\chi(t)dt =$$

$$\int_0^T (s_i(t) + n(r(t),t) - s_i(t))\chi(t)dt =$$

$$\int_0^T n(r(t),t)\chi(t)dt < \frac{p\sqrt{T}(2z-1)}{2m}.$$

Thus, if $|n(r(t),t)| \leq N$:

$$\int_0^T n(r(t),t)\chi(t)dt \leq N\sqrt{T} < \frac{p\sqrt{T}(2z-1)}{2m}$$

and therefore:

$$N < \frac{p(2z-1)}{2m}.$$

Thus, we can define

$$\Phi_{T,M,\delta,m-PAM}(D_1) = \{(p,n,r) : |n(r(t),t)| \leq \frac{p(2z-1)}{2m}\},$$

where z depends on the disturbance bound $D_{1,\max}$, as indicated above. This equation then translates the specifications given at the controller–plant level to specifications at the communication system level.

IV. Hybrid Mathematical Model of the Protocol Stack Dynamic Configuration

In the previous sections, we defined a set of feasible solutions to our control problem by means of a set of admissible *static* configurations of the communication parameters $(T, M, \delta, mod, p, r, n)$. In a real wireless channel, parameters as the distance r between the controller and the plant, and the disturbance n introduced by the channel, are time–varying. It is still possible to apply a static approach to a time–varying scenario, by restricting the maximum distance and disturbance over time

$$\max_t (n(r(t),t)),$$

thus guaranteeing that the control algorithm works. However, using the "strongest" configuration would lead to a waste of energy. We propose an adaptive configuration of the communication parameters to minimize the transmission power.

First, we need to define the set of parameters we are able to tune: we assume that the sampling time T and the quantization threshold M are fixed and the tunable parameters are:

1) **Quantization Width** δ can be selected in a finite set of admissible values: $\Delta = \{\delta_1, \cdots, \delta_{|\Delta|}\}$;
2) **Modulation scheme** Mod can be selected in a finite set of admissible values: $MOD = \{2^1-PAM, 2^2-PAM, \cdots, 2^{|MOD|}-PAM\}$;
3) **Power level** p can be selected in a finite set of admissible values $P = \{p_1, \cdots, p_{|P|}\}$.

Furthermore, we assume that the evolution of the **distance** r between the plant and the controller is described by the (autonomous) dynamics $\dot{r} = f(r)$.

The idea of adapting the communication parameters is widely studied in the communication community literature (e.g. [9] , [10] , [18]) and applied in communication systems, as for example UMTS. In this paper, we use the mathematical formalism of Hybrid System [14] to give a rigorous formulation of an adaptive communication system. Being able to formally define properties of an adaptive communication system (e.g. feasibility and probability of 'out-of-service') is the advantage of this theoretical approach. As a first step, we formally introduce a hybrid system as a tuple

$$\mathcal{H} = (Q \times X, Y, S_q, \Sigma, E),$$

where:

- $Q = \{q_1, \cdots, q_N\}$ is the finite discrete state space;
- $X = \mathbb{R}^n$ is the continuous state space;
- $Y = \mathbb{R}$ is the continuous output space;
- S_q associates dynamics $\dot{x} = f_q(x), y = g_q(x)$ to each discrete state $q \in Q$, where $x \in X$ is the continuous state and $y \in Y$ is the continuous output variable;
- $\Sigma = \{\sigma_1, \cdots, \sigma_M\}$ is the finite set of discrete input symbols;
- $E \subseteq Q \times \Sigma \times Q$ is a collection of directed and labeled transitions.

The dynamic behaviour of the discrete and continuous state of $\mathcal{H}$ is determined by the continuous dynamics S_q, by the discrete dynamics of the underlying Finite State Machine defined by (Q, Σ, E). For a formal definition of semantics of hybrid systems we refer to [14].

We now define a hybrid system $\mathcal{H}_c$ to model the dynamic behaviour of a wireless channel and an adaptive control of a communication system. We define the set Q as the set of all tunable parameters in the transmission scheme, namely:

$$Q :\, = \Delta \times MOD \times P.$$

A discrete state $q \in Q$ is a triple (δ, mod, p) that defines the current configuration of the communication system. We define Σ as the finite set of configuration commands to the Quantizer and the Physical Layer (configuration of (δ, mod, p)), and the set of edges $E \subseteq Q \times \Sigma \times Q$ such that each arc models an admissible switching of the communication scheme, and can be triggered by the discrete control input $\sigma \in \Sigma$. For instance, the Physical Layer can accept configuration commands to set the current transmission power p by means of increments and decrements or power level value. In the first case, the set of arcs E connects only states associated to neighbor values of power, while in the second case the graph will be fully connected.

