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Feedback Control Applications in New Radio

Exploring Delay and Control Alignment

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In a new radio (NR) communication system, low latency and limited jitter are critical to support new use cases exploiting e.g. haptic feedback and other closed loop feedback control applications. Therefore, mechanisms for delay control and delay alignment become important. The simplest approaches to mitigating delay jitter, using buffering techniques, come at a price of memory and increased delay. More recently, techniques using feedback of delays experienced have shown great promise for improved performance with low overhead. The scope of the paper is to discuss and motivate the need for delay alignment in general.

Delay in Modern Communication Systems

Delay is inevitable in modern communication systems such as the 5G new radio (NR) system. There are several sources contributing to this delay, as exemplified by the vehicle to vehicle (V2V) control setup of Figure 1: (a) Internet transport delays between the data source node and the NR base stations (gNBs), including input queue delays; (b) delays to the transmission queues in the gNBs; (c) Transmission queue dwell time delays in the gNBs; (d) Radio transport delays; (e) NR air-interface delays; and (f) user equipment (UE) processing delays. The Internet transport delays (a) are physical delays that depend on the distances between the cloud server and the gNBs. Intermediate queues, gNB input layer queues, and traffic congestion may add significant jitter (temporal variations in delay) to the delay [1], [2]. The delays (b) depend on the transport technology between the gNBs. The transmission queues in the gNBs reduce the effect of rapid radio interface data rate variations due to fading or interference [3], therefore the queue dwell time delays (c) need to be about as large as the round-trip delay from the gNB to the UE and back. The connections to other gNBs may enable Dual Connectivity functionality as depicted in Figure 1. The distances of the connection from the base stations to the advanced antenna system (AAS) radios are usually small with low latencies (d). The air interface of NR (e) is designed to have a very low latency, with some jitter introduced by re-transmissions [4]. The UE processing delays depend on the UE devices. However, the delays, at least for future UEs, are also believed to be small and with low jitter.

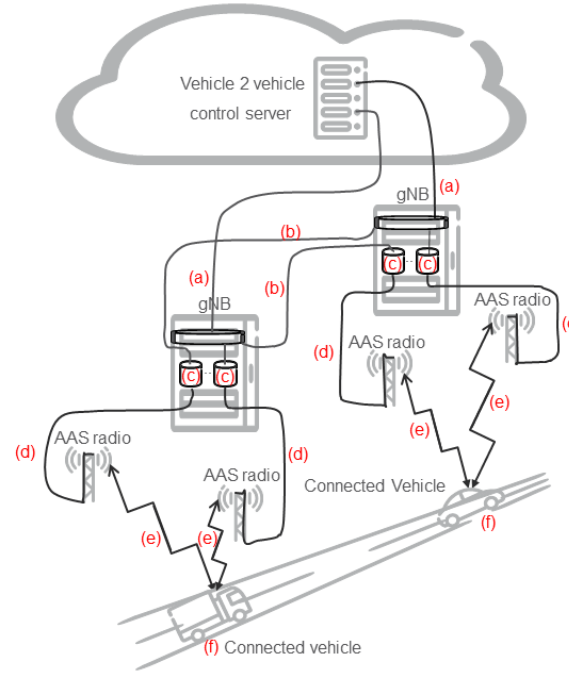

Figure 1: *Sources of delay and jitter in a V2V control network. The signal paths (a)-(e), carry information both in downlink and uplink. Queues are used to mitigate radio fading. An example supervisory control loop for autonomous driving could e.g. consist of a controller in a cloud server, using feedbacked position and speed measurements from cars ahead.*

It is the round-trip delay that is relevant for feedback control applications [5], [6]. Negative effects of delay and jitter on feedback control systems include oscillating control loops, instability and an increased controller complexity, as discussed in the following section. The delay, jitter and reliability requirements posed by several feedback control applications have been investigated by 3GPP [7]. Table 1 summarizes the 3GPP findings to be fulfilled by the NR system. Factory automation is not listed in Table 1 as a separate use case. Instead the requirements for different factory automation use cases, ranging from the very low delay requirements for closed loop industrial robot arm control to slower use cases involving e.g. self-driving trucks, are treated by using the listed requirements on Discrete automation - motion control and Discrete automation. Refined factory automation requirements and expected performance can e.g. be found in [8]. Automation in process industries are addressed by the Process automation use cases, see [7] for details. Since a low delay makes it harder to

reach a given reliability requirement, required reliabilities also appear in Table 1. In summary, delay and jitter of 1 ms is sufficient, except for motion control applications and some discrete automation applications.

