Poster Abstract: Predictable Wireless Networking for Real-Time Cyber-Physical-Human Systems *

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CCS CONCEPTS

•**Networks** →Network protocols;

KEYWORDS

Predictable Wireless Networking, Real-Time, Cyber-Physical-Human Systems

Abstract. Predictable wireless networking is a basis for real-time cyber-physical-human (CPH) systems such as those in augmented reality, connected and automated vehicles, and industrial automation, and a fundamental problem in predictable wireless networking is predictable control of intra-network interference in the presence of dynamics and uncertainties. We present the Physical-Ratio-K (PRK) wireless interference model, and we discuss PRK-based scheduling in both mostly immobile and mobile networks. By enabling predictable control of intra-network interference while only requiring local coordination between close-by nodes, PRK-based scheduling enables holistic, multi-scale approaches to predictable wireless networking by enabling effective integration of scheduling with channel assignment, power control, rate control, and advanced communication techniques to address complex dynamics and uncertainties in wireless communication (e.g., fast-varying channel fading and external interference).

Real-time wireless networked CPH systems. Embedded wireless networks have been being explored for real-time cyber-physical-human (CPH) systems in various domains. In real-time augmented vision, for instance, wireless networks can enable the fusion of real-time video streams from spatially distributed cameras to eliminate the line-of-sight constraint of natural human vision and thus enable seeing-through obstacles [2]. In industrial automation, wireless-enabled mobile, pervasive, and reconfigurable instrumentation and the significant cost of planning, installing, and maintaining wired network cables have made wireless networks attractive for industrial monitoring and control; industrial wireless networking standards such as WirelessHART, ISA100.11a, and WIA-PA have also been defined and deployed in practice [1]. In road transportation, wireless communication has become a basic enabler for connected and automated vehicles, which cooperate with one another and with transportation infrastructures to ensure safety, maximize fuel economy, and minimize emission as well as congestion [3]. Machine-type communication for real-time sensing and control has also become a major focus of the emerging 5G wireless network research and development.

The mission-critical nature of real-time CPH systems such as the control of industrial plants and vehicles requires predictable reliability, timeliness, and throughput in wireless communication. Nonetheless, wireless communication is subject to inherent *dynamics and uncertainties* within the system and environment. Wireless communication channels exhibit complex, environment-specific spatiotemporal dynamics and uncertainties; interference between concurrent transmissions is a major source of uncertainty, and it cuts across multiple aspects of wireless networking such as scheduling, channel assignment, power control, rate control, and routing; dynamic control strategies in CPH systems introduce dynamic network traffic patterns and pose different requirements on communication reliability, timeliness, and throughput; for connected and automated vehicles, vehicle mobility introduces another dimension of uncertainty and complexity.

While wireless networking has been extensively studied, existing mechanisms have not solved fundamental problems such as predictable intra-network interference control in the presence of uncertainties. Hence we still lack mechanisms for ensuring predictable communication reliability, timeliness, and throughput. Accordingly, the current research and practice in WirelessHART, ISA100.11p, and WIA-PA adopt a centralized architecture where a network manager centrally collects statistics of the network state (e.g., wireless channel gain) and centrally decides routing paths and transmission schedules. The centralized architecture makes it difficult to ensure predictable communication reliability and timeliness in the presence of uncertainties. Without addressing predictable control of interference among concurrent transmitters, these work have largely avoided channel spatial reuse too, leading to underutilization of network real-time capacity. The deficiencies of centralized architectures and no-channel-spatial-reuse become especially acute in large-scale wireless networks [1]. In recognition of this, the research community have started examining distributed approaches to industrial wireless networking based on standards such as IEEE 802.15.4e and IETF 6TiSCH. In vehicular networks of potentially unlimited number of highly-mobile vehicles, distributed approaches and channel spatial reuse may well be the only option. Having not resolved fundamental challenges posed by intra-network interference, however, existing distributed approaches in industrial and vehicular CPH systems cannot ensure predictable reliability and timeliness in communication either. Accordingly, the current real-world deployments of CPH systems have mostly been limited to open-loop sensing such as industrial monitoring [1] and vehicle active-safety warning [3], with a wide spectrum of high-impact closed-loop sensing and control applications yet to be realized in practice [1, 3].

