©2023 IEEE. Personal use of this material is permitted. Permission from IEEE must be obtained for all other uses, in any current or future media, including reprinting/republishing this material for advertising or promotional purposes, creating new collective works, for resale or redistribution to servers or lists, or reuse of any copyrighted component of this work in other works.

Goal-Oriented Transport Layer Protocols for Wireless Control

Polina Kutsevol*, Onur Ayan*, Nikolaos Pappas**, and Wolfgang Kellerer*
*Chair of Communication Networks, Technical University of Munich, Germany
**Department of Computer and Information Science, Linköping University, Linköping, Sweden
Email: {polina.kutsevol, onur.ayan}@tum.de, nikolaos.pappas@liu.se, wolfgang.kellerer@tum.de

***Abstract*—Goal-oriented communication is a promising approach to tailor the network resource management algorithms to the needs of particular applications, thus enhancing the efficiency of resource utilization and boosting the application performance. In the context of distributed cyber-physical systems and networked control systems, the design of a control-aware transport layer (TL) represents a realistic approach for goal-oriented communications since it can be integrated into generic control setups without making assumptions on particular hardware or network technologies and deliver enhanced end-to-end performance. This demo showcases the application performance of different TL schemes used for communication between the sensors and the controllers monitoring and actuating inverted pendulums, i.e., multi-dimensional plants. The nodes of the control loops are realized with Zolertia Re-Mote devices, and multiple control loops communicate over the shared wireless network using IEEE 802.15.4 standard. We use the demonstration testbed to compare the performance of conventional, state-of-the-art, and novel goal-oriented TL schemes by observing the emulated dynamics of inverted pendulums.**

I. INTRODUCTION

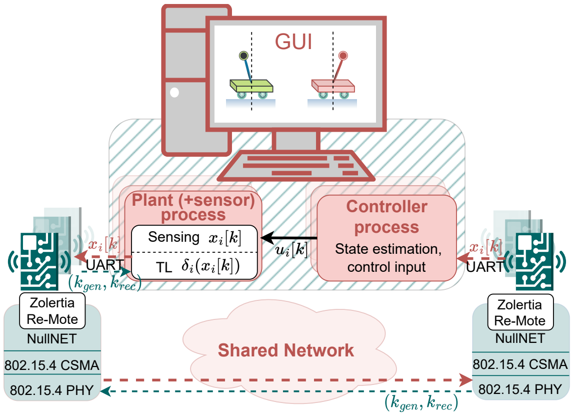

Fig. 1: The demonstration testbed scheme. Plant and controller processes of all loops and GUI showing the pendulums' dynamics run in parallel on one PC. Each process connects to one Zolertia Re-Mote sensor. Sensors communicate over a real wireless network.

The performance of cyber-physical system applications, including wireless network control systems (WNCSs), is tightly coupled with efficient network management. In such scenarios, the network connects the remote sensor to the controller that monitors the plant state and decides on the plant's actuation. The network adverse effects, such as delays and packet losses, determine how accurate the controller's knowledge regarding the plant is and, consequently, how efficiently the controller's actuation is. These adverse effects can be partially mitigated by adequately designing the transport layer (TL) scheme used within WNCSs. The adaptations w.r.t. TL have several advantages, including the transparency to lower networking layers and guaranteed end-to-end performance, eased integration into software, and reduced costs for the manufacturers and users due to relaxed requirements for specific hardware. Most importantly, as we have experimentally shown in [1] and as has been discussed in [2], [3], existing approaches at the TL underperform in terms of control performance in scenarios with limited wireless resources availability. Conventional networking approaches such as UDP and TCP are agnostic to the control objective. They might use the limited network resources to transmit irrelevant data w.r.t. the application goal. The idea of filtering the status updates and thus offloading the network is known in control theory as event-triggering (ET). However, control theory approaches typically oversimplify the effects of the actual network on the control performance [4]. The main idea of goal-oriented or semantic communication [5], [6] is to design network resource management algorithms in an application-aware manner and take the application-defined metrics as an ultimate performance indicator. Moreover, the algorithms should consider how the adverse effects of the actual network influence the application goal, and these effects should be limited to minimize the application performance degradation. In the context of control, our work [1] proposes a goal-oriented TL scheme that filters the input traffic to the network based on its relevance for the control process, current network state, and how much overhead the additional transmission brings w.r.t. control performance.

