Value of Updates: Which Packets Are Worth Transmitting?

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***Poster Abstract*—In the context of control systems over a communication network, status updates can be discarded based on their content to unload the network and prevent network congestion. In this work, we propose a transport layer scheme that not only considers the current system state, but also its significance w.r.t. already transmitted updates, including those that are not yet acknowledged. The benefit of admitting a packet to be sent is compared to its transmission cost to obtain the value of update (VoU). Using Zolertia Re-Mote sensors, we show that the consideration of VoU allows improving the control performance by at least 70%.**

I. INTRODUCTION

Connected robotics, smart grids and IIoT are driving use cases for the next-generation networks [1]. Such systems are constituted by networked control systems (NCSs), with the controller that monitors the plant state through the sensor sending state measurements to the controller over a communication network as shown in Fig. 1. Control performance is coupled with the efficiency of network resource management, as it is affected by delays and packet losses caused by network [2].

Event-triggering (ET) is used to avoid performance deterioration caused by network. If the sensor witnesses a high plant deviation from the desired state, this information is more valuable for the controller, representing the event for ET. Thus, status updates can be discarded if they are less relevant. However, ET schemes proposed in the State of the Art (SotA) reduce the traffic in a network-unaware manner [3], [4]. As shown in [5], network-unaware ET, as well as conventional networking transport layer (TL) schemes concede to approaches combining network awareness and ET. In this work, we propose a novel ET scheme that takes network into account. It includes a new method to obtain the benefit of a status update for a control process. We compare the benefit to the transmission cost to obtain the value of update (VoU), based on which packets are admitted to the network. To assess the benefits of the update, we estimate the network status of the previously sent packets, building the *belief network* (BN). We prove the superiority of our new TL scheme by conducting experiments with sensor devices Zolertia Re-Motes [6].

II. SYSTEM MODEL

We consider N linear time-invariant control loops sharing the wireless network as shown in Fig. 1. The discrete-time representation of the dynamics of each loop is:

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

where $\boldsymbol{x}_i[k] \in \mathbb{R}^{n_i}$ and $\boldsymbol{u}_i[k] \in \mathbb{R}^{m_i}$ are the state of the plant $\mathcal{P}_i$ and control input applied by controller $\mathcal{C}_i$ at time step k. $\boldsymbol{A}_i$ and $\boldsymbol{B}_i$ are state and input matrices. The disturbance vectors $\boldsymbol{w}_i[k]$ are independent and identically distributed (i.i.d.) and follow a zero-mean Gaussian distribution with a covariance matrix $\boldsymbol{W}_i$. Sensors $\mathcal{S}_i$ measure plant states and decide on their transmission to corresponding controllers based on the admission policy. The controllers and plants are co-located.

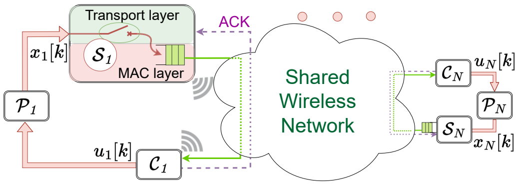

Fig. 1: Considered NCSs scenario.

Control inputs are determined by the control low, minimizing linear quadratic Gaussian (LQG) cost:

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

where $\boldsymbol{Q}_i$ and $\boldsymbol{R}_i$ are weighting matrices for the system state and control effort. The controller state estimation $\hat{x}_i[k]$ is an expectation of $x_i[k]$ given the last available to it state observation [7]. $\boldsymbol{u}_i[k]$ depends on $\hat{x}_i[k]$, thus, the estimation precision affects the control performance. The estimation error is expected to reduce if controller receives a fresh update.

When admitted to the network, packets are pushed to the medium access control (MAC) layer as shown in Fig. 1. Further control over the packet is not possible, and its network status is unknown to the sensor unless the acknowledgement (ACK) is received or ACK timeout expires, indicating the reception or packet loss, respectively. Each packet is subject to potential delay and loss in the network.

III. VALUE OF UPDATE

After sending several updates, sensor should infer which information is available at the controller, is it sufficient to stabilize the plant and how beneficial the current update is for the control process. Consideration of the transmission cost within VoU allows to defer admission of even significant updates if they are expected to congest the network.

Benefits of Update. BN is formed by considering the network state of previously sent packets. If packet is ACKed or its ACK timeout expires, its state is known. The status of the rest sent outstanding packets (OPs) is unknown and is to be estimated. The possible OP states and the scheme for the calculation of their probabilities are given in Fig. 2. With delay statistics obtained from ACKs, we estimate the probability of the OP to be in service and to be received or lost for a given time elapsed since its transmission.