Use Case	End-to-end delay	Jitter	Reliability
Discrete automation -Motion Control	1 ms	1 µs	99.9999%
Discrete automation	10 ms	100 µs	99.99%
Process automation – remote control	50 ms	20 ms	99.9999%
Process automation-monitoring	50 ms	20 ms	99.9%
Electricity distribution – medium voltage	25 ms	25 ms	99.9%
Electricity distribution – high voltage	5 ms	1 ms	99.9999%
Intelligent transport systems– infrastructure backhaul	10 ms	20 ms	99.9999%
Tactile Interaction	0.5 ms	To be confirmed	99.999%

Table 1: *End-to-end delay, jitter and reliability requirements for feedback control use cases. Source Table 7.2.2-1 of [7].*

The NR air interface specifications fulfill the 1 ms delay requirement with margin, in particular for millimeter wave (mmW) frequencies, see [4]. This is because the cell radii are generally smaller at mmW frequencies than at lower frequency bands [3], [9]. Consequently, lower delay spread is experienced and less cyclic prefix margin is required. This allows the NR mmW air interface resource grid to rely on higher subcarrier spacing, with a proportionally lower symbol time, down to about 1/100 ms, for a subcarrier spacing of 240 kHz, see Table 4.2-1 and Table 4.3.2-1 of [4]. The end-to-end air interface delay is therefore reduced at mmW frequencies, provided that the UE processing delay can be correspondingly reduced. However, motion control and discrete automation jitter requirement may require additional solutions.

These uses cases motivate us to consider delay control and alignment, and the focus is on sources of delay and jitter other than Internet transport delays.

Effects of Delay and Compensation Methods

In the NR systems, multiple use cases are expected to require high throughput, high demand feedback control loops, see Table 1, [8] and [10]. It is well known that for such feedback loops, unknown, un-compensated or variable delays can have a range of serious impacts on performance [5], [6].

Delays in Feedback Loops May Cause Instability

Unmodeled delays (delays that are either not known or not compensated for) in a feedback loop can lead to instability. In the linear case instability can be understood by the classical Nyquist stability criterion, that is stated and used by [11]. When the delay is close to the loop response time and increasing, a transition from poorly damped oscillatory response to instability occurs.

Side Effects of Jitter

As well as the delay itself causing problems, variable delay (delay jitter) can cause a range of problems, including feedback loop instability, see [5] and the references therein. Another side effect is that jitter over the interfaces of Figure 1 leads to sampling period variations at the feedback control application layer, as illustrated by the qualitative Figure 2. This can be compensated for, either by introduction of performance reducing margins, or by application of time variable sampled control, cf. [5]. These compensation methods do however suffer from both significantly increased computational complexity and much reduced stability guarantees, see [5].

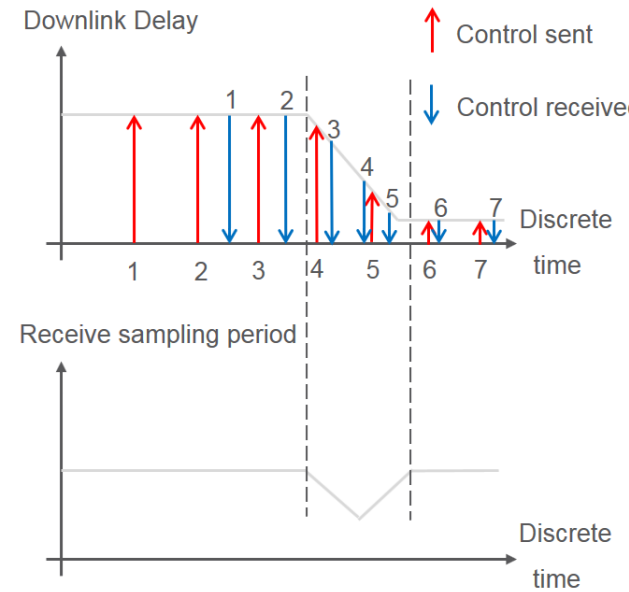

Figure 2: *Uniform sampling of control signals in a controller node become irregularly sampled in the plant node (that is the node where the application layer interfaces with the physical device to be controlled) when the delay over the interface between the nodes varies.*

In many versions of TCP/IP protocols, with multiple flows, timing jitter may lead to out of sequence packet receptions with the potential to cause groups of packets to be discarded and retransmitted. In many feedback control cases this means that the information is lost, since significantly delayed information is useless for feedback control. Note that rapid capacity variations may be experienced e.g. in factory environments where moving

metal objects may block transmission paths [12]. The NR- and related 5G systems are likely to depend on multi-connectivity to enhance the coverage for the high mmW frequency bands [3], [13]. This may add to the jitter since non co-located radio interfaces fade independently, but correct controlled split of data may decrease the jitter by utilizing the path diversity.

