Deterministic Scheduling of Periodic Messages for Cloud RAN

Dominique Barth[1], Maël Guiraud[1,2], Brice Leclerc[2], Olivier Marcé[2], and Yann Strozecki[1]

[1]David Laboratory, UVSQ
[2]Nokia Bell Labs France

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1 Model and Problems

We use the notation $[n]$ to denote the interval of n integers $\{0,\ldots,n-1\}$.

1.1 Network modeling

The network is modeled as a directed graph $G = (V,A)$. Each arc (u,v) in A is labeled by an integer weight $\Omega(u,v)$ which represents the time taken by a message to go from u to v using this arc. A **route** r in G is a directed path, that is, a sequence of adjacent vertices $u_0,\ldots,u_l$, with $(u_i,u_{i+1}) \in A$. The **weight of a vertex** u_i in a route $r = (u_0,\ldots,u_l)$ is defined by $\lambda(u_i,r) = \sum\limits_{0 \leq j < i} \Omega(u_j,u_{j+1})$. We also define $\lambda(u_0,r) = 0$. The wieght of the route r is defined by $\lambda(r) = \lambda(u_l,r)$. We denote by $\mathcal{R}$ a set of routes, the pair $(G,\mathcal{R})$ is called a **routed network** and represents our telecommunication network. The first vertex of a route models an antenna (RRH) and the last one a data-center (BBU) which computes the messages sent by the antenna.

1.2 Messages dynamic

Time is discretized, hence the unit of all time values is a **tic**, the time needed to transmit a minimal unit of data over the network. TODO: parler des différents débits et de ce que ça change. The weight of an arc is also expressed in tics, that is the time needed by a message to go through this arc. In the process we study, one and only one **frame** is sent on each route at each period, denoted by P, and expressed in tics. A frame F is composed of several **datagrams**. The cardinal of a frame, denoted $|F|$ is the number of datagrams in the frame. The datagrams $\{d_0,\dots,d_{|F|-1}\}$ of a frame represent one or several *consecutive tics*. The size $|d_i|$ of a datagram is an integer, expressed in tics. Once a datagram have been emitted, it can not be fragmented during its travel in the network. Thus, the size of a frame is $\sum_{i=0}^{|F|-1}|d_i| = \tau$. In this paper, we assume that τ is the same for all routes. Indeed, the data flow sent by an RRH to its BBU is the same, regardless of the route.

Let $r = (u_0,\dots,u_l)$ be a route, a datagram d_j can be buffered in a node u_i, during at least $|d_j|$ tics. This is due to some technical constraints of the network; a message must be totally buffered before being re-sent by a node of the network. Each datagram d_j is thus associated to a sequence $\{b_j^0,\dots,b_j^l\}$ of **buffers** corresponding to the buffering time of this datagram in each nodes of the route. We call **offset** of a datagram on a route on a route r, denoted by $o_r(d_j)$, the time at which a datagram d_j is sent from u_0, the first vertex of r.

Since the process is periodic, if the datagram from r goes through an arc at time $t \in [0,P-1]$, then it goes through the same arc at time $t + kP$ for all positive integers k. Therefore, every time value can be computed modulo P and we say that the tic at which a datagram d_j sent at time $o_r(d_j)$ on r reaches a vertex u_i in r is $t(d_j,u_i,r) = o_r(d_j) + \lambda(u_i,r) + \sum_{k=0}^{i-1} b_j^k \mod P$.

Let us call $[t(F,u,r)]_P$ the set tics used by a frame F on a route r at vertex u in a period P, that is $[t(F,u,r)]_{P,\tau} = \{\{t(d_0,u,r) + i \mod P \mid 0 \leq i < |d_0|\} \cup \ldots \cup \{t(d_{|F|-1},u,r) + i \mod P \mid 0 \leq i < |d_{|F|-1}|\}\}$. Let r_1 and r_2 be two routes, on which frames F_1 and F_2 are sent. We say that the two routes have a **collision** if they share an arc (u,v) and $[t(F_1,u,r_1)]_P \cap [t(F_2,u,r_2)]_P \neq \emptyset$.

