A Study on Dynamic Connectivity Establishment and Cooperative Scheduling For QOS-Aware Wireless Body Area Networks

[1]Ramayanam Dorababu, [2]Prof. Kuda Nageswara Rao
[1]M.tech. Student, [2]Professor
Department of Computer Science and System Engineering,
Andhra University College of Engineering (A), Visakhapatnam, AP, India.

Abstract: The emerging 5G networks are intended to enable new feedback control applications, run over multiple wireless interfaces. 5G wireless technologies then need to match the state-of-the-art wired network performance, experienced by present commercial feedback control systems. Fiber-optic circuit switched communication is characterized by constant and very low loop delays, uniform and very high sampling rates, very low error rates and an almost unlimited capacity. The non-trivial challenge is then to meet these characteristics with a packet switched wireless 5G network that may be associated with varying latency, time varying sampling rates, significant error rates and a varying air-interface capacity. The paper contributes with a summary and discussion of basic requirements that need to be in place for successful commercial deployment of feedback controllers using such 5G wireless networks. One key requirement is a need to mitigate the problem of delay skew between different transmission paths. A novel delay skew data flow control algorithm is therefore proposed for 5G dual connectivity. The stability of the controller is analysed and conditions for global $\mathscr{L}2$-stability are stated. Test bed results are also reported in the paper, indicating that the delay skew controller can meet the requirements on the delay characteristics of 5G networks.

IndexTerms **- 4G, 5G, Wireless, Delay, Internet of Things, MIMO Control, Networked Control, Stability.**

I. INTRODUCTION

Fifth generation wireless networks aim to expand wireless technology to new fields of application, among these feed-back control using critical machine-type communications (C-MTC) [4]. Examples of new use cases include massive high bandwidth industrial mobile robot control [20] and the tactile internet [9], [10], where virtual reality is expected to become a significant use case [14]. Automatic control of rotating machinery also benefits, since wireless feedback signaling avoids the need for electro-mechanical devices like slip rings [1].

However, the reduced latency of the new 5G wireless interfaces is only one of several enablers for a successful deployment of feedback control applications. The reason is that the 5G networks will be packet switched, sometimes with control algorithms located in the cloud, resulting in feedback control application data transfer over shared internet connec-tions. This means that the end to end data transport perfor-mance experienced by the feedback control applications may be subject to varying delay, non-uniform sampling, data errors, and a varying capacity caused by wireless fading [11], [13].

These effects are obviously less pronounced when dedicated fibre-optic and copper wire based communication is used. Therefore, to enable the cost saving and increased flexibility associated with a replacement of wire, 5G wireless networks may need to be further controlled to reduce the challenges listed above. An additional challenge arises when millimeter-wave carrier frequencies are used, since the increased ra-dio shadowing then makes multi-point wireless transmission needed for coverage reasons [4], [11]. The feedback control application data signaling may then also need to be split over multiple paths, while keeping the delay characteristics aligned between the different transmission paths. New methods for delay control are therefore needed in support of 5G wireless networked feedback control applications. This fact has also been noticed by the IEEE control systems society in [12]. The contributions of the paper therefore include a first discussion of the effect of delay, delay variation, sampling and capacity, on feedback controllers and control systems running over packet switched 5G multi-point transmission networks. This motivates the need for network control algorithms that mitigate the challenges caused by the packet switched wireless combination. As a second contribution, a non-linear round trip delay skew feedback controller for 5G dual connectivity (DC) based C-MTC is proposed. This controller ensures that the packet switched data transport used by the C-MTC application feedback controllers is characterized by better defined delay properties. The round trip delay skew algorithm is also proved to be globally stable. It is stressed that this is a practically relevant result, since the C-MTC applications rely on stable delay properties of the underlying data transport, *at all times*. The control algorithm is also evaluated using a test bed C++ implementation. The obtained results show that the algorithm can regulate away the delay variations discussed above and [19]. The paper [2] also treats a delay skew controller for C-MTC. The present paper differs in that the focus is on general (delay) requirements for C-MTC. In addition, the non-linear processing differs, thereby allowing a stability analysis based on a combination of the Nyquist- and Popov-criteria [15], rather than on the more advanced integral quadratic constraint (IQC) method [7] used for the + 1-node controller treated in [2]. The DC algorithm described in [19] is designed to control the delay skew from the data split point to the downlink wireless interface, thereby securing the simultaneous reception of originally adjacent data packets, in the mobile. The control objective of the present paper is different and focused on control of the round trip delay skew from the data packet split point to the mobile interface connecting to the controlled plant at the other side of the air interface, and back. This provides the possibility to control the loop delays expe-rienced by feedback control applications. One consequence as compared to [19], is that the inner control loops need to be selected as the one described in [17]. The papers [3] and [8] both treat a multi-point delay skew controller for control of the downlink delay skew, as in [19]. Here [8] treats classical sensitivity and regulation performance properties, while [3] analyzes the stability properties with IQC methodology.