This demo paper showcases the real-life control performance of different TL schemes, including conventional networking methods, ET, and proposed in [1] goal-oriented alternatives. It confirms the results from [1] displaying the benefits of goal-oriented TL w.r.t. application performance. Furthermore, this work goes beyond [1] by demonstrating the integration of our TL solution into multi-dimensional control applications, whereas [1] only considers scalar plants. The demonstration framework is depicted in Fig. 1. It includes up to three sensor-controller pairs, where the industrial IoT Zolertia ReMote devices [7] communicate over a wireless network using IEEE 802.15.4 protocol [8]. The Graphical User Interface (GUI) demonstrates real-time dynamics of the inverted pendulum plants (IPs) extensively used in control theory demonstrations.

The authors acknowledge the financial support by the Federal Ministry of Education and Research of Germany in the programme of "Souverän. Digital. Vernetzt.". Joint project 6G-life, project identification number: 16KISK002

The work of N. Pappas has been supported in part by the Swedish Research Council (VR), ELLIIT, and the European Union (ETHER, 101096526).

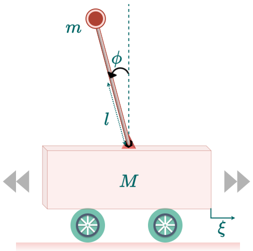

Fig. 2: Inverted pendulum - example of a multi-dimensional plant. ϕ and ξ denote the angular deviation and the cart position.

II. CONTROL AND NETWORK MODELS

The considered system includes N linear time-invariant (LTI) control loops, the components of which communicate over a shared wireless network as shown in Fig. 1. At each time step k, the sensor of each control loop i captures the plant state $\boldsymbol{x}_i[k]$ and, in case of positive admission, transmits it to the remote controller in a separate packet. The controller uses this data to estimate the current plant state and to determine the control input $\boldsymbol{u}_i[k]$ to actuate the plant. Controllers and plants are co-located. The dynamics of the plant follows

$$\boldsymbol{x}_i[k+1] = \boldsymbol{A}_i \boldsymbol{x}_i[k] + \boldsymbol{B}_i \boldsymbol{u}_i[k] + \boldsymbol{w}_i[k], \tag{1}$$

where $\boldsymbol{A}_i$ and $\boldsymbol{B}_i$ are state and input matrices, and $\boldsymbol{w}_i[k]$ is random disturbance vector following Gaussian distribution.

The TL resides at the sensor's side and dictates the decision $\delta_i[k] \in \{0,1\}$ regarding admission/dropping of newly captured state updates. The TL learns the network state through acknowledgments (ACKs), with which the controllers respond upon the reception of each update. Status updates and ACKs can be delayed or even lost. ACKs contain the updates' reception timestamps. Thus, the sensor can track delays and round trip times (RTT) statistics. Although the TL is agnostic to the underlying communication stack, we implement the system with low-power Zolertia ReMote sensors that use IEEE 802.15.4 for communication. The controller decides on the plant actuation with the goal of minimizing the linear quadratic Gaussian (LQG) control cost:

$$\mathcal{J}_i \triangleq \limsup_{\mathcal{T}\to\infty} \left(\frac{1}{\mathcal{T}} \sum_{k=0}^{\mathcal{T}-1} (\boldsymbol{x}_i[k])^T \boldsymbol{Q}_i \boldsymbol{x}_i[k] + (\boldsymbol{u}_i[k])^T \boldsymbol{R}_i \boldsymbol{u}_i[k] \right), \tag{2}$$

where $\boldsymbol{Q}_i$ and $\boldsymbol{R}_i$ are prioritization matrices, and $\mathcal{T}$ is the time horizon. The control cost is the application-defined performance metric. Thus, different TL schemes can be compared based on the accumulated LQG cost of the control system, and we aim to design the TL that leads to the minimum control cost.

In [1], we have studied TL policies based on scalar plant applications. In this demo paper, we focus on demonstrations with realistic multi-dimensional IP plants. In case of IP, we have $\boldsymbol{x}[k] = [\xi[k] \quad \dot{\xi}[k] \quad \phi[k] \quad \dot{\phi}[k]]^T$ as shown in Fig. 2. The weights m of the ball and M of the cart are set to 0.2 kg and 0.5 kg, and the pole length l is 0.3 m. The surface's friction coefficient is 0.1 N/m/s, and the IP's inertia coefficient is 0.006 kg$\cdot$ m^2. The sampling periodicity is set to 10 ms. The selection of the parameters defines the state-space representation (1) of IP, the details of which can be found in [9].