For all OPs, all possible combinations of four states are built, forming the nodes of the BN. Note that OPs sent earlier

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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

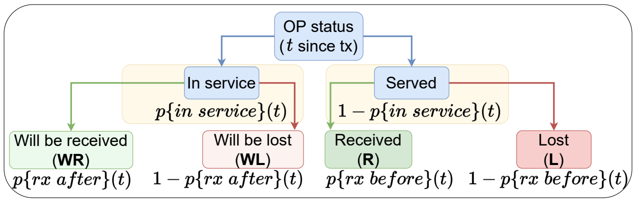

Fig. 2: Possible states of outstanding packets.

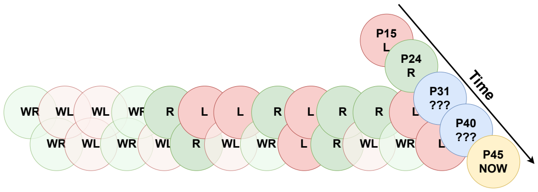

Fig. 3: Example nodes of the *belief network*.

can not be of state **WR(WL)**, when more fresh OPs are **R(L)**, as we do not allow out-of-order transmissions in the network. The probability of a node is the product of the probabilities of each OP being in the corresponding state. Fig. 3 gives an example of the BN construction. Here, the TL decides on the admission of the current packet at $k = 45$. ACK timeout has passed for the packet sent at $k = 15$, ACK has been received for the packet sent at $k = 24$. The BN nodes are built for two OPs, the exact state of which is not known.

After defining which information is presumably available at the controller for each BN node, the sensor augments the controller's state by repeating its estimation process. The difference between the current measurement value and the augmented controller estimation $\tilde{x}_i^{node}$ represents the relevance of the current update for the control process. The expression for the benefit of transmitting the current update is:

$$B_i[k] = \sum_{possible\ nodes} p(node)|x_i[k] - \tilde{x}_i^{node}[k]|. \qquad (3)$$

The computational complexity of (3) grows exponentially with OP count Ω. In our experiments, we recorded that Ω was less than 5, and the computation time was below the sampling period of 10ms. The complexity-accuracy trade-off is part of future work.

Cost of Update. The sensor approximates the expected packet delay depending on the time elapsed since the previous transmission. The delay scaled by maximum delay gives the cost of transmission $C_i[k] \in [0, 1]$. The admission decision is represented by $\delta_i[k] = \mathbb{1}(B_i[k] \geq \lambda C_i[k])$, where λ is a threshold. Note that the delay as a function of time passed since the previous transmission is typically a descending function. Indeed, if a new packet is sent right after another, there is a high probability that the second packet would wait in the MAC queue until the first packet is served. For control applications, it is desirable to eliminate unnecessary waiting times and deliver fresh updates. Our VoU policy prevents sending packets in bursts unless they are very significant.

IV. Experimental Results

We conduct experiments with two control loops including Zoleria Re-Mote sensors following IEEE 802.15.4 standard [8]. There is a cross-traffic in the network independent of the actions of considered loops. We compare the LQG cost of the VoU TL scheme with other two ET schemes. As in [4], both of them trigger sending updates based on the deviation of the current state from augmented controller estimation. The first scheme limits $\Omega \leq 1$, the second one allows $\Omega \leq 2$. Note that Ω for VoU scheme is not limited.

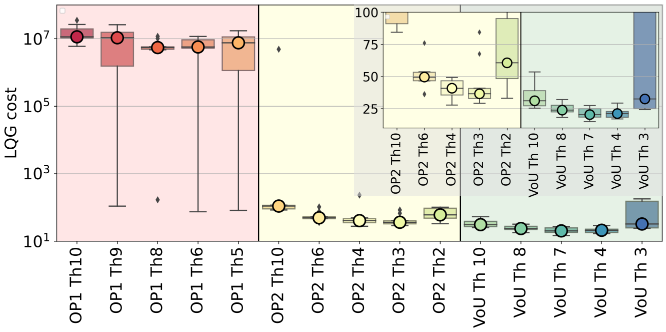

Fig. 4: Control performance of ET with the maximum OP count of 1, 2 and of proposed TL utilizing VoU.

LQG costs from (2) averaged over two loops and 10 simulation runs by 60 seconds are given in Fig. 4 for different λ. The performance of ET with maximum Ω of one is unsatisfactory as when packets are lost because of cross-traffic, new updates are not admitted to the network until the ACK timeout expires, allowing for the state to grow. With maximum Ω of two, LQG cost is lower, because losses can be secured by extra transmissions, but frequent sending of two consecutive packets results in higher waiting times, especially for the second admitted packet, deteriorating the control performance. The proposed VoU scheme achieves the 75% better performance as it admits new updates only when they carry relevant information provided that their expected delay is limited and the congestion level is controlled. Additional experiments show that perfect knowledge of the controller estimation by the sensor, i.e., perfect BN, would lead to a further performance increase of 15%, which is significantly smaller than 75% gain that can be achieved with the proposed BN construction method. That fact witnesses the accuracy of our method.

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