FEEDBACK CONTROL APPLICATIONS IN NEW RADIO

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Exploring Delay Control and Alignment

Richard H. Middleton, Torbjörn Wigren, Lisa Boström, Ramón A. Delgado, Katrina Lau, Robert S. Karlsson, Linda Brus, and Eddie Corbett

In a new radio (NR) communication system, low latency and limited jitter are critical to support new use cases exploiting haptic feedback and other closed-loop feedback control applications. Therefore, mechanisms for delay control and delay alignment are important. The simplest approaches to mitigating delay jitter, using buffering techniques, come at the 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 this article is to discuss and motivate recognition of the need for delay alignment in general.

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Delay in Modern Communication Systems

Delay is inevitable in modern communication systems, such as those for 5G NR. Several sources contribute to this delay, as exemplified by the vehicle-to-vehicle (V2V) control setup of Figure 1(a)–(f): these include Internet transport delays between the data source node and the NR base stations (gNBs), including input queue delays [Figure 1(a)]; delays to the transmission queues in the gNBs [Figure 1(b)]; transmission queue dwell time delays in the gNBs [Figure 1(c)]; radio transport delays [Figure 1(d)]; NR air-interface delays [Figure 1(e)]; and user equipment (UE) processing delays [Figure 1(f)].

The Internet transport delays 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

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(temporal variations in delay) to the delay [1], [2]. The delays depend on the transport technology between the gNBs. The transmission queues in the gNBs reduce the effect of the rapid radio interface data rate variations due to fading or interference [3]. Therefore, the queue dwell-time delays need to be approximately 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 gNBs to the advanced antenna system (AAS) radios are usually small with low latencies. The air interface of NR is designed to have a very low latency, with some jitter introduced by retransmissions [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.

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 the 3rd Generation Partnership Project (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, for example, self-driving trucks—are treated by using the listed requirements on discrete automation and motion control. Refined factory automation requirements and expected performance can be found in [8]. Automation in process industries is addressed by the process automation use cases [7]. Since a low delay makes it more difficult 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.

THE TCP AND ACTIVE QUEUE MANAGEMENT ALGORITHMS PROVIDE BASIC DELAY CONTROL OVER INTERNET CONNECTIONS.

The NR air interface specifications fulfill the 1-ms delay requirement with margin, in particular for millimeter-wave (mm-wave) frequencies [4]. This is because the cell radii are generally smaller at mm-wave 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 mm-wave air interface resource grid to rely on higher subcarrier spacing, with a proportionally lower symbol time, down to about 1/100 ms,