Fig. 3: The demonstration testbed. Six Zoleria ReMote sensors communicate over the shared wireless network. The control loops are closed over a mini PC.

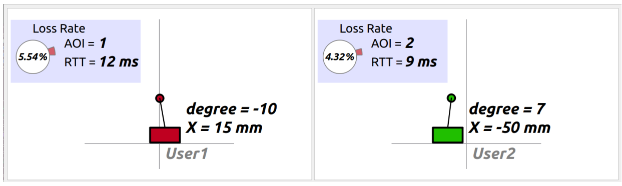

Fig. 4: Example output of the GUI illustrating real-time dynamics of emulated IPs.

III. DEMONSTRATION TESTBED

For the demonstration, we use up to 6 Zolertia ReMotes forming up to 3 control loops, as shown in Fig. 3. Each device is connected to a mini PC through the UART interface, thus closing the control loops via "ideal“ controller-to-plant links. The PC emulates IP plants and controllers in real-time by running them as separate processes. In particular, the state of each IP plant evolves in discrete steps with the periodicity 10ms as in (1), where the IP parameters are used. GUI running on the PC visualizes the IPs' dynamics as shown in Fig. 4. In case of a positive admission by TL, the update forms a single packet that is pushed to the corresponding ReMote over UART. There is also a feedback UART link to the TL for ACKs. The controller process receives the packets from the second ReMote. It builds plant estimations with the same periodicity of 10m, and control inputs are handed to the corresponding plant process at each time step, as shown in Fig. 1(a).

From the network side, as soon as the ReMote sensor gets a new packet, it forwards it to the controller node. In particular, the packet goes down through the IEEE 802.15.4 network stack of the Zolertia device. In more detail, CSMA/CA is employed at the MAC layer, i.e., the access to the communication medium is contention-based. At PHY, all the communication nodes operate in the same channel at 2.4GHz with the transmit power of 7dBm, resulting in a 250 kbps data rate. If the controller ReMote receives an update, it responds immediately with an ACK containing both the timestamp of the update generation and reception. The status update is forwarded to the corresponding controller process on the mini PC.

IV. TRANSPORT LAYER PROTOCOLS FOR WNCS

Our experimental framework supports several configurations of TL. In particular, we explore and demonstrate if the TL schemes studied in [1] show respective application performance in the realistic scenario with multi-dimensional plants.[1]

---

[1] We refer the reader to Fig. 4 and Fig. 5a in [1] for the LQG cost performance of selected TL mechanisms used for scalar plant applications.

Among the conventional networking schemes, we consider UDP and TCP. UDP admits all the sampled updates to the network. TCP, in turn, controls network congestion by limiting the number of backlogged packets. As we show in [1], these schemes are control-agnostic and lead to unsatisfactory performance due to strong network congestion or updates' increased waiting times in the network buffers[2]. The demonstrations with IP that we present allow capturing poor control performance when more than 1 control loop is active. In particular, the IP gets destabilized, i.e., the pole angle deviation of IPs increases. Higher plant disturbance implicitly indicates higher control efforts required and increased control cost from (2). The Zero-Wait (ZW) TL scheme does not admit a new packet until the ACK for the previous one is received, or ACK timeout occurs. ZW limits the waiting times, which is beneficial for WNCSs, as we show in [1] for a scalar plant. Finally, we re-implement an age control protocol (ACP) from [10] that adapts the sending rate of the updates such that the freshness at the monitor is maximized. ZW and ACP allow keeping the IP disturbance limited also for 2 and 3 control loops, witnessing the superiority of these schemes compared to TCP and UDP.

All the previously mentioned TL schemes limit the network congestion in a control-unaware manner. Filtering the updates based on their value and relevance for the control is another way to reduce transmissions while maintaining high control performance. In this demonstration, we show that the network-unaware ET mechanism, according to which the updates are admitted to the network if their magnitude is higher than a threshold, achieves comparable control performance with drastically reduced control traffic. However, when resources become sparse, i.e., more than 2 control loops share the network, the ET results in bursty transmissions, substantial network congestion, and IP destabilization.