Compensation for Delay

The design of additional compensators implemented in the feedback controller of the application can help mitigate the undesirable effects of time delays, when they are known. One way to achieve this would be to augment a rational delay model, of the known nominal delay in the dynamic model of the system, and using the augmented model for controller design, see Figure 3. In case of jitter, the controller would also need to be frequently re-tuned. A prerequisite for this is that the delay be known in real time at the application layer for the feedback compensator. This typically requires tight clock synchronization between distributed nodes in the communication system. Even if synchronization is possible and therefore the delay is known, compensation generally requires detuning feedback loop performance.

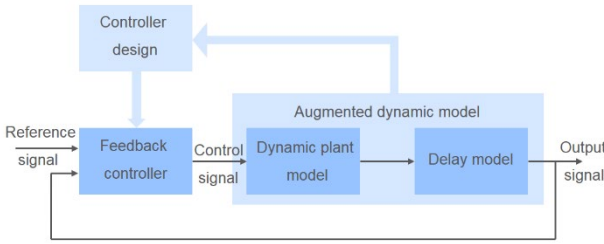

Figure 3: *The principle of delay compensating controller design.*

Aligning the Delay in Industry NR Networks

One could also resort to using NR ultra-reliable low latency communications (URLLC) protocols ([4]) to reduce the delays, since this is a hallmark of NR. This entails the use of techniques such as grant free access, with consequent trade-offs in throughput and additional switching overheads. Moreover, in cases where the application feedback controllers are in the cloud, cf. Figure 1, the end-to-end delays may be dominated by Internet transport delays. In such cases it is of interest to consider schemes providing predictable/consistent latency, without relying on URLLC. This can be achieved by delay regulation and by delay alignment, as discussed in the following section.

In factory automation it is reasonable to assume that the application controllers are located close to the gNBs with a small network delay. The main feedback control difficulty is then the rapidly varying air interface fading ([3], [12]) and the associated queues that result in delay and jitter. By resorting to URLLC properties of the NR air interface it is then possible to use existing field buses and associated transmission schemes like those of the PROFINET™ ([10]) depicted in Figure 4. When applied wirelessly, these schemes recognize that the transmission times of control- and feedback signals may vary, however *variations are assumed to be contained within specified ranges consistent with the control cycle and bus-cycle times shown in Figure 4*. The discretized control signals can then be computed assuming they take effect in the plant at a specified time of the bus cycle interval, while the feedback signals can be assumed to have been measured close to the beginning of an adjacent bus cycle interval. In this way, a regular and *fixed* sampling period can be secured. In case the controller node is synchronized to the plant node as for the PROFINET™ Synchronized Real-Time Communication transmission scheme, the timing of the control and feedback sampling becomes very accurately defined, while an additional delay is present for the PROFINET™ Non-Synchronized Real-Time Communication transmission scheme.