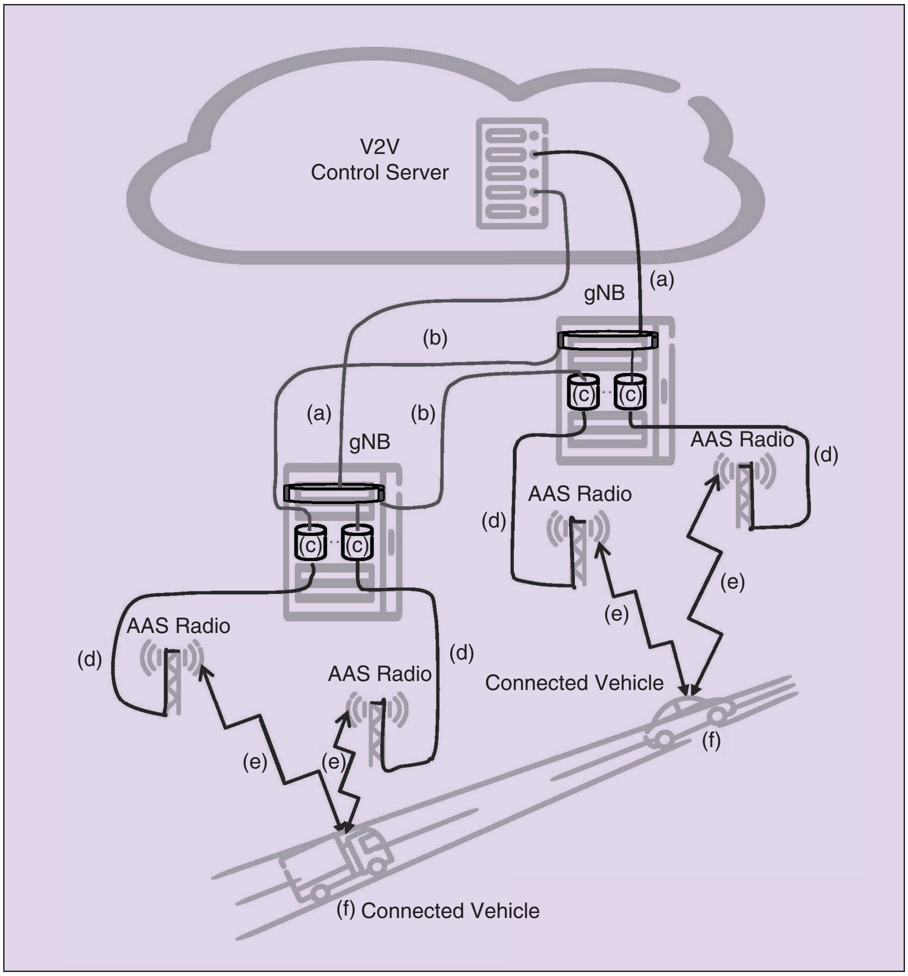

FIGURE 1 (a)–(f) Sources of delay and jitter in a V2V control network. The signal paths (a)–(e) (dark) carry information both in downlink and uplink. Queues are used to mitigate radio fading. An example supervisory control loop for autonomous driving could consist of a controller in a cloud server using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

A CAREFUL ONLINE ANALYSIS OF THE TIME HISTORY OF THE ROUND-TRIP DELAY IS USED TO ALLOW OPERATION AT THE OPTIMAL OPERATING POINT.

TABLE 1 End-to-end delay, jitter, and reliability requirements for feedback control use cases.

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%

(Source: [7, Table 7.2.2–1]).

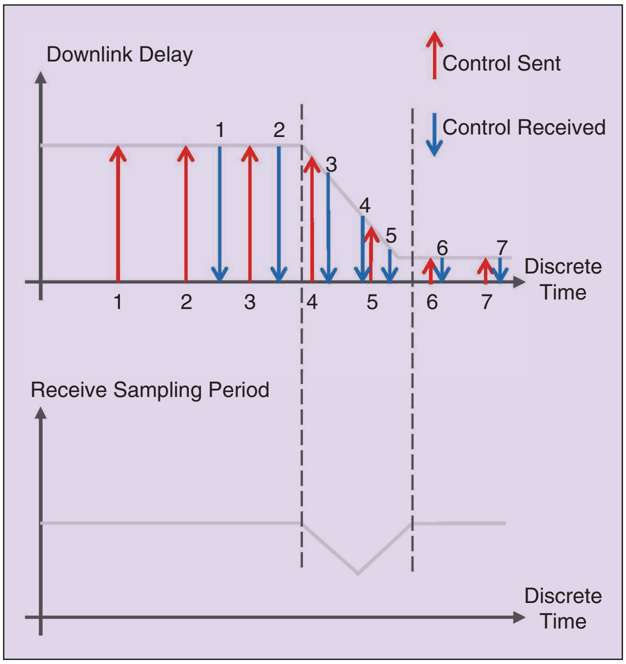

FIGURE 2 Uniform samplings of control signals in a controller node become irregularly sampled in the plant node (that is, the node where the application layer interfaces with the physical device to be controlled) when the delay throughout the interface between the nodes varies.

for a subcarrier spacing of 240 kHz [4, Tables 4.2-1 and 4.3.2-1]. The end-to-end air interface delay is therefore reduced at mm-wave frequencies, provided that the UE processing delay can be correspondingly reduced. However, motion control and discrete automation jitter requirements may necessitate additional solutions.

These uses cases motivate us to consider delay control and alignment, and the focus is on the 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, uncompensated, 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 using the classical Nyquist stability criterion 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

In addition to 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, through the interfaces of Figure 1, leads to sampling period variations at the feedback control application layer, as illustrated by Figure 2. This can be compensated for, either by introducing performance-reducing margins or by applying time-variable sampled control [5]. These compensation methods do, however, suffer from both significantly increased computational complexity and much-reduced stability guarantees [5].

