A Double per Priority Queue Dynamic Wavelength and Bandwidth Allocation Algorithm in Healthcare Applications Service

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Abstract—**The development of medical applications aims to upgrade the provision of services to patients and the healthcare staff involved. This upgrade can improve critical performance parameters of healthcare units such as reducing treatment time and saving both material and human resources. These state of the art applications, which include the Tactile Internet (TI) medical, have very high requirements from the communications network that supports them in order to ensure the required quality of services (QoS). The network infrastructure of healthcare units in turn needs to be upgraded in order to follow the evolution of the applications it must be able to support. Installing passive optical networks (PON) in healthcare environments is the best option for upgrading their telecommunication infrastructure. An important parameter for the performance of PONs is the effective allocation of their resources both in time and in frequency domain, with the entity responsible for the above operation to be the dynamic wavelength and bandwidth allocation (DWBA) algorithm. In this paper, we present a specially designed DWBA algorithm for healthcare environments that ensures the fair and efficient distribution of network resources, thus satisfying the required QoS to all categories of medical applications. The results of the simulation reveal that the implementation of the proposed algorithm in healthcare environments improves the metrics concerning the QoS provided, compared to others well known schemes from the literature.**

Keywords—Passive Optical Networks, Healthcare applications, Tactile Internet , Quality of Sevice

I. INTRODUCTION

The TI medical (TIM) applications are expected to lead to a new dimension of real-time interaction between medical staff, patients and medical equipment, offering haptic sensations to the end users. The requirements of TI applications are very strict and require a high level of security, great availability at a rate of more than 99.999% and a maximum end to end latency of 1 msec. [1]. Of the above requirements the one that creates the most important problems is the latency due to the time of the propagation required between the tactile control/steering server and the tactile edge. However the mentioned delay issue, is eliminated when TI applications run on Local Area Networks LAN , where the propagation delay is negligible [2].

The majority of existing healthcare facilities still rely on traditional copper-based LAN. In many cases, this equipment, namely cabling and network architecture, has been in place for a decade or longer and was not purposefully built to support the demanding TIM applications and the IoT era. Passive Optical LAN (POL) technologies are the ideal solution to meet the high-bandwidth and high-availability demands of life-saving services now and in the future. The main advantages of POLs include improved efficiency and reliability, ease of use and administration, energy efficiency, advanced security and reduced maintenance costs [3]. Modern healthcare campuses (Figure 1) equipped with POL should be able to support simultaneously many different tasks, including the stringent QoS demands for TIM applications, the storage and access of high resolution medical images, the distribution of patient medical information and the control of life support devices.

An important parameter that affects the operation of PON is the efficient distribution of their available resources. In the uplink, the optical network units (ONU) share the optical fiber, resulting in the possibility of collisions when two or more ONUs simultaneously transmit at the same frequency. For this reason, the multipoint control protocol (MPCP) has been developed for Ethernet PONs (EPONs) that supports time slot and wavelength allocation from the optical line terminal (OLT) to the ONUs. The MPCP supports a platform that can be used to implement the DWBA algorithms by providing signaling infrastructure for coordinating upstream data transmissions.

A large number of DWBA algorithms have been proposed in the literature over the last twenty years, but without taking into account the high demands of the TI applications nor the peculiarities or importance of the healthcare environments. In this paper we present a novel double per priority queue (DPPQ) DWBA algorithm which is specially designed for implementations of POLs in healthcare environments. The proposed algorithm's main goal is the efficient and fair allocation of network resources in order to meet the QoS requirements of medical applications. For this purpose the algorithm uses several techniques, with the main one being the implementation of two priority queues for each class of service (CoS) in each ONU. Using this technique, the algorithm adapts the allocation of network resources according to the specific requirements of each CoS, thus increasing its effectiveness to cope with the burstiness of the created traffic.

