Adaptive Resource Allocation Scheme for TETRA Networks with Multi-operators

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***Abstract*— In this paper, we evaluate various aspects of packet data transmission in terrestrial trunked radio (TETRA) networks giving particular emphasis on the performance of applications transmitting data between a number of radio terminals and a fixed server. The utilization of such applications is constantly increasing in public safety networks and so does the need to dimension and configure TETRA networks to meet their reliability, delay and loss requirements. Without an efficient radio resource management (RRM), one operator can exhaust the capacity of others. This study tackles an efficient scheduling to provide maximum system throughput and proportional fairness in accordance with operator capacity share through adaptive resource allocation scheme. We refer to this new scheme as multi-operators time division generalized processor sharing scheme (M-TDGPS). It employs both adaptive rate allocation to maximize the resource utilization and GPS techniques to provide fair services for each operator. The performance analysis of this scheme is derived using the GPS performance model and compared with the normal static rate M-TDGPS scheme. The simulation results show that the proposed adaptive rate M-TDGPS scheduling scheme improves both system utilization (throughput) and average delays.**

Keywords-adaptive rate scheduling; GPS; multi-operator; utilization; TETRA

I. INTRODUCTION

Several IP-based data services are used today in Terrestrial Trunked Radio (TETRA) networks. The traffic of these IP-based applications is characterized by small messages (e.g., in the order of 80–150 bytes) being sent occasionally between a number of TETRA radio terminals and a fixed server. These messages are typically transmitted on a TETRA packet data channel (PDCH), and consequently we term such client-server applications as packet data messaging applications [18].

For current and next TETRA and beyond time division with multiple access (TDMA) networks, sharing the radio access network has become an important issue for TETRA operators. TETRA and beyond network rollout is a very costly and time consuming process. Therefore, sharing of network infrastructure among operators offers an alternative solution to reducing the investment in the coverage phase of TETRA. Another advantage of the deployment of shared networks is the increased coverage, since operators can cooperate on coverage and sites as a more cost-effective way to cover large geographical areas. All together, this will result in reduced time to market and earlier user acceptance for TETRA and its related services. The sharing methods available for similar wireless network operators are proposed in many literatures [1-3]. These sharing methods include, site sharing, radio access network (RAN) sharing, common network sharing, and geographical network. The previous proposals and studies of wireless sharing methods present the problem from an architectural and technical point of view without investigating how the shared radio resources are going to be managed and controlled through radio resource management (RRM) procedures. The RAN based sharing method is of special importance as it reflects the most recent and critical sharing option where more than one operator shares the same RAN. In RAN sharing method, which is the focus in this study, each operator has its own core network and only the RAN is shared as depicted in Fig. 1. This implies that multiple operators fully share the same RAN. Without an efficient RRM, one operator may exhaust the capacity of others. Therefore, there is a critical need for radio resource control between the multiple operators to prevent one operator from exhausting the capacity of others.

Service level agreements (SLA) specify the usage of the radio network capacity for each operator under the RAN based sharing agreement [16]. Each operator receives the agreed upon Quality of Service (QoS) level by following the specified operation rules in the SLA. More about SLA and service management can be found in [16].

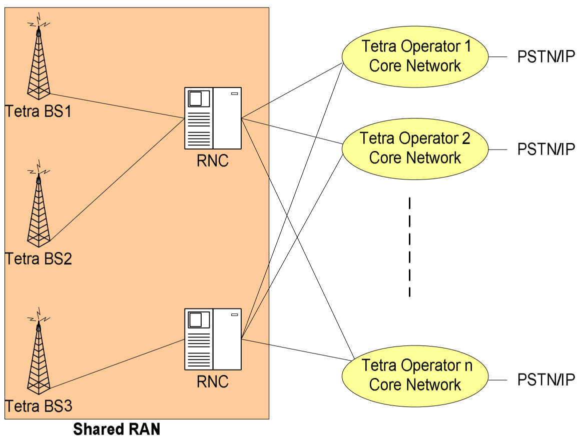

Figure 1. Tetra RAN Sharing

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In order to secure the fair access to the network resources and to optimize the usage of the allotted capacity, it is very important to allow the RRM to separately control each operator and guarantee its minimum required capacity. In other words, the RRM procedure should guarantee that the maximum traffic per operator as defined by SLA is not exceeded unless permitted. RRM can allow an operator's traffic to exceed its limit in an adaptive way if there are unused resources related to other unbacklogged operator in order to increase the overall system utilization. Hence, the shared radio resources must be controlled in a fair and efficient way between operators. The Scheduling scheme, as part of RRM, controls the packets transmissions during the connection time. This study proposes the same idea in the case of TETRA networks. It focuses on designing an efficient and fair scheduling scheme for multi-operator TETRA system.

A. Related Works and Motivation

An ideal fair scheduling discipline is the well known generalized processor sharing (GPS), and also known as weighted fair queuing (WFQ) [4][5]. The GPS discipline was introduced in [4][5].Several GPS-based fair scheduling schemes have been proposed for wireline packet network [4]-[6]. Also, these GPS-based scheduling algorithms have been adapted to wireless networks. The work in [7]-[9], extend fair scheduling schemes developed for wireline networks to time division multiple access (TDMA)-based and hybrid time-division/code-division multiple access (TD/CDMA) based wireless networks. These schemes are implemented using a conventional time-scheduling approach, requiring high complexity due to the intensive computation for the virtual time of each packet [10].