In many versions of the transmission control protocol (TCP)/Internet protocol (IP), 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, because significantly delayed information is useless for feedback control. Note that rapid capacity variations may be experienced in factory environments where moving metal objects can block transmission paths [12]. NR and related 5G systems are likely to depend on multiconnectivity to enhance the coverage for the high mm-wave frequency bands [3], [13]. This may add to the jitter, because noncollocated radio interfaces fade independently, but a correct controlled split of data may decrease the jitter by utilizing 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 use the augmented model for controller design (see Figure 3). In case of jitter, the controller would also need to be frequently retuned. 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.

Aligning the Delay in Industry NR Networks

One could also resort to using NR ultrareliable low-latency communication (URLLC) protocols [4] to reduce the delays, because this is a hallmark of NR. Doing so entails the use of techniques such as grant-free access, with consequent tradeoffs in throughput and additional switching overheads. Moreover, in cases where the application feedback controllers are in the cloud (see 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 and consistent latency, without relying on URLLC. This can be achieved by delay regulation and 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

THE STEADY-STATE STANDARD DEVIATIONS OF THE ROUND-TRIP DELAYS OF THE DATA PATH ARE KEPT CLOSE TO 1 MS.

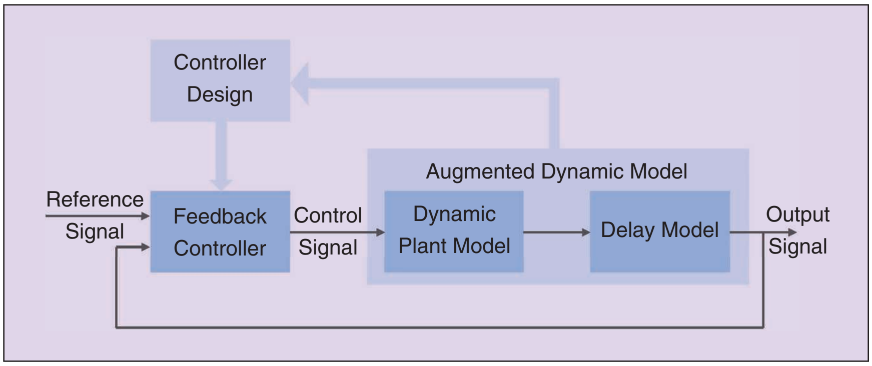

FIGURE 3 The principle of delay-compensating controller design.