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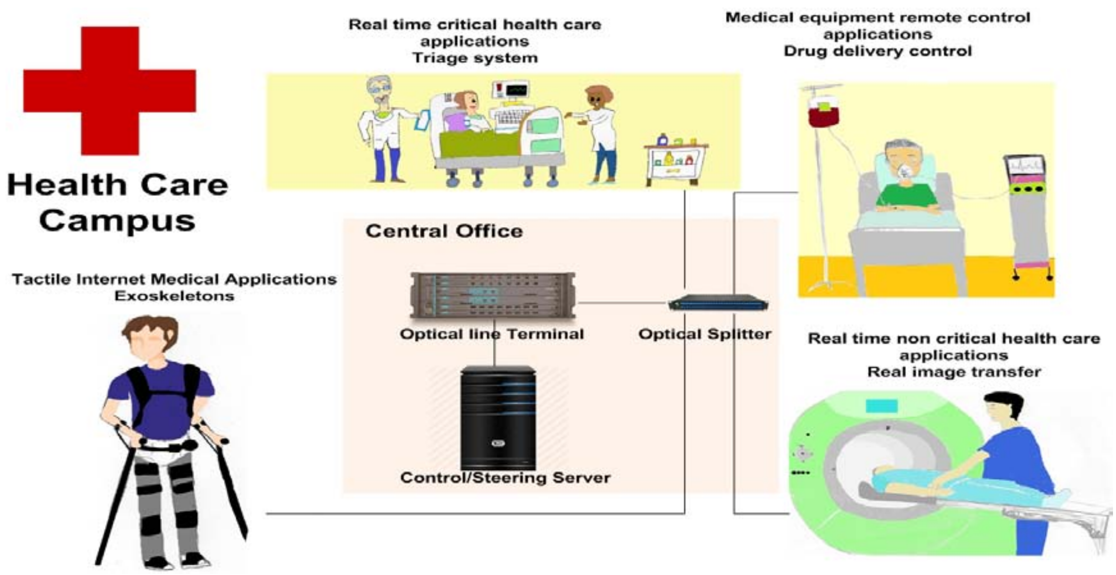

Fig 1. A healthcare campus with passive optical local area network infrastructure supporting various medical applications.

II. Related Work

A considerable research work in the literature concerning DWBA algorithms was carried out during the last twenty years. The operation of the proposed algorithms varies depending on the options adopted in four key design parameters [5].

- *Grant scheduling framework* which considers the timing of DWBA operation triggering and includes four design types (Online, Offline, ONU load status and Double Phase Polling).
- *Grant sizing policy or Inter-ONU Scheduling* which determines the type and size of the allocated resources, both in time and frequency domain, which will be used by each ONU during the next upstream transmission. This policy has five major design approaches (Fixed, Gated, Limited, Limited with excess distribution and Exhaustive using queue size prediction).
- *ONU Queue Scheduling or Intra-ONU Scheduling* which is implemented by each ONU and concerns the priority transmission policy between its buffering queues during the grant timeslot assigned by the OLT. There are two main classes of *Intra-ONU* scheduling (Strict priority and Weighted fair queuing).
- *Scheduling policy* which prioritizes ONUs transmission during each poll cycle according to three main policies (Shorter grant first, Larger frame first and the Shortest propagation delay first).

Another important issue in DWBA algorithm design is the fairness in the distribution of network resources between ONUs. According to the study in [6], in order to preserve fairness in resources allocation among the ONUs, a compromise to the overall efficiency is necessary. For this reason, a DWBA scheme called IFAISTOS was presented to balance the trade-off between fairness and efficiency.

In addition to the design parameters mentioned above, an important role in the evolution of DWBA algorithms is determined by both the improvements in the physical layer of PON technology and the continuously increased QoS requirements of the running applications. The majority of the latest proposed DWBA algorithms in the literature deal with the reduction of delay in various PON topologies so that TI applications can be properly serviced. In [7], a DWBA scheme is introduced which is able to meet the QoS requirements of tactile services in an optical cloud distribution network. A first-fit DBWA algorithm which reduces transmission latency and mitigates the frame resequensing problems for NG-PON is presented in [8]. In [9] a maximum likelihood sequence estimation (MLSE) DWBA scheme that reduces the buffering time in the ONU queues by using traffic prediction techniques is presented. However, simulation results revealed a poor performance to preserve TI applications latency constraint when the injected traffic is pareto distributed. Finally, in our previous work in [10] we presented an improvement of MLSE-DWBA by using a knapsacking dynamic programing algorithm for efficient resources distribution according to the traffic volume for poisson traffic distribution.

III. Operation of the Proposed Dynamic Wavelength and Bandwidth Allocation Algorithm

This section presents the basic functions of the proposed DWBA algorithm and the options adopted by the design parameters previously mentioned.