C-MTC REQUIREMENTS FOR FEEDBACK CONTROL APPLICATIONS

Control systems are best designed from empirical and/or theoretical models. Very often, linear models are used, see e.g. In practice, various constraints also need to be accounted for and in such cases linear models may be augmented with constraint handling using model predictive control [6]. As will be seen, the possibility to easily apply the standard controller design techniques depends on well defined delay properties of the bearer of the control system signals. Later in the paper the exact location of the controller node, the network delays, the wireless interfaces and the plant node with the UE interface will be defined. In the present section, the effect of delay is considered from the point of view of the feedback control application. In particular, wireless packet switched delay effects are characterized. This leads to the formulation of a set of basic requirements for 5G network design.

A. Effects of delay on stability

To quantify the effect of delay on stability it is assumed that the continuous time transfer function of the linear system is given by ( ) and that the transfer function of the controller is given by ( ), where is the Laplace transform variable. In addition the closed loop system is affected by a round trip loop delay . The loop gain of the system is then given by Under mild conditions the stability of the closed loop linear system of Fig. 1 is then given by

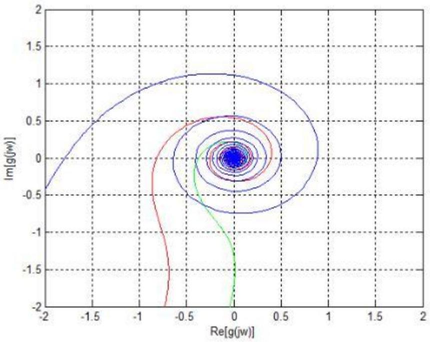


Fig. 1.

B. Effects of delay on regulation performance

As may also be seen in Fig. 2, an increasing delay causes the critical point of intersection between the Nyquist plot and the negative real axis to correspond to a point further out on the Nyquist plot. The shape of the Nyquist plot is also changed. This is analyzed in [16]. To understand the main result of [16] the sensitivity function ( ) needs to be defined [5].
e.g. [15]. Since stability is such an important engineering property, time variable models are often avoided. Nevertheless, several controller design methods do allow a time varying model, among them the Linear Quadratic Gaussian (LQG) design method [5]. However, since both the system matrices and the controller gains need re-computation at each sampling instance, the computational complexity is much higher than for the time invariant counterpart based on uniform sampling. Another advantage of using uniform sampling together with linear systems is the wide variety of standard controller design methods. I

***Effects of varying data flow delay:* When** the delay of the packet switched data bearer is varying, the delay between transmission of controller commands ( ) from a controlling node to the arrival of feedback information from the plant at the other side of the air interface also varies. The consequence is that uniform sampling instances at the controller node become asynchronous with the feedback signals.

One solution is then to *define* the sampling instant as the time when feedback information arrives back at the controlling node. This allows a use of the exact sampling relation (10). The penalty would be a very significant computational cost.