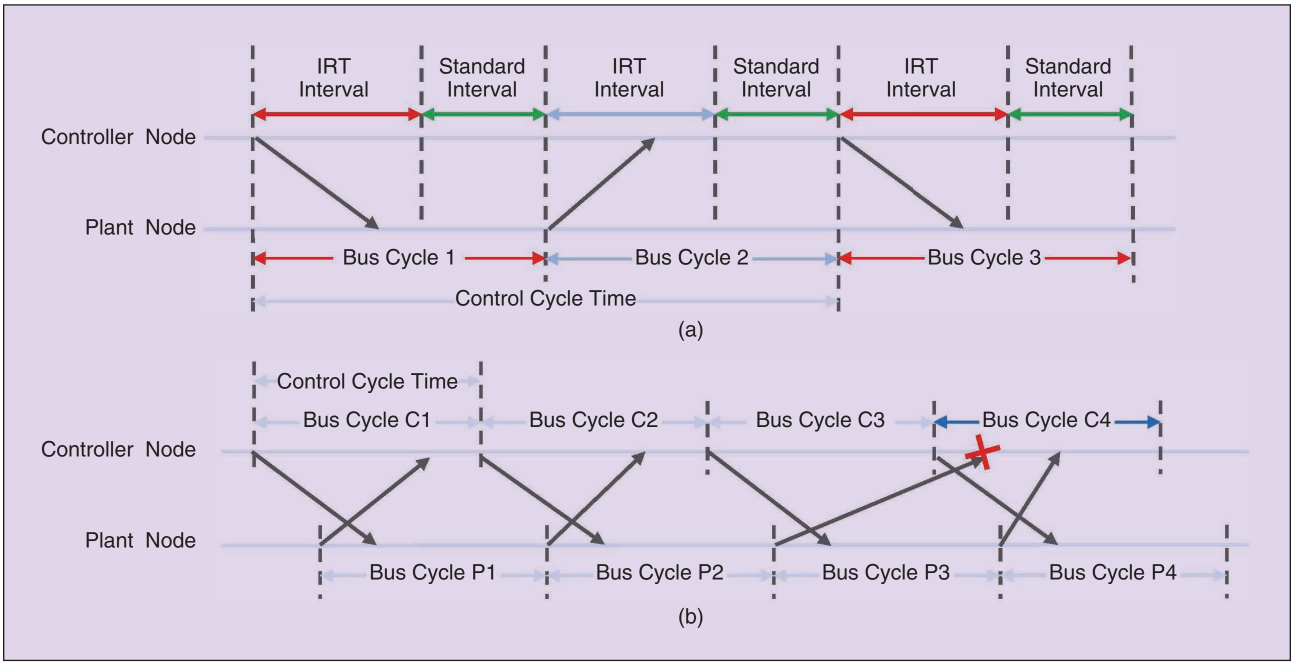

FIGURE 4 An example of the operation of PROFINET (a) synchronized and (b) nonsynchronized transmissions. The red cross indicates a late feedback signal transmission. Here, the outer- and inner-loop controllers of Figure 5 are optional. IRT: isochronous real-time communication.

MODIFICATIONS OF FEEDBACK CONTROL COMPENSATORS AT THE APPLICATION LEVEL MAY BE EMPLOYED TO MITIGATE THE EFFECTS OF DELAYS.

interface fading [3], [12] and the associated queues that result in delay and jitter. By resorting to the URLLC properties of the NR air interface, it is possible to use existing fieldbuses 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. If 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 nonsynchronized, real-time communication transmission scheme.

Delay Control and Alignment

Internet Delay Control and Alignment Algorithms

The TCP and active queue management (AQM) algorithms provide basic delay control over Internet connections [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 carefully regulate application data flows to utilize only the available bandwidth, with minimal buffering. A careful online 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 do 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 during a slower time scale than the variation of the application traffic flow will.

In principle, multiple instances of, for example, the BBR algorithm may be applied to the networked multipoint control structure of Figure 5. Further research is needed, however, 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 among delays encountered by the data