A. Intra-ONU scheduling

Ensuring the QoS in PONs requires the planning of transmissions by ONUs. This planning must prioritize the resources allocation between the CoS according to their

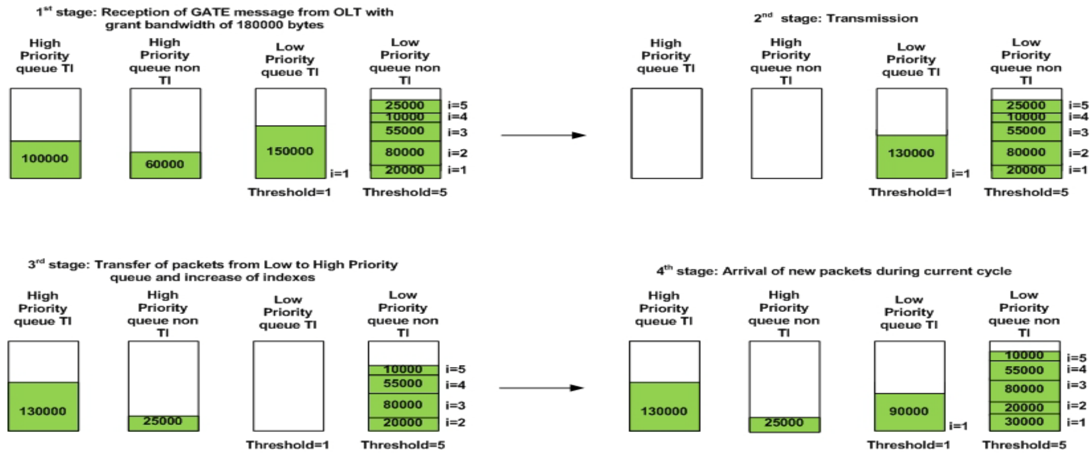

Fig. 2 Operation of Intra-ONU scheduling during a poll cycle.

importance without leading to starvation the less demanding of them. Also an important design parameter for the *intra-ONU scheduling* is to maintain low complexity so as to ensure its execution speed as well as saving computing resources from the ONU. The DPPQ algorithm uses the technique of two buffering queues per CoS to simplify the *intra-ONU scheduling* while ensuring both fairness and efficiency in the allocation of resources.

The implementation of the aforementioned technique in each poll cycle by the ONU is described by the following steps:

1. The ONU implements two buffering queues for each CoS; the low priority (LP) one and the high priority (HP) one.
2. The ONU calculates a threshold value Thr_i for each CoS which is determined by its corresponding latency constraint. For the TI application CoS, which is the most demanding one, this value is set to 1 while for the rest it is calculated as follows:

$$Thr_i = floor\left(0.9L_{cons} / T_{poll}\right) \quad (1)$$

where L_{cons} is the latency constraint for CoS i and T_{poll} is the fixed duration of the poll cycle.
3. Each packet received during the current poll cycle is buffered in the corresponding LP queue of its CoS.
4. At the end of the poll cycle, at each LP queue an index Ind_i is assigned to the last new buffered packet that is initialized to the value 1.
5. For the buffered packets in LP queues arrived at previous cycles, it increases the existing indexes by one.
6. The ONU compares all the indexes values with the equivalent Thr_i value and when Ind_i=Thr_i it transfers the packets to the corresponding HP queue.
7. During the assigned transmission window, ONU offloads the packets following the strict priority policy.

Using the aforementioned process, the *intra-ONU scheduling* takes advantage of the individual latency constraint demands of each CoS so that it can effectively allocate the available resources at the right time. The operation of the *intra-ONU scheduling* serving two CoS is depicted in a four-stage diagram in Figure 2.

