Jitter Suppression for Very Low Latency Feedback Control Over NR

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***Abstract*—The 5G New Radio standard is intended to support delay and reliability critical use cases, reaching round-trip latencies at least as low as 1 milli-second, and error rates of the order of 10^{-6}. This paper first summarizes why redundant transmission over independent wireless interfaces is beneficial to meet the reliability requirements. Redundant transmission then leads to a need for delay aligning control between the data paths. However, due to high bandwidth radio channel fading and the physical end-to-end delay itself, remaining high bandwidth jitter is shown to require a substantial back-off with respect to the URLLC delay requirement. The main contribution of the paper therefore proposes the use of UE and gNB combining of redundant decoded application control data, received over the wireless interfaces. Simulations show that the use of 3-4 independent and redundant data paths allows a 1 milli-second high reliability requirement to be met, at an error rate of 10^{-5}, with a delay back-off of 25-30%, as compared to more than 400% without redundancy processing.**

***Index Terms*—5G, C-MTC, Delay control, Feedback control, Jitter, Latency, New Radio, Redundancy, Reliability, URLLC.**

I. Introduction

Feedback control applications will be at the focal point when the New Radio (NR) system is deployed. The Ultra Reliable Low Latency Communication (URLLC) standard [1], [2], e.g. specify reliability, delay and jitter requirements for a variety of new use cases. These include tactile interaction over the wireless internet [3], [4], applications in intelligent and safety critical transportation systems, [5], [6], and motion control in factory automation [7], [8]. Many of these use cases share error rate requirements in the 10^{-6}-10^{-4} range, together with close to 1 milli-second latency and jitter requirements. The delay and jitter requirements are easy to understand for use cases that involve feedback control, since delay and jitter impair performance as well as compromise fundamental stability requirements of the application controllers, see e.g. [2], [9], [10]. The reliability requirements are derived from existing *wired* factory automation systems, that NR is supposed to replace with similar performance, see [1] and [7].

To meet the URLLC requirements, new methods to tackle high bandwidth jitter remaining after round-trip delay and delay skew control need to be applied, Fig. 1. The reason for the high bandwidth jitter is the high bandwidth fading of the wireless channels that cause a corresponding rapid variation of the data rate over the wireless interfaces. The data volume and the latency of the transmit data queues of the gNBs (base stations) will therefore vary with the same high bandwidth. Furthermore, the delays inherent in the wireless and network interfaces cause delays in the uplink delay and delay skew feedback signaling, as well as in the downlink delay and delay skew control signaling of Fig. 1. Delay and delay skew feedback control actions therefore arrive late at the transmit data queues that act as actuators. The high bandwidth delay variations caused by fading can therefore *never* be completely compensated for by any type of delay control loop. Hence high bandwidth jitter is inevitable in URLLC.

Previous delay and delay control schemes typically vary the data volume in a queue, that is used as an actuator. Active queue management (AQM) algorithms vary queue data volumes by means of intentional discarding of data packets. When the transmission control protocol (TCP) is used, this results in a reduction of the data rate from the data source [12], thereby achieving round-trip delay control. More modern variants include the bottleneck bandwidth and round-trip propagation time (BBR) algorithm that monitors round-trip time and bandwidth, to optimize the data rates [13]. However, both AQM in general, and BBR in particular, need to be further studied to better understand their multi-point wireless operation. Control-theoretic based delay and delay skew controllers for multi-point transmission, based on high bandwidth feedback measurements of round-trip delays and delay skews, have been developed in [14]–[17]. These controllers provide the starting point for the present paper. They use the gNB transmit queues, i.e. the radio link control (RLC) buffers, as actuators that are manipulated with the application plant data rates determined by the delay skew controller. Referring to Fig. 1, the delay skew controllers of [14], [16] and [17] all exploit the inner loop delay controller of [15]. The reason for this is that the inner loop delay controller is proven to be globally stable in [15] using the classical Popov criterion [10]. The more general method of integral quadratic constraint (IQC) analysis of [18] underpins the proof of global stability of [17].