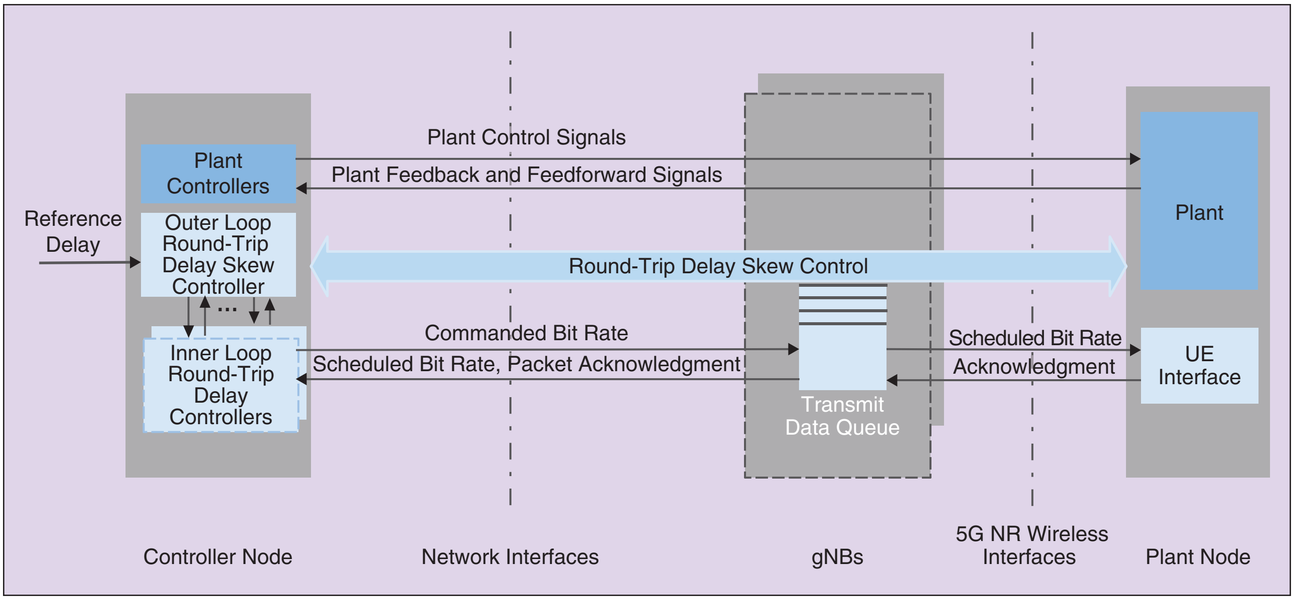

FIGURE 5 A general block diagram of a networked control system with the control system and plant located in different nodes. The interfaces constitute a combination of wired network interfaces and wireless interfaces. Control and feedback signals are routed over the gNBs that handle multipoint transmission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

paths in a multipoint connection due to the differently fading NR air interfaces. These time differences may introduce significant delay variability when switching occurs between the data paths. 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.

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 multipoint and multiflow systems are considered, and delay skews are controlled. *Delay skew* is defined as the deviation of the overall timing (e.g., the round-trip delay) of a data path from 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 zero) using a total delay budget set by the delay sum reference value. The transmission queues thus act as actuators. Static decoupling is applied so that the round-trip delay of each data path can be separately

MODIFICATIONS OF FLOW MANAGEMENT PROTOCOLS CAN BE APPLIED TO MINIMIZE DELAY VARIABILITY AND ACHIEVE DELAY ALIGNMENT FOR NR MULTIPOINT TRANSMISSION.

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.

Simulated Three-Path Delay Skew Control

To illustrate the achievable application layer performance, three gNBs of a multipath transmission network were 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 shown in Figure 7(a) and (b). The reference value of Figure 6 for the delay sum was $3 \times 5 = 15$ ms, while the delay skew references were 0 ms. The sampling rate was 2,000 Hz. The results in Figure 7(c) show that, when the delay of a data path increases, the corresponding transmit queue