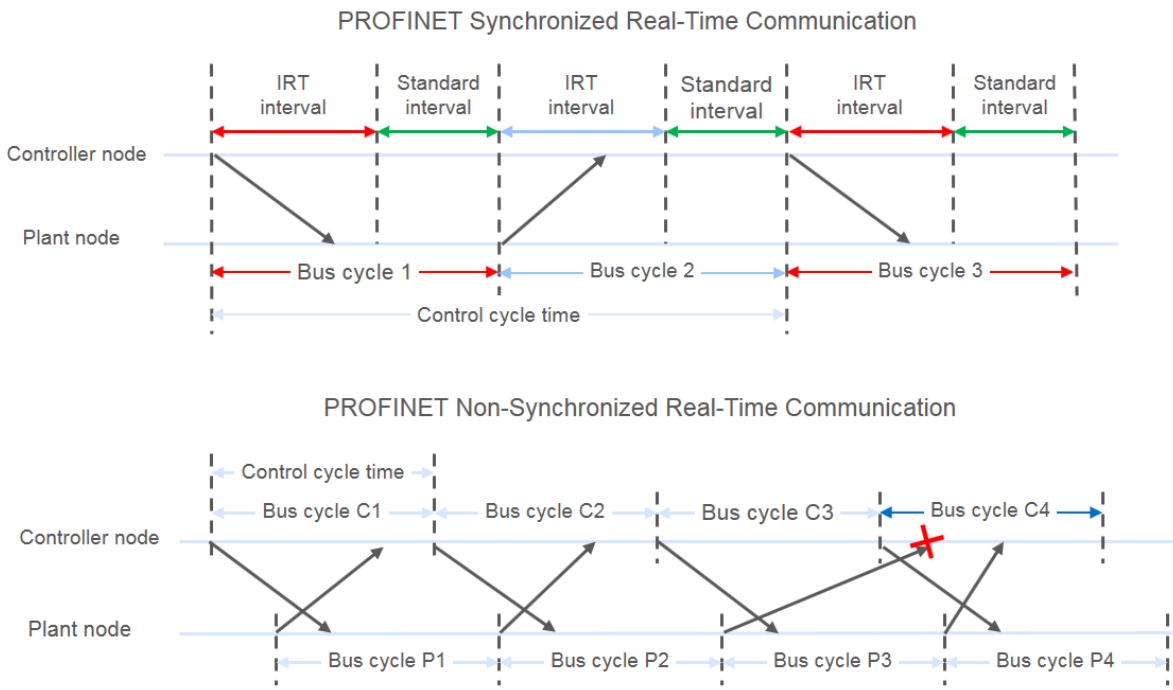

Figure 4: *An example of the operation of PROFINET™ synchronized and non-synchronized transmissions (IRT stands for Isochronous Real-Time Communication). The red cross indicates a late feedback signal transmission. Here, the outer- and inner-loop controllers of Figure 5 are optional.*

Delay Control and Alignment

Internet Delay Control and Alignment Algorithms

The transmission control protocol (TCP) and active queue management (AQM) algorithms provide basic delay control over internet connections, see [2]. Modern variants of AQM, for example the bottleneck bandwidth and round-trip propagation time (BBR) algorithm [1], use techniques to estimate the available bandwidth, and to carefully regulate the application data flows to just utilize the available bandwidth, with minimal buffering. A careful on-line analysis of the time history of the round-trip delay is used to allow operation at the optimal operating point. To achieve this, estimates of the minimum achievable round-trip delay and the bottleneck bandwidth are generated, using deliberately induced short bursts of bottleneck queue filling and emptying. For systems where the path and the bottleneck queue does not change, this produces a consistent, minimal round-trip delay data flow. When either the network path or the bottleneck queue changes, variable round-trip delay will continue to be experienced, however as argued in [1], in many cases, the variation in the delay will take place over a slower time scale than the variation of the application traffic flow. In principle multiple instances of, for example, the BBR algorithm may be applied to the networked multi-point control structure of Figure 5. Further research is however needed to see whether these algorithms can be adapted to the URLLC time scale, and to the handling of "delay misalignment". This term refers to the time difference between delays encountered by the data paths in a multi-point connection due to the differently fading NR air interfaces. These time differences may introduce significant delay variability when switching between the data paths occurs. Another approach to achieve delay alignment is to use buffering, which is applied in [14]. The additional buffering delays are added to obtain regulation headroom, so that a consistent overall delay results.