Since none of the above delay and delay control schemes can suppress high bandwidth jitter, other solutions are needed. A first option is to back-off and control the application delay at a much lower reference value than the URLLC delay requirement. This is undesirable since the increased sampling rate increases the lowest delay that NR can handle [19],

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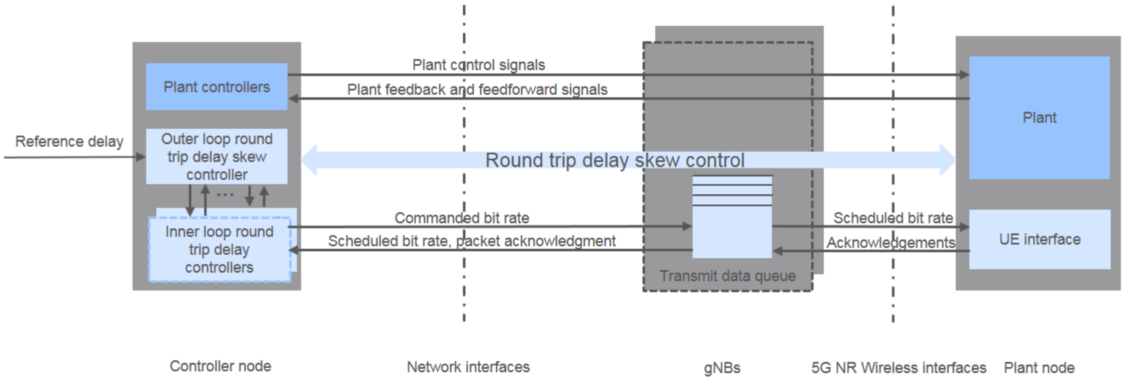

Fig. 1. Delay and delay skew control in a multi-point transmission architecture. The application plant control loop (dark blue) exploits delayed control user data that is transparent to the underlying delay skew and delay control loop (light blue) between the controller node and the plant node (grey). The round-trip delay skew controller uses the application control data rates as control signals and the transmit data queues as actuators, cf. [2], [11]. Multiple gNBs (grey) are used to implement redundant transmission over independent wireless interfaces, which explains why the *delay skew* between the data paths needs to be feedback controlled, in addition to the mean delay. The UE provides the plant node user interfaces. Multiple RF chains or multiple UEs may be needed unless a coordinating scheduler would control a single time-frequency grid.

[20]. Another option proposed here is to use a selection processing algorithm over multiple redundant application data paths, at the receiving ends of the downlink (in the UE) and the uplink (in the controlling node). The redundant data paths are obtained by replication of application control signals in the controlling node and by replication of application feedforward and feedback signal data in the UE. The details of the selection processing, and an evaluation using test bed software simulation, constitute the main contribution of the paper.

The paper is organized as follows. Section II sets out to motivate the need for redundant application data transmission and delay skew control, to meet URLLC requirements. The algorithms for selection processing of redundant data paths are then presented in section III, followed by a performance evaluation in section IV. Conclusions appear in section V.

II. URLLC Requirements, Redundancy and Delay Skew Control

A. URLLC requirements

Organizations such as the third generation partnership project (3GPP) publish requirements on URLLC performance, to establish a common ground for system design. One such sub-set of requirements can be found in Table I. As can be seen, motion control, high voltage electricity distribution and tactile interaction all share application error rate requirements in the 10^{-6}-10^{-4} range, end-to-end delay requirements close to 1 milli-second and sub milli-second jitter requirements, all of which need to be met simultaneously. Similar requirements occur in automotive safety applications. It can be noted that the jitter requirements can often be relaxed by a back-off of the delay requirement since many industrial field bus systems like the PROFINET are frame based [2], [7].

It is the feedback control application itself that should determine the needed requirements. A strict implementation following the tabulated values below may then not be needed,

TABLE I
End-to end delay, jitter and reliability requirements for selected feedback control use cases [1, Table 7.2.2-1].

Use Case	End-to-End Delay	Jitter	1-Reliability
Discrete automation: motion control	1 ms	1 µs	1e-6
Discrete automation	10 ms	100 µs	1e-4
Process automation: remote control	50 ms	20 ms	1e-6
Process automation: monitoring	25 ms	20 ms	1e-3
Electricity distribution: medium voltage	5 ms	25 ms	1e-3
Electricity distribution: high voltage	10 ms	1 ms	1e-6
Tactile interaction	0.5 ms	TBD	1e-5

and could lead to increased cost. The present paper will therefore focus on a case with an error rate of 10^{-5}, an end-to-end delay of 1 milli-second, where the allowed jitter is set by the requirement that the jitter is contained in the delay requirement with a likelihood significantly better than 10^{-5}.