C. C-MTC capacity dimensioning

To estimate the air interface capacity needed to sustain closed loop feedback control of high bandwidth robotic ma-chinery in a manufacturing plant using wireless connections, a rough dimensioning example is useful.

Example 1: Consider a plant with 100 mobile robots used for manufacturing purposes. Assume that there are 10 degrees of freedom of each robot, requiring one feedback signal and one control signal each. Assuming a required bandwidth of 250 leads to a sampling frequency close to 5 (10 times the Nyquist frequency), a figure consistent with current 5G standardization. A round trip loop delay of 1 or better is needed to avoid a too large phase loss. If all signals are encoded with 4 bytes, and if a code rate of 1/5 is assumed, the total bit rate for each machine becomes $2\times10\times4\times8\times5000\times 5$ / $=16$. / The plant therefore requires a capacity exceeding 1.5 / .This is reasonable for the first 5G DC deployments. In case 0.5 is allocated for transmit data buffering, user data corresponding to 1000 bytes per machine will reside in each buffer on average.

D. Requirements

It should now be clear that in case a packet switched bearer of control information is associated with a large delay, feedback control stability margins, disturbance rejection per-formance and closed loop bandwidth are negatively affected. In addition, in case of significant delay variations, additional negative impacts is likely to affect the application perfor-mance. The feedback control system application may either need to resort to time varying controller design, a path that can result in a very high computational complexity, or it has to apply additional margins to account for sampling errors. Such margins tend to reduce the performance of the application. Finally, the high capacity that may be needed then dictates that air interface resources need to be efficiently used. In particular this means that data should (almost) always be available at the air-interface for transmission Together this means that the following basic requirements can be stated for the use of 5G packet switched wireless networks for automatic control.

Loop delay: The round trip (single path) loop delay should be minimized.

Utilization: The air interfaces should (almost) always be fully utilized.

Delay variation: The round trip delay variation should be minimized.

Delay alignment:Round trip delays over multiple air inter-faces should be aligned.

In the following section a new delay skew control algorithm is introduced. This algorithm is designed to control the loop delays, while simultaneously managing the utilization and aligning the loop delays.

III. ROUND TRIP DELAY SKEW CONTROL FOR 5G DUAL CONNECTIVITY

A. Dual connectivity for C-MTC in 5G

5G DC allows simultaneous transmission over two wireless interfaces. This improves reliability when radio shadowing occurs at high carrier frequencies [11]. Fig. 5 shows that the plant controllers are assumed to be located in or near the primary/controller node to minimize latency. Control signals and feedback signals are sent between the plant controllers and the plant at the other side of the wireless interfaces. To meet the delay alignment requirement an outer loop round trip delay skew controller is operating in the primary node, below the application layer, c.f. [19].

IV. SCOPE

The Main Scope is study the down link delay skew from the controller to the wireless interfaces should remain in a specified range. The transmit data queue dwell times should be controlled to avoid wireless data starvation, whilst maintaining low dwell times. [2] The delay skew control algorithm should be globally stable. The computational complexity should be small. Analysing and characterized a new delay skew control algorithm, supporting dual connectivity downlink data transmission in 4G and 5G wireless networks. The main aim of this project to maintain an efficient utilization of the air-interface resources and to maintain a stable data flow without re-ordering buffer resets. The proposed delay skew controller achieves the control objective addition; the paper mainly proves that the delay skew controller is globally input-output stable, provided that the data path delays are below a pre-computable limit. the project aims to study the good performance is related to high performing inner control loops, and to a symmetric design of the data paths and inner control loops. This information is useful e.g. when new wireless networks are deployed. The tuning of the control loops in the field is facilitated by the fact that the global input-output stability of the control system is quantified by the graphical frequency domain

V. RELATED WORK

F.-S. Ho and P. Ioannou “Traffic flow modeling and control using artificial neural networks”