B. Duration and Active Wavelengths of Poll Cycle

Applying the *double per priority queue technique* the algorithm requires the use of fixed poll cycle duration T_{poll} . The exact duration of the cycle is calculated based on two key factors. The first one is the minimum buffering time of the packet, which is three cycles, in accordance with the buffering procedure previously described. The duration of buffering is analyzed as follows, in the first cycle the packet is buffered in the LP queue, in the second it is transferred to the HP queue and during the third it is offloaded. The final T_{poll} duration that additionally takes into account both the processing timeT_{proc} required by the OLT as well as the delay in propagation between the OLT and the furthest ONU is:

$$T_{poll} = \frac{L_{cons} - 3T_{proc} - T_{rtt}}{3} \quad (2)$$

The DPPQ algorithm is also energy efficient as in each poll cycle it uses the necessary spectral resources depending on the traffic load being offered. Having chosen the *Offline* approach for the *Grant scheduling framework*, the OLT is able to have the full knowledge of the resources required by the ONUs to serve their buffered traffic, and it calculates the number of wavelength G_{WL} that will be used in the next poll cycle as follows:

$$G_{WL} = min\left(NUM_{WL},\ ceil\left(R_{BW} / WL_{BW}\right)\right) \quad (3)$$

where NUM_{WL} is the number of available wavelengths, RN_{BW} is the total requested by the ONUs bandwidth and WL_{BW} is the offered bandwidth of a single wavelength.

C. Grant scheduling framework

The *Offline* approach is used for the grant scheduling by the algorithm. There are two main reasons that led us to this choice. The first one is the necessity for comprehensive knowledge from the algorithm concerning the size and type of buffered information in the ONUs, so that the calculation of the network resources allocation to be effective and fair. The second reason is the one previously mentioned and concerns the energy efficiency of the network.

Moreover, for maximizing the exploitation of the available optical spectrum, the algorithm uses the *interleaved polling with stop* technique. Despite its proven efficiency, this technique has one major drawback, which is the creation of an idle period in the uplink [11]. In order to deal with this issue, a minimum transmission period G_{min} for each ONU is set which is:

$$G_{\min} = T_{proc} + T_{rtt} \quad (4)$$

D. Grant sizing policy

The size of the assigned bandwidth and the wavelength that each ONU will use in each poll cycle is calculated by the OLT in three basic stages. In the first stage, the number of wavelengths to be used in the next poll cycle is calculated according to traffic conditions as described in section II B. In the second stage, the algorithm first sorts the ONUs based on their buffer occupancy in their HP queues. It then creates sets of ONUs for each active wavelength in such a way so that the final composition of the sets consists of overloaded and underloaded ONUs.

In the third step, the algorithm firstly calculates the portion P_i of the available wavelength bandwidth which will be assigned to each ONU which is calculated as:

$$P_i = \frac{RBW_i}{\sum_{i=1}^{Num\_ONU} RBW_i} \quad (5)$$

where RBW_i is the ith ONU requested bandwidth for its HP queues. Finally, the exact bandwidth GBW_i to be assigned to each ONU is calculated as:

$$GBW_i = G_{min} + P_i \cdot BW_{WL} \quad (6)$$

where BW_{WL} is the available bandwidth of a single wavelength.

Following the described *grant sizing* policy, the algorithm becomes more flexible and in this way it has the ability to allocate network resources more efficiently, thus tackling traffic burstiness and limiting the overall delay to levels acceptable for the provided QoS.

E. Grant scheduling policy

The main goal of the design approach concerning the *grant scheduling* policy is to reduce the overall delay. For this reason, the option of *longer grant first*, which provides transmission priority to ONUs that are more loaded and therefore more vulnerable to delays, has been chosen.

	Requirement	
Medical Application	**Delay**	**Packet loss rate**
Tactile Internet medical (TIM)	<500 μsec	$<10^{-5}$
Medical equipment remote control (MERC)	<3 sec	~0
Real time critical health care (RTCH)	<300 msec	$\sim10^{-6}$
Real time non-critical health care (RTNH)	<10 msec	$<10^{-4}$
Office medical IT (OMIT)	<1 sec	$<10^{-2}$

TABLE I.: Medical applications requirements

Parameter	**Value**
Number of ONUs	64
Number of priority classes	5
Line rate of user-to-ONU	1 Gbps
Number of wavelengths	4
Upstream bandwidth per wavelength	10 Gbps
Downstream bandwidth per wavelength	10 Gbps
Buffer size in ONU	10 Mbytes
TI packet size	64 bytes
Non-TI packet size distribution	64-1518 bytes
Interframe gap	12 bytes
Frame preamble	8 bytes
Maximum distance between OLT and ONU	200 m
Guard time between adjacent slots	1 μsec
Traffic distribution	Pareto
Traffic packets	10^8

TABLE II.: Simulation parameters

IV. ALGORITHMS EVALUATION

The evaluation of the DPPQ algorithm was carried out in comparison with three corresponding DWBA algorithms from the literature. These algorithms are the two versions of the state-of-the-art wavelength division multiplexing interleaved polling with adaptive cycle time with single table (WDM-IPACT-ST) [12], with the first version IPACT-ST applying the *strict priority* policy while the second one IPACT-WFQ the *weighted fair queuing* policy which concerns the *intra-ONU scheduling*. The third algorithm of the evaluation is the MLSE-DWBA [9] which is specially designed to support the stringent TI applications QoS demands in healthcare environments.