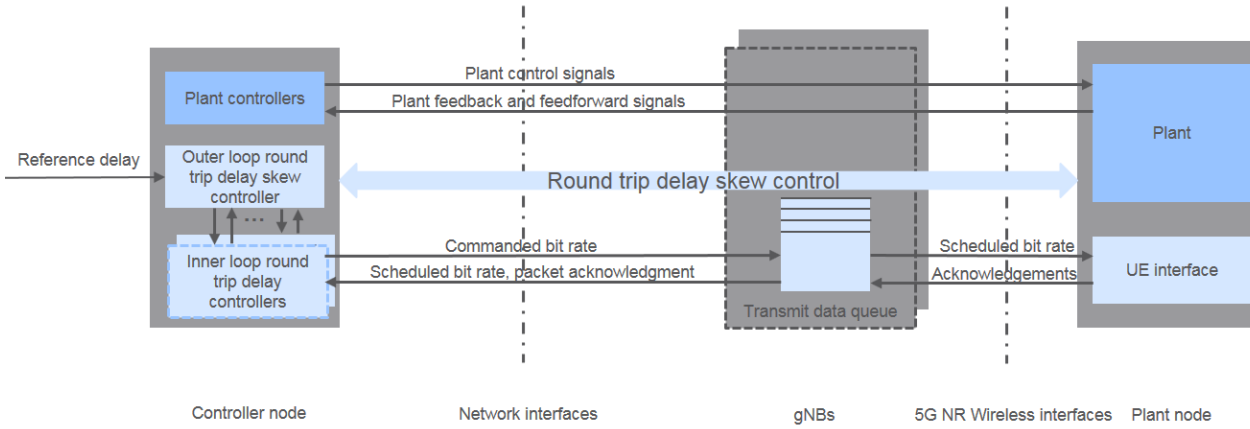

Figure 5: *A general block diagram of a networked control system with the control system and plant located in different nodes. The interfaces constitute a combination of wired network interfaces and wireless interfaces. Control- and feedback signals are routed over the gNBs that handle multi-point transmission/reception to/from the UE, for further distribution to/from the plant. The application control layer is shown blue, with delay aligning functionality appearing in light blue.*

Delay skew control

A related approach to the one of [14], though with lower overall latency has been pursued in [5] and [11]. Here NR multi-point and multi-flow systems are considered, and delay *skews* are controlled. Delay skew is defined as the deviation of the overall timing (e.g. round-trip delay) of a data path, to the timing of a selected reference data path. Then, feedback regulators can be designed, that control the data rates to the transmission queues of the gNBs. These control actions adjust the momentary dwell time delay of each gNB transmission queue, to maintain the desired round-trip delay of each data path. Such a delay skew controller is depicted in Figure 6. It controls the round-trip delays of the data paths to meet set delay skew reference values (typically 0), using a total delay budget set by the delay sum reference value. The transmission queues hence act as actuators. Static decoupling is applied, so that the round-trip delay of each data path can be separately controlled. The control signals of the outer loop controller filters become round-trip reference delays for the inner loop controllers, after limitations to secure the positivity of the reference values. The inner loop controllers are instances of the globally stable data flow controller of [15], which computes the data rate to each transmit data queue.

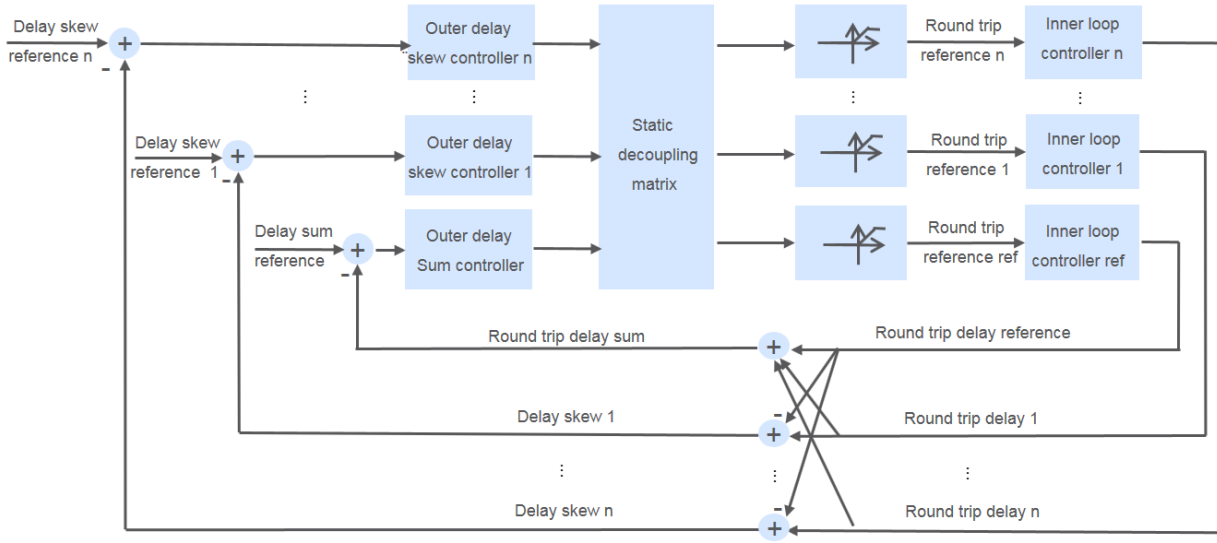

Figure 6: *Block diagram generalized to n nodes from the multi-point round trip delay skew controller of [5], [15], operating in the controller node of the block diagram of Figure 5.*