In this article we use an artificial neural network technique to model and control highway traffic in a single lane with no on- or off-ramps. The developed controllers generate the speed commands for each section of the lane that vehicles need to follow in order to achieve a desired traffic flow density distribution along the lane. In today's traffic, these speed commands could be communicated to drivers, who would then have to respond to them. This raise human factors issues that need further investigation in order to assess the possible benefits. In an automated highway, speed commands cn be communicated to the vehicle's computer control system and followed directly without human errors or delays. We simulate an automated highway environment with such a system to alleviate congestion. We demonstrate that the use of feedback control on the macroscopic level could bring dramatic improvements to traffic flow characteristics.

J. Baillieul and P. J. Antsaklis, "Control and communication challenges in networked real-time systems"
A current survey of the emerging field of networked control systems is provided. The aim is to introduce the fundamental issues involved in designing successful networked control systems, to provide a snapshot assessment of the current state of research in the field, to suggest useful future research directions, and to provide a broad perspective on recent fundamental results. Reflecting the goals of the Special Issue itself, this paper surveys relevant work from the areas of systems and control, signal processing, detection and estimation, data fusion, and distributed systems. We discuss appropriate network architectures, topics such as coding for robustly stable control in the presence of time-varying channel capacity, channels with fixed versus adaptively variable data width, issues in data rate problems in nonlinear feedback problems, and problems in routing for stability and performance. In surveying current research on networked control systems, we find that recent theoretical advances and target applications are intimately intertwined. The common goal of papers in the Special Issue which follows is to describe key aspects of this relationship. We also aim to provide a bridge between networked control systems and closely related contemporary work dealing with sensor networks and wireless communication protocols

R. Delgado, K. Lau, R. H. Middleton and T. Wigren, "Networked delay control for 5G wireless machine type communications using multiconnectivity"
Automatic control using ultrareliable and low latency communication is one of the potential applications of the new fifth-generation wireless systems. A remaining challenge is then to guarantee a low end-to-end delay with low jitter over combined internet and wireless interfaces that are packet switched and capacity optimized. The main novelty of this paper is to introduce stringent delay control to meet this challenge, over simultaneous multiple data paths. The proposed multiple-input-multiple-output (MIMO) cascade control system is nonlinear since the dwell times of the transmission node queues used as actuators cannot be negative. Stability analysis based on integral quadratic constraint theory is, therefore, applied to characterize the global stability of the controller. The practical performance is evaluated with experiments using product like test bed C++ code. It is stressed that the proposed controller does not require internode time synchronization.

R. A. Delgado, T. Wigren, K. Lau and R. H. Middleton, "Stability properties of a MIMO data flow controller"
The increasing demand for data in mobile applications has created a need for better communications systems. To satisfy this growing data demand next generation wireless systems are planned to use millimetre wave carrier frequencies. At these frequencies, radio shadowing is severe. To compensate for shadowing, incoming data flows must therefore be split and sent over several radio interfaces, that may have different delay properties. This paper analyses the stability properties of a MIMO data splitter that controls the delay skew between the data paths. The stability analysis is performed using IQC stability theory.

C.-Y. Kao and A. Rantzer, "Stability analysis of systems with uncertain time-varying delays"
In the paper we mainly study the system stability for a class of an uncertain neutral time-varying delay. Firstly, we construct a Lyapunov function with integrals of different structures. Secondly, making use of this function, we can get the conclusion about this system stability by using the methods and shills of some types of inequalities. This conclusion is represented with LMI form and numerical examples verified the validity of this method

VI. METHODOLOGY

PDCP layer:

The controlling node is located at the PDCP layer of the primary node of the dual connectivity architecture, whereas the wireless transmission nodes correspond to the RLC, MAC and PHY layers of the primary and secondary nodes. It can be noted that the flow control loop that is a part of the primary node is usually significantly faster than the one between the primary and secondary node, and in some implementations it may not be needed at all. In this paper, however, it is assumed that primary node flow control is present.