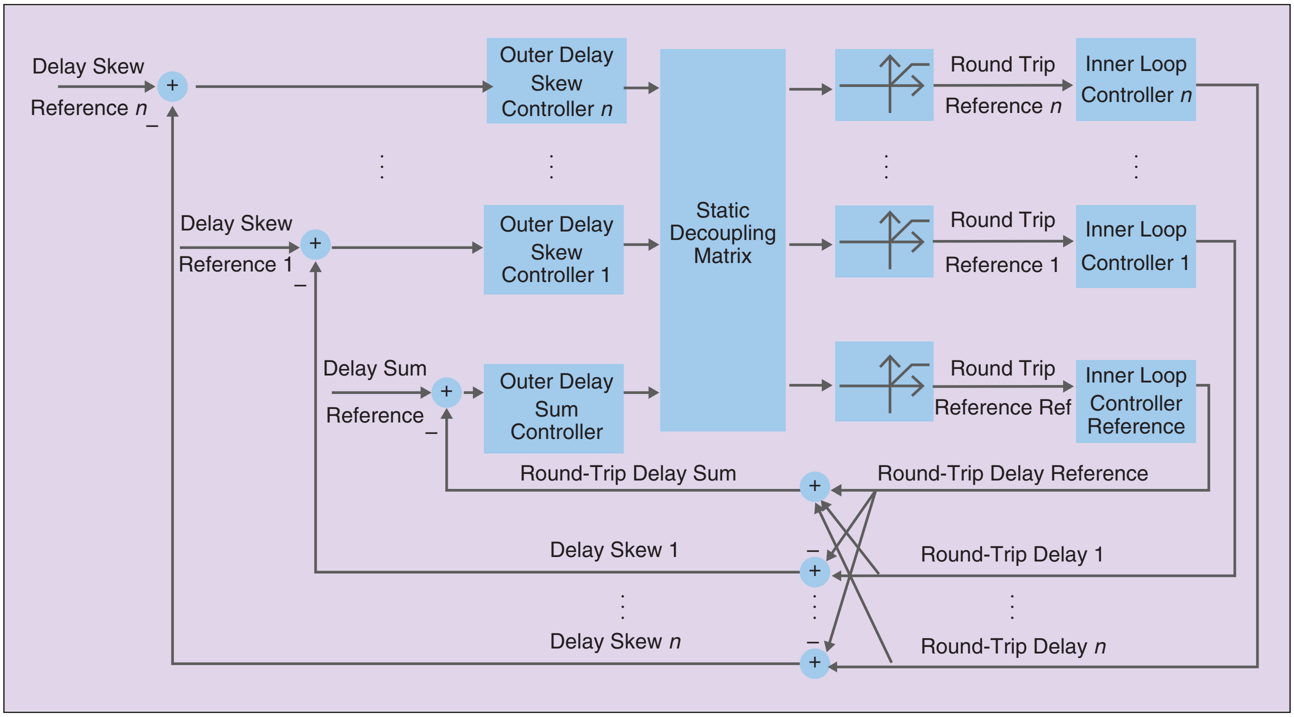

FIGURE 6 A block diagram generalized to n nodes from the multipoint round-trip delay skew controller of [5] and [15] operating in the controller node of the block diagram of Figure 5.