A (P)**-periodic assignment** of a routed network $(G,\mathcal{R})$ is a function that associates to each datagram of each route its offset and its buffers. In a (P)-periodic assignment, *no pair of routes has a collision.*

Periodic Routes Assignment (pra)

Input: a routed network $(G,\mathcal{R})$, and an integer P

Question: does there exist a (P)-periodic assignment of $(G,\mathcal{R})$?

1.3 Periodic assignment for low latency

In the context of cloud-RAN applications, we need to send a frame from an RRH u to a BBU v and then we must send the answer from v back to u. We say that a routed network $(G,\mathcal{R})$ is **symmetric** if the set of routes is partitioned into the sets A of **forward routes** and B of **backward routes**. There is a bijection ρ between A and B such that for any forward route $r \in A$ with first vertex u and last vertex v, the backward route $\rho(r) \in B$ has first vertex v and last vertex u. In all practical cases the routes r and $\rho(r)$ will be the same with the orientation of the arcs reversed, which corresponds to bidirectional links in *full-duplex* networks, but we do not need to enforce this property.

We now give a new interpretation of a (P)-periodic assignment of a $(G,\mathcal{R})$ symmetric routed network, so that it represents the sending of a frame and of its answer. This assignment represents the following process: First, the datagrams of a frame F_r is sent at u, through the route $r \in A$, at time $\{o_r(d_0),\dots,o_r(d_{|F_r|-1})\}$. Those datagrams are received by v, i.e., the last vertex of r at times $\{t(d_0,v,r),\dots,t(d_{|F_r|-1},v,r)\}$. Once v has received all the datagrams of a frame, the answer is computed and sent back in a frame F_{ρ_r}. Note that $|F_{\rho_r}|$ may be not equal to $|F_r|$, i.e. the answer is not necessarily under the same form as the initial frame. Thus the node v send F_{ρ_r} to u on the route $\rho(r)$.

We denote by $f(F_r,v)$ and $l(F_r,v)$ the time at which the first (respectively the last) datagram of a frame has reach the vertex v. Thus, $f(F_r,v) = \min\limits_{i\in\{0,\dots,|F_r|-1\}} t(d_i,v,r)$ and $l(F_r,v) = \max\limits_{i\in\{0,\dots,|F_r|-1\}} t(d_i,v,r)$. We define the **reception time** of a frame F_r the difference $rt(F_r,v) = l(F_r,v) - f(F_r,v)$.

The time between the arrival of the last datagram of a frame in the BBU and the time the answer is sent back is called the **waiting time** and is defined by $w_r = o_{\rho(r)}(d_0) - l(F_r,v)$ if $o_{\rho(r)}(d_0) > l(F_r,v)$, i.e. the answer is sent in the same period. Otherwise, if the answer is sent in the next period, $w_r = o_{\rho(r)}(d_0) + P - l(F_r,v)$.

Note that, in the process we describe, we do not take into account the computation time a BBU needs to deal with one message. It can be encoded in the weight of the last arc leading to the BBU and thus we do not need to consider it explicitly in our model.

The whole process time for a frame r is equal to $PT(r) = \lambda(r) + rt(F_r,v) + w_r + \lambda(r) + rt(F_{\rho_r},u)$, where u is the RRH. In the process time, we count the time between the time the first tic of the frame is emitted and the time at which the last tic of the message comes back.Each route must respect a time limit that we call *deadline*. To represent these deadlines, we use a deadline function d, which maps to each route r an integer such that $PT(r)$ must be less than $d(r)$.

We consider the following decision problem.

Periodic Assignment for Low Latency (pall)

Input: A symmetric routed network $(G,\mathcal{R})$, the integers P, τ and a deadline function d.

Question: does there exist a (P)-periodic assignment m of $(G,\mathcal{R})$ such that for all $r \in \mathcal{R}$, $PT(r) \leq d(r)$?

We define by **jitter** of a frame the greatest buffering time of a datagram in the network. The jitter of a frame F_r is thus defined by $J_r = \max\limits_{i\in\{0,\dots,|F_r|-1\}} t(d_i,v,r) - m_r(d_i) - |d_i|$, where v is the last vertex of the route. TODO: pas tres utile pour l'instant