B. Reliability requirements and multi-point transmission

The NR mobile broadband transmission is designed around HARQ re-transmission and link adaptation concepts. Here the operating range for the block error rate (BLER) is typically in the 1-10% region, i.e. typically below a reliability of 0.99. Furthermore, the low end-to-end delay may prevent any significant use of HARQ re-transmission [19], [20]. Hence, current link adaptation design may be inconsistent with the reliability requirements of Table I.

The consequence is that redundant transmission of application plant feedback control commands and application plant feedback signals over multiple data paths and independent wireless interfaces may be needed. To quantify this need, assume that the wireless interfaces of Fig. 1 are the dominant source of application data errors. Further assume that each of the n wireless interfaces has a data error rate of p_i, $i = 1, \ldots, n$. If the wireless interfaces fade independently and a desired application data reliability of at least r is desired, it follows that n needs to meet the following inequality

$$r \leq 1 - \prod_{i=1}^{n} p_i \qquad (1)$$

In case the wireless data error rates all equal p, the following value for dimensioning of the number of data paths results:

$$n = \mathrm{ceil}\left(\frac{\ln(1-r)}{\ln(p)}\right). \qquad (2)$$

It can be noted that the most demanding use cases of Table I require at least 3 redundant paths if reliability alone is considered for $p = 10^{-2}$.

When URLLC application feedback control is implemented close to the gNB, the application data path split and data replication can be performed close to the Packet Data Convergence Protocol (PDCP) layer, leading to a generalization of standardized dual connectivity functionality to multi connectivity. Another alternative for multi-point transmission and reception would be to exploit carrier aggregation (CA). However, CA would only use one delay controller from the PDCP layer to the RLC layer. In this paper the multi connectivity alternative is treated since the delay control redundancy from PDCP to RLC may serve to further enhance the jitter suppression.

C. Delay requirements and delay skew control

1) Delay requirements: Meeting an end-to-end loop delay requirement of 1 milli-second is challenging since the requirement includes uplink and downlink network delays, transmit queue delays, uplink and downlink wireless interface delays as well as UE delays. Yet, the NR standard is designed to enable even sub milli-second end-to-end delay, however then with very small contributions from the network and the transmit queues. The requirement to use redundant application data transmission over independent wireless interfaces to meet the reliability requirements complicates the situation further, motivating the need for delay skew control. In this context it is very important to note that control loops require real time feedback. In particular, a late control or feedback signal is in effect a lost piece of data! This is so since feedback control actions need to be based on the current system state. Delayed actions or measurements give past information, and it is well known (see for example [2], [14]) that delay in feedback control systems can easily lead to instability.

2) Delay skew control: The globally stable delay skew controller applied in this paper is developed in [17], with a dual connectivity version appearing in [14]. Block diagrams relating to the description below appear in [2], [5] and [17] and are not repeated here due to size constraints. The delay skew controller measures the uniformly sampled real time round-trip-delay of $n+1$ data paths. This is done by registering the time of transmission of downlink application plant control packets from the controlling node close to the PDCP layer, until acknowledgements return. A total of n delay skew signals are then formed as differences between the round-trip delay of one selected reference data path, and each of the other round-trip delays of the remaining data paths. In addition, a round-trip delay sum is formed over all data paths, this signal is needed to perform a static decoupling of the delay skew control channels. The round-trip delay sum channel is subtracted from the delay sum reference value which determines the total delay budget distributed between the data paths. This forms the delay sum error signal. Delay skew error signals are formed in the same way. Due to the exact static decoupling derived in Theorem 1 of [17], each delay skew error signal can be separately controlled by a scalar outer delay skew controller filter with a high low frequency gain that allows unmodelled effects to be suppressed. This is a standard technique in automatic control, see e.g. [21]. After static decoupling the round-trip delay reference signals for the inner loop controllers are limited to positive values.

The inner loop controllers provide round-trip delay control, using the round-trip delay reference signals provided by the outer delay skew control loop. The inner loop controllers control delay by an embedding transformation to the data volume domain, where packets-in-flight control is performed as described in [15]. The number of packets in flight is hence the actuator that is adjusted by the commanded input bitrate. The inner loop control algorithm is proved to be unconditionally globally $\mathcal{L}_2$-stable in [15]. This property holds for any controller gain and underlying loop delay.