Controlling Node:

The delay skew controller thereby also solves the data flow split problem at the controlling node. It does so by using the downlink data flows themselves in order to control the total downlink delays, from the controlling node to the wireless interfaces. As stated above the delay skew need not be controlled to exactly zero since the communication protocols are able to perform packet re-ordering in case the arrival times of originally adjacent packets differ by less than the re-ordering buffer length.

Scheduled Wireless Rate:

Next the inner loop controllers need to be discussed. These controllers apply feedback from the transmit queue data volume and optionally feed-forward from the scheduled wireless rate. The dwell time control is obtained by a reference value transformation from a dwell time reference to a data volume reference, using the wireless rate, see. The dwell time control is therefore obtained by a combination of the reference value transformation and the transmit data queue volume feedback control. The inner loops of are also subject to a saturation since the flow of data is one directional. The inner loop modeling of this paper assumes that the loops operate as intended so that the saturation can be neglected.

Disturbance Rejection:

In summary, it could be concluded that a good inner loop controller design is essential if good disturbance rejection shall be achieved. In addition, a system design with similar inner control loop dynamics is beneficial in terms of decoupling between the transmission node paths. The state space controllers of do not have a direct term and are therefore strictly proper. Straight forward calculations then show that also is strictly proper, and A5 holds in case of state space control as well.

VII. RESULTS

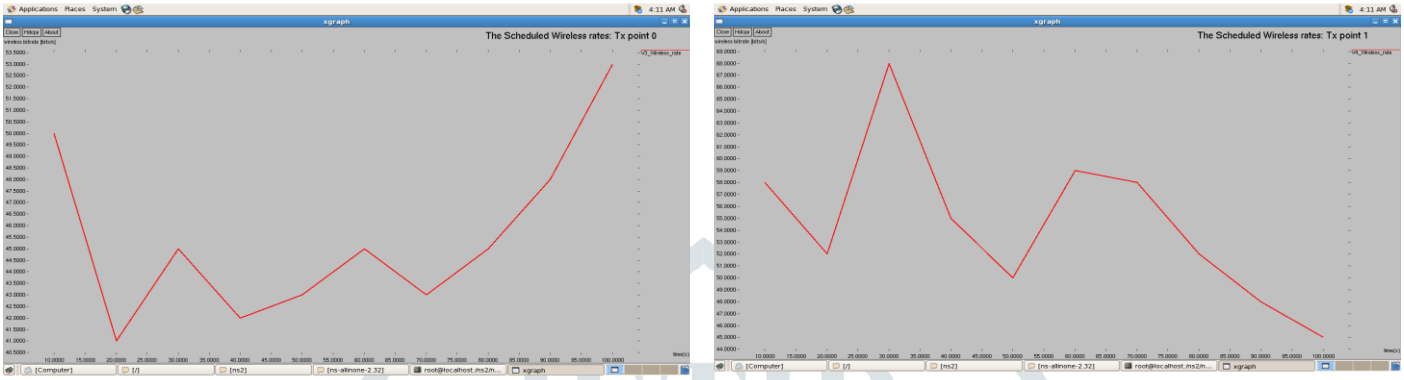


Fig. 2 - The Scheduled Wireless rates at Tx points ‘0’ and ‘1’