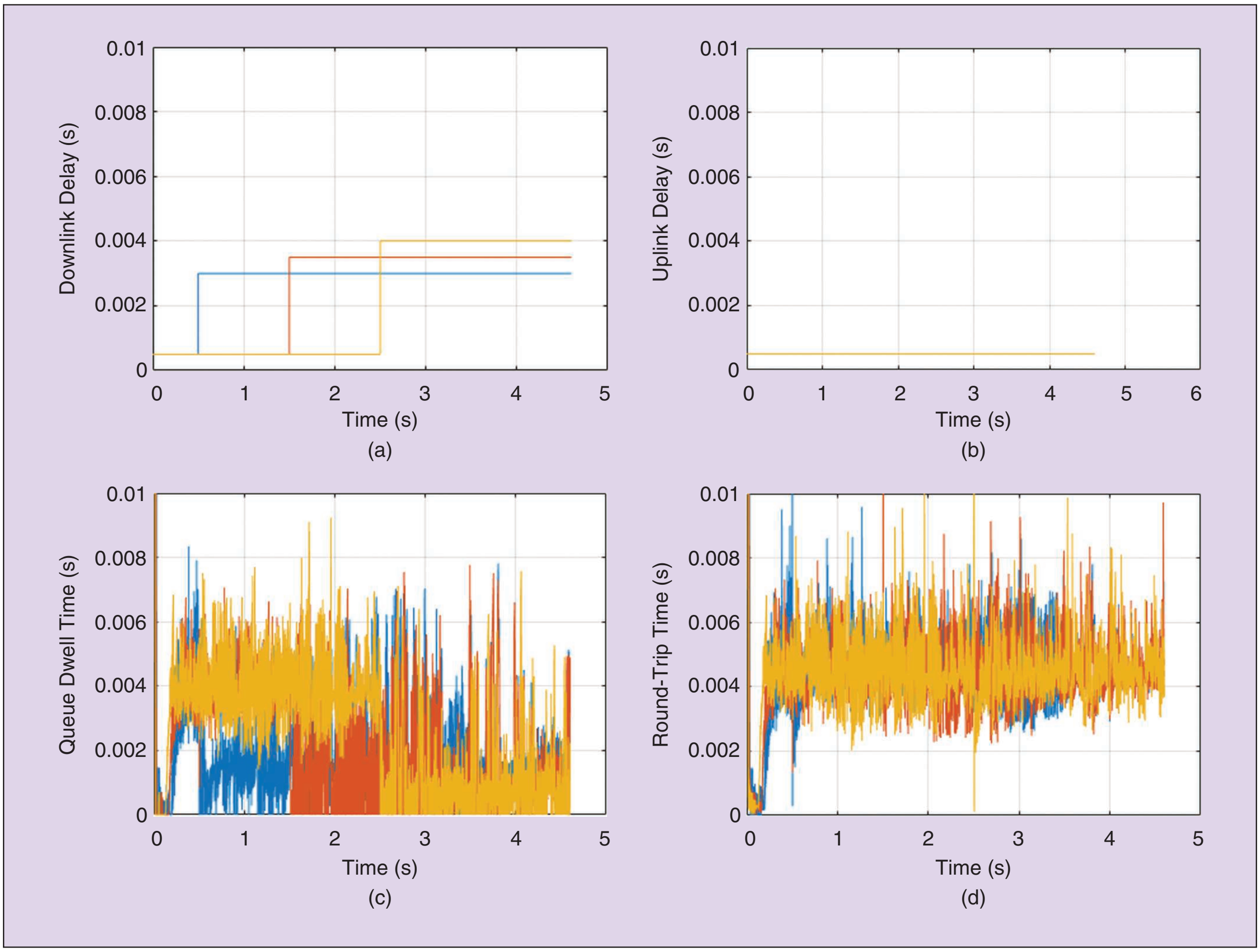

FIGURE 7 The (a) and (b) color-coded (per data path) delays, (c) queue dwell times, and (d) resulting round-trip times.

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 that the loop delays themselves 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 because it consists of acknowledgments of received data packages.

Conclusions

Delay, with its inevitable increase in the 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. Furthermore, this article showed how modifications of flow management protocols can be applied to minimize delay variability and achieve delay alignment for NR multipoint transmission. This strategy can also be used for nonfactory use cases, such as V2V communication and mobile virtual reality.

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Author Information

Richard H. Middleton (richard.middleton@newcastle.edu.au) received his Ph.D. degree from the University of Newcastle, Australia, in 1987, where he is currently a professor. His research interests include a broad range of control systems theory and applications. In 2011, he was president of the IEEE Control Systems Society. He is a Fellow of the IEEE.

Torbjörn Wigren (torbjorn.wigren@ericsson.com) received his M.Sc. degree in engineering physics and his Ph.D. degree in automatic control from Uppsala University, Sweden, in 1985 and 1990, respectively. He is with Ericsson AB, Stockholm, Sweden, where he works with signal processing and control for the new radio (NR) system. His research interests include nonlinear networked system identification and control for wireless networked systems, like NR.

Lisa Boström (lisa.bostrom@ericsson.com) received her M.S. degree in media engineering from Luleå University of Technology, Sweden, in 2006. She is with Ericsson AB, Stockholm, Sweden, where she works with research and concept development for 5G. Her research interests include critical communications and the Industrial Internet of Things.

Ramón A. Delgado (ramon.delgado@newcastle.edu.au) received his M.S. degree in electronic engineering from Universidad Técnica Federico Santa María, Chile, in 2009. He received his Ph.D. degree in electrical engineering from the University of Newcastle, Australia, in 2014, where he is currently a research academic. His research interests include system identification, control, signal processing, and optimization.

Katrina Lau (k.lau@newcastle.edu.au) received her B.E. degree in electronics and her B.Math. and Ph.D. degrees from the University of Newcastle, Australia, in 1997, 1999, and 2003, respectively. Since then, she has been a research academic working on a number of industrial projects. She is currently working on next-generation control and telecommunications problems with Ericsson AB. Her research interests include fundamental performance limitations, switched control systems, and stability analysis.

Robert S. Karlsson (robert.s.karlsson@ericsson.com) received his M.S. degree in electrical engineering and his Ph.D. degree in radio communication systems from the Royal Institute of Technology, KTH, Sweden, in 1995 and 2001, respectively. Since 2008, he has been with Ericsson AB, Stockholm, Sweden, where he works on the standardization of new radio. His research interests include algorithms for radio resource management, admission control, overload handling, scheduling, and link adaptation.

Linda Brus (linda.brus@ericsson.com) received her Ph.D. degree in electrical engineering, specializing in automatic control, from Uppsala University, Sweden, in 2008. She is with Ericsson AB, Stockholm, Sweden, where she works as strategic product manager in Business Area Networks. Her research interests include nonlinear system identification and automatic control of challenging problems in wireless network systems.

Eddie Corbett (eddie.corbett@ericsson.com) received his M.S. degree in technology management from University College Dublin, Ireland, in 2005. He is with Ericsson AB, Stockholm, Sweden, where he works as an R&D manager for radio resource management of the new radio system.

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