Predictable intra-network interference control. Despite decades of research in interference control (e.g., interference-oriented channel access scheduling), existing literature are largely based on either

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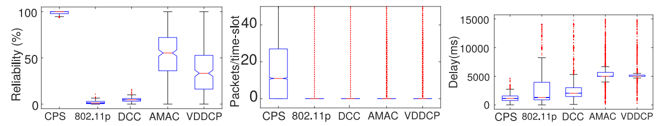
the protocol interference model or the physical interference model, neither of which is a good foundation for distributed interference control in the presence of uncertainties [6, 7]. The protocol model is local and suitable for distributed protocol design, but it is inaccurate and does not ensure reliable data delivery [6]. The physical model has high-fidelity, but it is non-local and combinatorial and thus not suitable for distributed protocol design in dynamic, uncertain network settings [6]. To bridge the gap between the existing interference models and the design of distributed, field-deployable protocols with predictable communication reliability, Zhang et. al [6] have identified *the physical-ratio-K (PRK) interference model* that integrates the protocol model's locality with the physical model's high-fidelity. In the PRK model, a node C' is regarded as not interfering and thus can transmit concurrently with the transmission from another node S to its receiver R if and only if $P(C', R) < \frac{P(S,R)}{K_{S,R,T_{S,R}}}$, where $P(C', R)$ and $P(S, R)$ is the average strength of signals reaching R from C' and S respectively, $K_{S,R,T_{S,R}}$ is the minimum real number chosen such that, in the presence of cumulative interference from all concurrent transmitters, the probability for R to successfully receive packets from S is no less than the minimum link reliability $T_{S,R}$ required by applications.

For predictable interference control, the parameter $K_{S,R,T_{S,R}}$ of the PRK model needs to be instantiated for every link $\langle S, R\rangle$ according to in-situ, potentially unpredictable network and environmental conditions (e.g., data traffic load and wireless signal power attenuation). To this end, Zhang et. al [7] have formulated the PRK model instantiation problem as a *model-predictive regulation control* problem where the "plant" is the link $\langle S, R\rangle$, the "reference input" is the required link reliability $T_{S,R}$, the "output" is the actual link reliability $Y_{S,R}$ from S to R, the "control input" is the PRK model parameter $K_{S,R,T_{S,R}}$, and the objective of the regulation control is to adjust the control input so that the plant output is no less than the reference input. Then control theory can be used to derive the controller for instantiating the PRK model parameter [7]. For every link $\langle S, R\rangle$, using its instantiated PRK model parameter $K_{S,R,T_{S,R}}$ and the local *signal maps* that contain average signal power between S, R, and every other close-by node C that may interfere with the transmission from S to R, link $\langle S, R\rangle$ and every close-by node C become aware of their mutual interference relations. With precise awareness of mutual interference relations with close-by nodes/links, nodes schedule data transmissions in a TDMA fashion using the distributed optimal-node-activation-multiple-access (ONAMA) algorithm [5], and the resulting PRK-based scheduling protocol is denoted as PRKS [7]. Through extensive measurement study in the high-fidelity Indriya and NetEye wireless network testbeds, Zhang et. al [7] observe that PRKS enables predictable interference control while achieving high channel spatial reuse. Accordingly, PRKS enables predictable link reliability, high network throughput, and low communication delay [7].

As a first milestone towards predictable intra-network interference control, Zhang et. al [7] have focused on mostly immobile networks and they did not consider highly-dynamic networks such as those of connected and automated vehicles. In vehicular networks, vehicle mobility makes network topology and inter-vehicle channel properties highly dynamic, which in turn makes interference relations between vehicles highly dynamic, especially for vehicles on different roads or in opposite driving directions of a same road. The highly dynamic nature of inter-vehicle interference relations challenges the precise identification of interference relations in terms



of both interference relation estimation and the signaling of interference relations. To address the challenges, we propose to leverage *cyber-physical structures of vehicle traffic flows* in interference control. In particular, we propose to leverage physical locations of vehicles to define the gPRK interference model, a geometric approximation of the PRK model, for effective interference relation estimation, and we propose to leverage spatiotemporal interference correlation as well as macro- and micro-scopic vehicle dynamics for effective instantiation and use of the gPRK model. Through experimental analysis with high-fidelity ns-3 and SUMO simulation, we observe that our approach, denoted by Cyber-Physical-Scheduling (CPS), enables predictable reliability while achieving high throughput and low delay in communication as shown by the figured above.

Predictable wireless networking. With PRK-based scheduling for both immobile and mobile networks, intra-network interference is controlled in a predictable manner, and this is achieved through local coordination between close-by nodes only. Accordingly, PRK-based scheduling enables addressing other sources of uncertainties (e.g., fast-varying channel fading and external interference) by effectively integrating scheduling with channel hopping, power control, and rate control, thus enabling predictable wireless communication in general. Our preliminary studies have shown promising results for the integrated solutions. In particular, the predictable control of communication reliability in PRK-based network solutions enables predictable control of the tradeoff between reliability, timeliness, and throughput, which in turn enables the joint optimization of wireless networking and networked sensing and control in CPH systems, thus enabling predictable real-time CPH systems in practice. PRK-based framework for predictable wireless networking is synergistic with advanced communication techniques such as interference cancellation, MIMO, and beamforming [6]. For instance, even though interference cancellation allows for concurrent transmissions of certain interfering signals, it still needs interference control to work correctly [4]. Detailed studies of these topics are promising future directions to pursue.

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