3) The need for additional jitter suppression: To understand why additional jitter suppression is needed, simulated round-trip delays for a four data path multi connectivity transmission appear in Fig. 2. The URLLC requirement to be met was 1.0 milli-second at the application layer. The delay sum reference value was therefore set to 4×0.75 milli-seconds and the delay skew reference signals were set to 0.0 milli-seconds. A sampling period of 125 micro-seconds was used, assuming availability of NR mini-slots, and /or implementation for higher bandwidth millimeter wave numerologies [2], [20]. This means that the target round-trip time for each data path was 0.75 milli-seconds. As can be seen the delay skew controller achieves the set reference value on average, but as stated in the introduction no delay skew control algorithm can compensate for the high bandwidth delay variations caused by high bandwidth fading in combination with the inherent loop delay. The high bandwidth fading impact on the round trip delays are due to sudden SINR variations, thus also flat channels cause problems. In the present case a back-off of more than 400% is needed to contain the jitter within the URLLC requirement of 1.0 milli-second. It is hence of great interest to develop high bandwidth jitter suppression algorithms, to support the delay skew controller that operates with a lower bandwidth.

III. Jitter suppression by selection processing

A. Data replication

The description assumes that the controller node is closely attached to the PDCP layer of an NR gNB, so that the delays

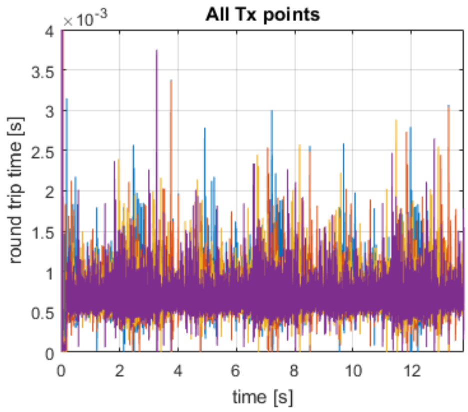

Fig. 2. Round trip delays of each of four delay skew controlled wireless interfaces. The generation of the simulated result is described in section IV-A.

between the controller node and the PDCP data queue are negligible as compared to the other delays of the application control loop. In the downlink, application plant control signals therefore enter the gNB PDCP layer queue, where a data replication mechanism creates multiple instances of each application plant control signal data item, at each regular sampling instance. One instance of each application plant control data item is then sent to a separate RLC queue, acting as a transmit data queue. The RLC queues may be implemented in different gNBs. Each RLC queue is managed by a scheduler that schedules each application plant control data item for transmission over a separate NR wireless interface, to the UE that acts as the plant node interface. The received data from the wireless interfaces are all sent to the new selection processing algorithm. The selected application plant control signal is then sent to the plant and applied for feedback control purposes. Note that the delay skew control algorithm operates between the PDCP layer and the RLC queues.

In the uplink the process is very similar, with the UE replicating feedback and feedforward signal data items at its PDCP layer, for transmission back to the PDCP layer of the gNB connected to the controller node. There, selection processing is applied for uplink jitter suppression.

B. Selection processing algorithm

The same selection processing algorithm may be applied in both the downlink and the uplink. The main objective of the algorithm is to reduce the (positive) high bandwidth variations of the round-trip delay experienced by the feedback control application, in and between different data paths. The selection processing algorithm operates by selection or combination of a subset of the received identical application plant control signal data items in the downlink, and similar for feedback and feedforward application plant signal data items in the uplink. To describe the main algorithmic alternatives, denote the round-trip delay associated with the ith data path by t_i.

The first alternative is then to use the data item that is first received in the UE, and in the gNB. That results in a round-trip delay (or time, RTT) given by

$$RTT = \min_i \, (t_i). \tag{3}$$

A second alternative would be to use the data item that is received in the middle of the transmitted data items, in the downlink and uplink. That results in a round-trip delay that is approximately

$$RTT = \operatorname{median}_i \, (t_i). \tag{4}$$

A third option is to use the kth received data item, to combine several received data items, or to use probabilistic methods.

IV. Performance and Gains

A. Testbed simulation software and data

The delay skew controller methods in the reference list are all implemented in a single configurable software (SW) used for tests. The SW is implemented in C++ and allows testing or simulation of delay skew control methods tailored for downlink delay skew control such as in [22], or for round-trip delay skew control needed for feedback control applications as specified for URLLC [14], [16], [17]. All delay skew controllers are scalable, and only require specification of the approximate maximum delay to be handled for the specific application, although the delays, inner loop control method, and controller gains of each data path may be set up separately. When applied for simulation, time varying delays can be used, and scheduled data rates generated over fading channels can be applied as in any system simulation tool.