Simulated three path delay skew control

To illustrate the achievable application layer performance, three gNBs of a multi-path transmission network was investigated. The target was to control the application layer round-trip delay to 5 ms for all data paths. The wireless air interface data rates were obtained from system simulations. The delays of the connections from the input queues of the gNBs to the air interface and back varied as in Figures 7 (a) and 7 (b). The reference values of Figure 6 for the delay sum was $3 \times 5\ ms = 15\ ms$, while the delay skew references were $0\ ms$. The sampling rate was $2000\ Hz$. The results in Figure 7 (c) show that when the delay of a data path increases, the corresponding transmit queue dwell time is reduced to match the increase. This keeps the round-trip time close to 5 ms for each data path, see Figure 7 (d). Note that the delay skew control cannot be perfect, the reason being the loop delays themselves that prevent control action to take effect directly based on present feedback measurements. However, the steady state standard deviations of the round-trip delays of the data path are kept close to 1 ms. Finally, the delay skew controller requires a fraction of the interface capacity for feedback signaling, as would the BBR algorithm [1]. This fraction is small since it consists of acknowledgements of received data packages.

Conclusions

Delay, with its inevitable increase in phase angle of a feedback response is a traditional enemy of feedback control loops. Large delays, unknown delays, and time varying delays all require careful attention in real-time feedback applications over NR communication systems. Modifications of feedback control compensators at the application level may be employed to mitigate the effects of delays. In addition, the use of bounding may make the application control signals consistent with the frames of wireless fieldbuses for factory automation. The paper also showed how modifications of flow management protocols can be applied to minimize delay variability and achieve delay alignment for NR multi-point transmission. This strategy can also be used for non-factory use cases like V2V communication and mobile virtual reality.

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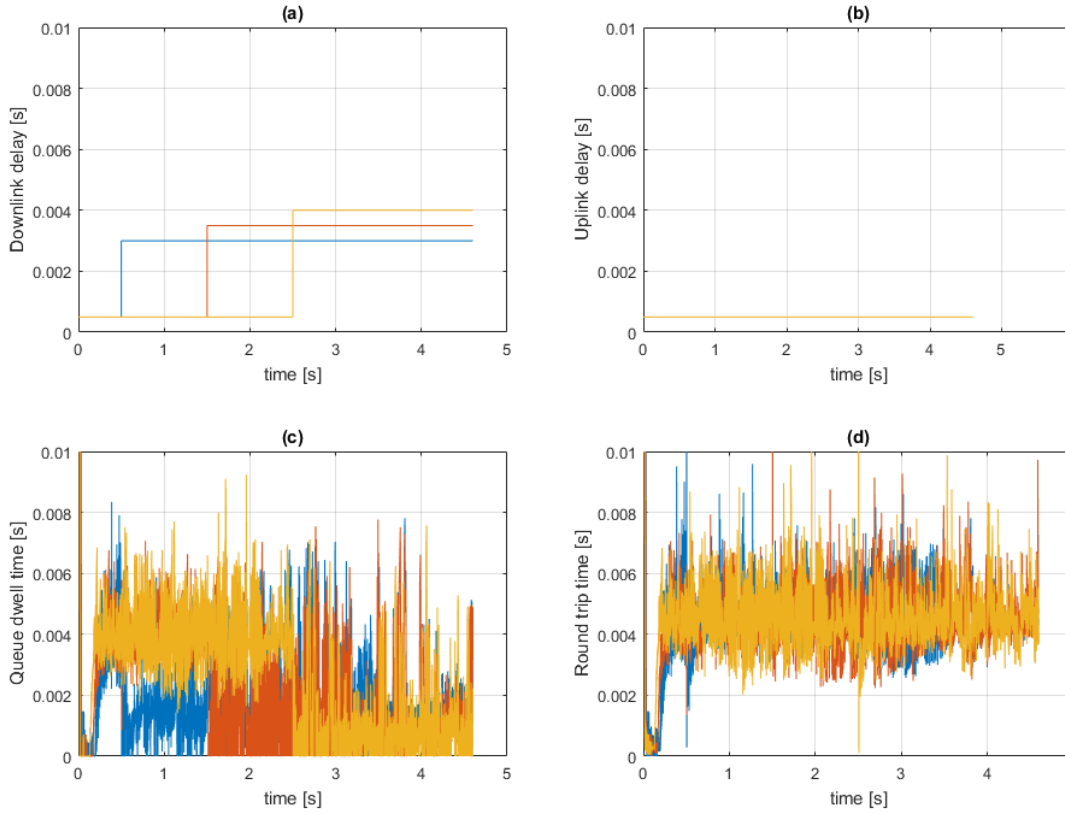

Figure 7: *Color-coded (per data path) delays ((a) and (b)), queue dwell times (c) and resulting round-trip times (d).*

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