ZW ET approach that we propose in [1] combines the benefits of congestion and control awareness. According to the ZW ET, the updates are admitted to the network if the state magnitude is higher than a threshold and there are no packets at the sensor awaiting ACK. With ZW ET, bursty transmissions and heavy congestion are eliminated, and the waiting time is limited. In addition, only relevant updates occupy network resources, boosting the efficiency of the TL. As a result, ZW ET shows the smallest IP deviations, i.e., the best control performance among previously considered schemes for up to 3 control loops [3]. ZW ET with augmentation (AUGM ZW ET) is an enhancement of ZW ET, where the sensor uses ACKs to build the augmentation $\bar{\boldsymbol{x}}_i[k]$ of the controller estimation. Then, the estimation error $|\boldsymbol{x}_i[k]-\bar{\boldsymbol{x}}_i[k]|$ is compared to the threshold rather than the state itself. Such a scheme allows further improvement in identifying the relevant data since it avoids transmitting the updates witnessing high deviation when the controller is already aware of it. AUGM ZW ET results in IP being more stable than ZW ET for low threshold values, i.e., when the resources are scarce. The critical component for the practical implementation of ZW ET and AUGM ZW ET is the choice of an appropriate threshold. Suppose the threshold is too low or too high for the specific network scenario. Then, it can result in increased delays due to the traffic volume or too conservative update rates. Together with conceptual TL schemes, we demonstrate the TL mechanism for threshold adaptation from [1] for the scenarios when the optimal threshold value varies or can not be set in advance that is based on capturing the congestion increase by increased RTT. We demonstrate that the threshold adaptation scheme stabilizes not only the scalar plant as in [1] but also the multi-dimensional IP.

The generalization of the results from [1] for multi-dimensional systems witnesses the versatility of the proposed mechanisms. This extends the applicability of the ZW ET, AUGM ZW ET, and the threshold adaptation schemes into a vast class of LTI systems utilizing quadratic control costs.

V. CONCLUSION

In this demo paper, we presented a demonstration framework that showcases the application performance of wireless control applications with different transport layer schemes that we study in [1]. We confirm and extend our results from [1] by demonstrating the real-time dynamics of the multi-dimensional inverted pendulum plant. The main goal of the demo is to motivate the need for goal-oriented networking by showing that the conventional transport layer mechanisms from networking and control theory can result in plant destabilization. In turn, the congestion- and relevance-aware schemes stabilize the pendulum even in scenarios with limited availability of network resources.

REFERENCES

[1] P. Kutsevol, O. Ayan, N. Pappas, and W. Kellerer, "Experimental study of transport layer protocols for wireless networked control systems," *IEEE SECON*, 2023.

[2] H. B. Beytur, S. Baghaee, and E. Uysal, "Towards aoi-aware smart iot systems," in *IEEE ICNC*, 2020.

[3] P. Kutsevol, O. Ayan, and W. Kellerer, "Towards semantic-aware transport layer protocols: A control performance perspective," *arXiv:2301.13653*, 2023.

[4] M. Balaghiinaloo, D. J. Antunes, M. H. Mamduhi, and S. Hirche, "Decentralized lq-consistent event-triggered control over a shared contention-based network," *IEEE Trans. Automat. Control*, vol. 67, no. 3, 2021.

[5] A. Kosta, N. Pappas, and V. Angelakis, "Age of information: A new concept, metric, and tool," *Foundations and Trends® in Networking*, vol. 12, no. 3, pp. 162–259, 2017.

[6] M. Kountouris and N. Pappas, "Semantics-empowered communication for networked intelligent systems," *IEEE Communications Magazine*, 2021.

[7] "Zolertia Remote: Lightweight Internet of Things hardware development platform," https://zolertia.io/product/re-mote/.

[8] "Ieee standard for low-rate wireless networks," *IEEE Std 802.15.4-2015 (Revision of IEEE Std 802.15.4-2011)*, 2016.

[9] O. Ayan, P. Kutsevol, H. Y. Özkan, and W. Kellerer, "Semantics-and task-oriented scheduling for networked control systems in practice," *IEEE Access*, vol. 10, pp. 115 673–115 690, 2022.

[10] T. Shreedhar, S. K. Kaul, and R. D. Yates, "An age control transport protocol for delivering fresh updates in the internet-of-things," in *IEEE WoWMoM*, 2019.

---

[2] The controller estimation precision and, consequently, control performance always benefit from receiving fresh updates rather than outdated ones.

[3] ZW ET is also efficient in terms of computation and signaling overheads. Indeed, it does not require any additional signaling apart from TL ACKs that are also utilized by conventional schemes. Moreover, it is a distributed TL mechanism, thus, it can scale if the network dimensions increase.