B. Jitter suppression performance

To study the performance of the new jitter suppression algorithm, the delay skew controller of [17], applying inner loops defined by [15], was simulated with the C++ test software using 1, 2, 3, 4, 5 and 6 data paths. These simulations generated the round-trip delay data that were used to evaluate the selection processing algorithms described above.

As above, a URLLC use case requiring 1.0 milli-second delay with an application error rate better than 10^{-5} was studied, with the jitter included in the delay for a framed sampling field bus system [7]. This delay is intended to allow application plants with dynamics that tolerate roughly 1 milli-second delay, to be controlled over the NR URLLC system. Since the delay dynamics has a frequency function given by

$$H(f) = e^{-2\pi i f T}, \tag{5}$$

where T is the loop delay, and f is the frequency, 1.0 radian delay induced phase lag occurs at the frequency

$$f_T = \frac{1}{2\pi T} = \frac{1000}{2\pi} \, Hz \approx 160 \, Hz \tag{6}$$

This is a measure of the maximum bandwidth the closed loop application control system can reach.

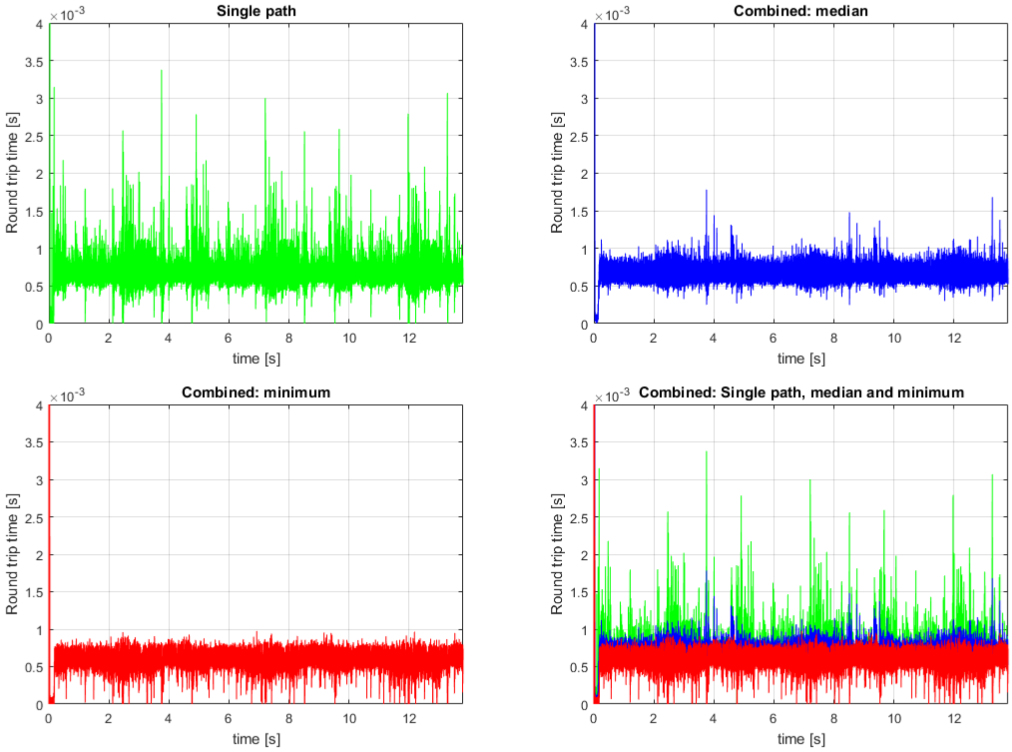

Fig. 3. Simulated application round-trip delay performance without redundant transmission and selection processing (green), with 4 redundant data paths and median round-trip time selection processing (blue), and with 4 redundant data paths and minimum round-trip time selection processing (red). The URLLC requirement is met with 10^{-5} error rate since the sampling period is 125 micro-seconds and the simulation time exceeds 12.5 seconds.

To meet the 1.0 milli-second URLLC application requirement, the delay skew controller was configured with a back-off to 75%, i.e. to 0.75 milli-second round-trip delay for all data paths. This means that the delay sum channel reference value was set to $n \times 0.75$ milli-seconds where n is the number of data paths. The delay skew reference values were set to 0.0 milli-seconds. In line with the control theoretic rule-of-thumb to use a sampling period roughly 10 times less than the dominating time constant of the dynamics of the controlled plant (here the round-trip delay), a sampling period of 125 micro-seconds was used for the delay skew controller, cf. e.g. [23]. The network and UE delays were 100 micro-seconds.