The continuous state $(n, r) \in \mathbb{R}^2$ is given by the disturbance introduced by the channel n and by the distance r between the transmitter and the receiver. The dynamics of r is given by the differential equation $\dot{r} = f(r)$. The observed continuous output $y \in Y$ is the Signal-to-Noise Ratio (SNR), which depends on the current hybrid state (namely the current communication configuration, the communication channel status, and the distance) as follows:

$$SNR = g_{(\delta,mod,p)}(n, r, t).$$

The current discrete state of $\mathcal{H}_c$, i.e. the current communication system configuration, is determined by the discrete input $\sigma \in \Sigma$ generated by the Controller of the Communication system C_c. This controller receives as input the continuous output of $\mathcal{H}_c$, as shown in Figure 6.

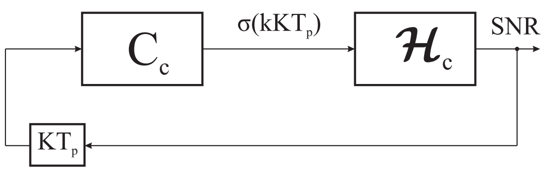

Fig. 6. Controller of the communication parameters

The controller C_c may not able to generate a control at each time instant $t \in \mathbb{R}^+$: we assume here that a command σ can be generated only after the transmission of K packets, namely at time instants kKT_p, where $k \in \mathbb{N}$ and T_p is the transmission time of a packet. Thus, C_c controls the discrete dynamics of $\mathcal{H}_c$ generating output symbols according to a strategy modeled by the function $\gamma : Y \to \Sigma \cup \{\epsilon\}$, where $\sigma(kKT_p) = \gamma(y(kKT_p)), k \in \mathbb{N}$. When the controller does not generate any symbol (no control command), $\gamma(kKT_p)$ is equal to the empty string ϵ.

Let Γ be the set of all control strategies γ on the hybrid system $\mathcal{H}_c$. Problem 1 has a solution if for any disturbance n introduced by the channel and motion $\dot{r} = f(r)$ of the transmitter/receiver, there exists a control strategy $\gamma \in \Gamma$ of the communication configuration such that the communication parameters belong at each time instant to the set $\Phi(D_1)$. Let $\Psi : \Gamma \to 2^{Q\times X}$ be a function that associates to each control strategy the set of all hybrid states that can be reached with a controlled evolution of the system $\mathcal{H}_c$. Note that the functions Φ and Ψ have the same codomain $2^{\Delta\times MOD\times P\times\mathbb{R}\times\mathbb{R}}$. Following the "meet-in-the-middle" argument of PBD, the space of control strategies $\bar{\Gamma} \subseteq \Gamma$ on $\mathcal{H}_c$ that satisfy a safety specification on a time-varying wireless channel (Problem 1) is defined as follows:

$$\bar{\Gamma} := \{\gamma \in \Gamma : \Psi(\gamma) \subseteq \Phi(D_1)\}.$$

Once the space of solutions is defined, it is possible to search for a specific strategy γ^* that minimizes a desired cost function, e.g. minimizes the transmission power p.

V. Conclusions and Future Work

In this paper, we proposed a methodology and a modeling paradigm for the robust design of control over wireless networks. To do so, we leveraged the Platform Based Design (PBD) methodology [19] and hybrid systems. According to the PBD principles, we first mapped control specifications to communication network specifications involving a set of values of the communication parameters such as quantization noise, coding, modulation scheme, and power level. Then, a communication scheme was chosen according to the communications specifications so that the control specifications are satisfied. To do so, we used a hybrid system formalism that models the dynamical behavior of the communication scheme to capture the mixed continuous-discrete characteristics of the configuration parameters.

Future work includes the design of particular solutions for a class of applications. In particular, we plan to develop a set of algorithms with guaranteed properties for the joint design of control and communication schemes for wireless sensor networks.

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