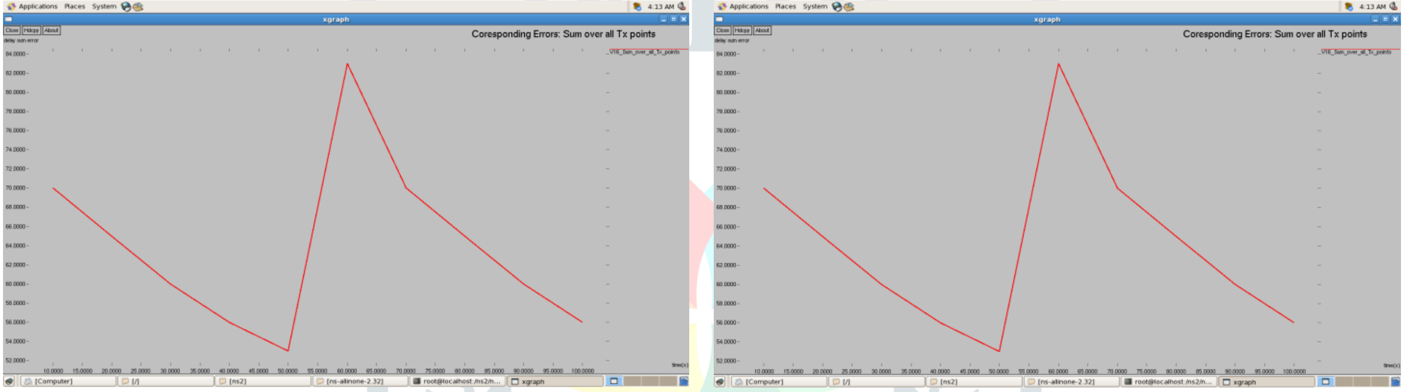
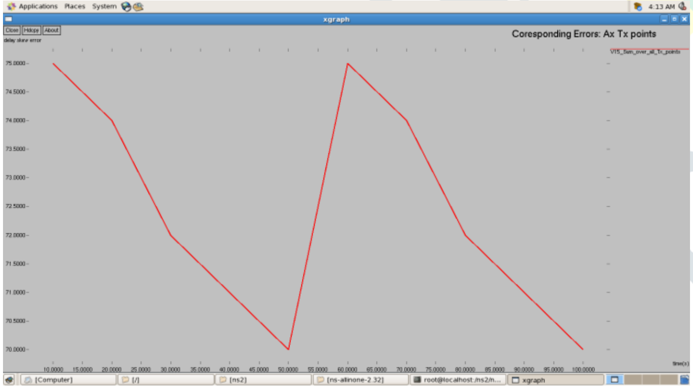
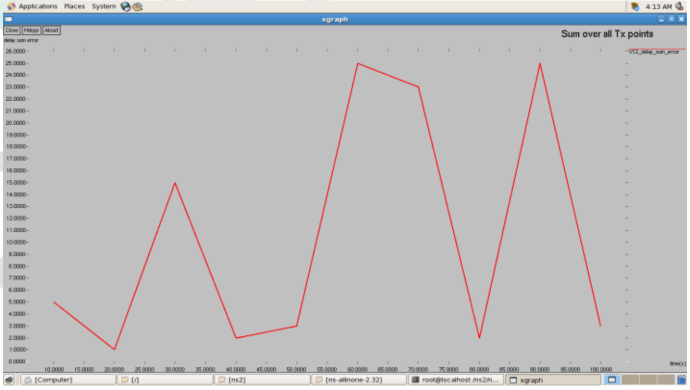


Fig. 3 - Delay sum errors of all Tx points considered in the network





CONCLUSION

The paper discussed the importance of delay characteristics, when the new 5G wireless networks are used to carry application data for feedback control systems. The effects of delay and delay variation on the stability, performance and computational complexity were treated, resulting in a set of basic requirements that support a successful deployment. It was also shown how a new delay skew controller can be used to align these delay characteristics, between the different transmission paths of 5G dual connectivity. Conditions ensuring a globally stable operation were defined, and testbed results indicate that the delay skew controller is capable of regulating away delay variations, as intended.

FUTURE WORK

The control objective includes a requirement on the transmit data queues, stating that they should not cause data starvation or an unnecessarily high dwell time. The data flow controller was therefore selected since it is based on dwell time feedback control. That controller consists of a lead-lag feedback link acting together with a feed forward filter, thereby combining queue dwell time feedback with wireless rate feed forward. The feed forward filter does neither affect the stability of the delay skew NCS, nor the outer delay skew control loop design and it is therefore not discussed in detail

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