The system model includes a modern healthcare campus that is equipped with a POL that serves various types of applications related to medical staff, patients and the control of medical equipment. The applications running in a healthcare environment can be categorized into five main CoS based on their particular QoS demands characteristics [13]. These CoS have their hierarchy determined by their importance; their individual QoS requirements as well as their order in hierarchy are shown in table 2. The selected traffic modeling for all the CoS follows the pareto distribution with Hurst parameter H=0.8. The reason for this choice is the burstiness of the traffic that characterizes all access networks.

The simulation scenarios ran on a PON simulator built in MATLAB. The exact parameters used in the simulation, which relate to both the particular characteristics of the POL operation and the characteristics of the injected traffic, are shown in table 2. The simulation parameters were selected in order to meet the specifications set by the IEEE 802.3av 10 Gigabit Ethernet Passive Optical Network protocol [14].

The comparison of the DWBA algorithm performance was carried out by two simulation scenarios. In the first scenario, the composition of the injected traffic consists of 60% TIM, 8% medical equipment remote control applications (MERC), 8% real time critical healthcare applications (RTCH), 12% real time non-critical health care applications (RTNH) and 14% office/medical IT applications (OMIT). The metric used in this scenario is the maximum end-to-end delay for each CoS as a function of a variable offered traffic load. This metric shows

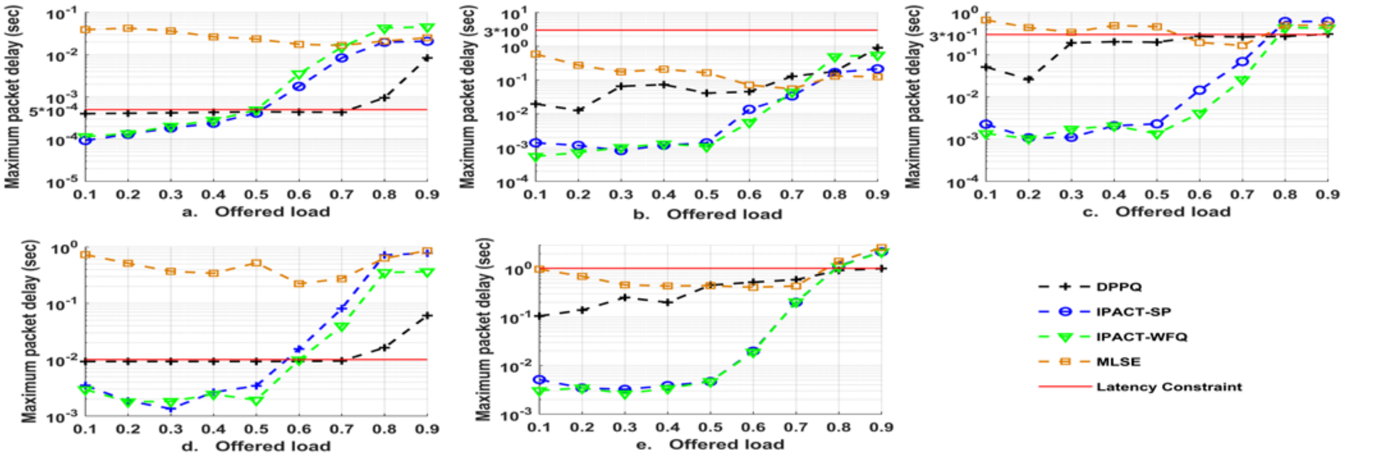

Fig 5. Maximum packet delay of (a) TIM,(b) MERC, (c) RTCH, (d) RTNH and (e) OMIT applications under variable offered load

the effectiveness of the DWBA algorithms to maintain the maximum delay at levels that are acceptable to the QoS requirements of each CoS.