The simulated 4 data path case was the case with the least data paths that met the URLLC requirement, provided that the first received application data item was selected, resulting in minimum round-trip time. The simulated results appear in Fig. 2 and Fig. 3. Fig. 2 summarizes the round-trip delay skew controller performance, while Fig. 3 depicts the effect of additional selection processing. Fig. 2 and Fig. 3 show that without selection processing, there are times where the round-trip delay exceeds 3 milli-seconds. Thus, without selection processing at the receiving end, a back-off of more than 300/0.75% = 400% would be needed. As shown by Fig. 3, the median alternative performs in-between the case without selection processing and the use of the first received data item.

To illustrate the selection processing gain as a function of the number of data paths, round-trip delay statistics for selection processing based on the first received data item is plotted in Fig. 4. It can be seen that the 1 milli-second requirement is contained when the number of data paths exceeds 3, also with jitter included in the round-trip delay. Selection processing based on the first received data item results in the lowest round-trip delay values and is generally preferred, however there is also a downward bias as compared to the reference value setting of 0.75 milli-seconds. In case that would be undesirable, selection processing for median round-trip delay could be an alternative. More redundant data paths would however then be needed. There are even more demanding URLLC use cases than the one studied here, where either the URLLC delay requirement is 0.50 milli-seconds, or where the error rate requirement is 10^{-6}. An additional delay control back-off is expected to enable also such use cases.

C. Dimensioning

As stated previously a delayed control signal or delayed feedback and feedforward signal mostly need to be treated as lost information. This means that the reliability, delay and jitter requirements for the URLLC use cases are coupled. For the more demanding use cases a dimensioning method is therefore needed, for determination of the number of data paths and the operating point in terms of the wireless interface signal to interference and noise ratios (SINR). To

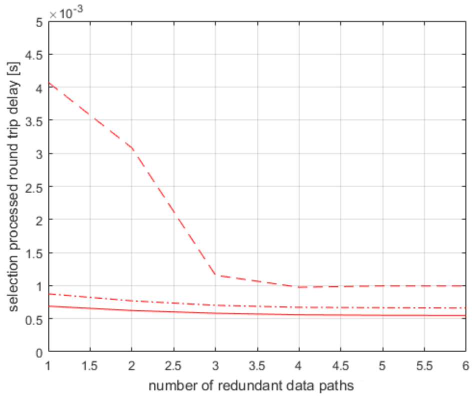

Fig. 4. Performance as a function of the number of data paths for minimum round-trip time selection processing (red). Mean values are shown solid, mean values with one standard deviation added dashed-dotted the most important mean values with maximum positive deviation, dashed.

outline such a method, assume first that the jitter requirement part is absorbed in the delay requirement part, as for frame based control [7]. In case a reliability of r is required, the corresponding error rate may be divided as

$$1 - r = f(1 - r) + (1 - f)(1 - r) \tag{7}$$

where f is a factor between 0 and 1. Then a first step would be to dimension the number of data paths by consideration only of the error rate affected by the SINR of the wireless interfaces. The individual wireless interface error rates $1 - r_w$ are then related to the number of independent data paths as

$$f(1 - r) = (1 - r_w)^{n_f}, \tag{8}$$

i.e.

$$n_f = \frac{\ln(f(1 - r))}{\ln(1 - r_w)}. \tag{9}$$

Then, the delay requirement is dimensioned with simulation over at least $((1 - f)(1 - r))^{-1}$ sampling periods, for varying number n_{1-f} data paths, until the round-trip delay requirement is met for all sampling periods. This guarantees that the probability of an application data item being lost due to a too long round-trip delay is less than the second term of (7). A final selection of the number of data paths as

$$n = \max(n_f, n_{1-f}), \tag{10}$$

then guarantees that the reliability and delay requirements are simultaneously met.

V. Conclusions

The paper presented new selection processing algorithms for jitter suppression for URLLC applications in NR systems. The results indicate that *combined* very high reliability and very low latency requirements are feasible. This conclusion was obtained by a combination of redundant application feedback loop data transmission over 3-4 data paths, delay skew control, and a new selection processing algorithm based on the first received redundant feedback control application data items. The use of redundancy is of course associated with a corresponding capacity loss.

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