The results of the simulation for the first scenario are presented in figure 5 for each CoS. In all cases we see that the DPPQ has the best performance compared to the other algorithms as it ensures the desired delay for most of the offered load range. The MLSE on the other hand has the worst performance as the prediction mechanisms it employs are not effective in dealing with the traffic burstiness. We can also observe in the results that the two versions of the IPACT-SP show low levels of delay in low load conditions, which gradually increases proportionally to the offered load increase, while the other two algorithms show a smoother slope in the delay. This is explained by the variable poll cycle period used by the IPACT-ST algorithms as opposed to DPPQ and MLSE which use a fixed poll cycle period. One last important observation in the results of the first simulation scenario is the adaptation of the DPPQ to the requirements of each CoS. According to the results, the maximum delay performance curve of the algorithm follows the corresponding curve of the latency constraint red line of each CoS.

The second simulation scenario includes the packet lost and delay rate (PLDR) metric for each CoS as a function of a variable percentage of TIM applications traffic relative to the total offered load traffic. A packet is considered lost, when it is dropped due to the buffering queues occupancy and delayed when the end to end delay exceeds the latency constraint of its CoS. The residual traffic in all cases consists of 20% MERC, 20% RTCH, 30% RTNH and 30% OMIT applications. The value of the total load offered is set to 0.8 which is a saturation point for the POL. Similar to the first scenario, in all CoS the DPPQ shows its superiority in ensuring the PLDR at lower levels compared to the other algorithms.

V. CONCLUSIONS

The evolution of medical applications and the IoT era makes it necessary to upgrade the network infrastructure of healthcare units. POL is the right choice to replace the old traditional copper-based network infrastructure. The importance and special features of medical applications create the need to design DWBA algorithms that will be specifically designed for healthcare environments. In this paper, we presented a DPPQ-DWBA algorithm. The evaluation of our proposed algorithm was carried out on a health care campus environment, where different crucial CoS including TIM applications need to be served. The simulation results reveal the superiority of the proposed algorithm to preserve the QoS

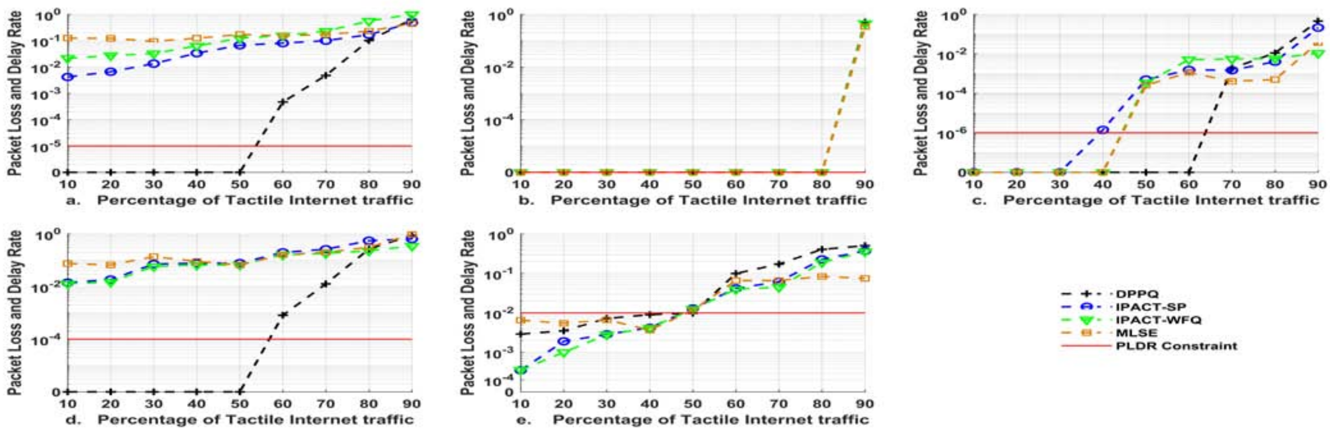

Fig 6. Packet loss and delay rate of (a) TIM,(b) MERC, (c) RTCH, (d) RTNH and (e) OMIT applications under variable Tactile Internet traffic

requirements of medical applications compared to other well-known schemes. We are currently working in the direction of testing the robustness of our proposed algorithm under extreme bursty traffic scenarios including the network-wide synchronized traffic, a situation where burst of data from different flows tend to synchronize in time.

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