In order to improve radio resource utilization and achieve fairness with low complexity in such TETRA-based wireless networks, number of recent algorithms for GPS-based uplink scheduling are studied and adapted in [11]-[15]. In [12]-[13], an uplink low-complexity code-division GPS (CDGPS) scheme for dynamic fair scheduling is proposed. The CDGPS scheduler makes use of the adaptability of the mobile wireless physical layer to perform fair scheduling on a time-slot basis by using a dynamic rate-scheduling approach rather than the conventional time scheduling approach as in GPS. At the beginning of each time slot, the scheduler adjusts only the channel rate of each session traffic flow in the system by varying the spreading factor and/or using a multiple of orthogonal code channels, rather than allocating service time to each packet as in GPS to reduce the implementation complexity of GPS [13]. A low-complexity GPS-based bandwidth scheduling scheme similar to the CDGPS is also proposed in [14], where a multi-carrier CDMA system is considered. Based on the minimum power allocation algorithm, a WCDMA GPS scheduling scheme is proposed in [15]. However, all these scheduling schemes are designed for single operator systems without considering how to control and schedule the resources that are shared among more than one operator in an efficient and a unified way.

B. Research Contribution

In this study, the CDGPS and GPS discipline idea is adapted and extended in order to design a new high performance GPS-based scheduling scheme which can effectively control the shared resources among TETRA multi-operators in an efficient and fair manner. Efficient means higher system utilization and fair means that each operator guaranteed at least a capacity equals to its capacity share specified in the SLA. Therefore, a multi-operator TDMA based of GPS (M-TDGPS) rate scheduling scheme for the uplink TETRA network is designed and analyzed. The scheme employs both adaptive rate allocation to maximize the resource utilization and M-TDGPS to provide fair services for each operator. The resource allocated to each operator session is proportional to an assigned weight factor as per the SLA specification. After the initial allocation of the allotted capacity, M-TDGPS scheme uses the GPS service discipline to dynamically schedule the assigned channel rates of one operator among the traffic classes within that operator independently.

The rest of this paper is organized as follows. Section II describes the system model and assumptions. Section III explains the proposed scheme in details while Section IV presents the obtained results, as well as the discussion. Finally, the paper is concluded in Section V.

II. SYSTEM MODEL AND ASSUMPTIONS

The original TETRA standard first envisaged in ETSI was known as the TETRA Voice plus Data (V+D) standard [17]. Because of the need to further evolve and enhance TETRA, the original V+D standard is now known as TETRA Release 1. An overview of the network elements covered in the TETRA standard is shown in Fig. 2.

1) Switching and Management Infrastructure (SwMI): The abbreviation SwMI is used to classify all of the equipment and sub-systems that comprise a TETRA network, including base stations.

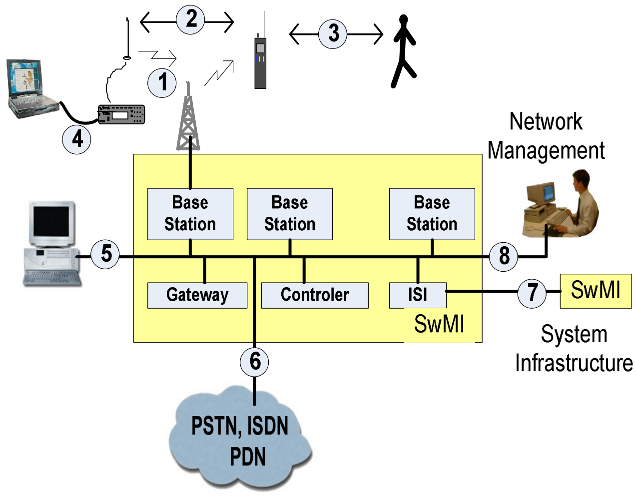

Figure 2. TETRA Standard Interfaces

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Even though some ETSI Technical Committee (TC) TETRA members felt that a standard base station interface would be useful (as provided in GSM) it was decided that owing to the way in which different manufacturers configure their networks for optimum performance and design flexibility, it would be impractical to implement.

It was also agreed, for the same reasons as the base station interface, that everything contained inside the SwMI would not be standardized, thereby allowing TETRA infrastructure manufacturers flexibility in design, and the ability to differentiate their portfolio offerings, when in competition with other TETRA manufacturers. This practical approach also meant that new technologies in the areas of transmission and networking could be used without having to go through a long standardization process.

2) Air Interfaces (1 & 2): The most important (and complex) interfaces are considered to be the 'air interfaces' between the base station and radio terminals (1) and the Direct Mode Operation (DMO) interface (2). DMO is a facility that allows terminals to operate in local radio nets independent of the main TETRA network infrastructure.

3) Peripheral Equipment Interface (PEI) (4): This interface standardizes the connection of the radio terminal to an external device, and supports data transmission between applications resident in the device and the connected TETRA radio terminal. The PEI also supports certain elements of control within the radio terminal from the external device and/or application.

4) Remote Dispatcher Interface (5): This interface was originally intended to allow connection to remote wire line dispatcher consoles like those located in major control rooms. Unfortunately, work on this interface was dropped in ETSI TC TETRA as the complexity to provide a universal interface without degrading performance was impractical. This was because the personal mobile radio (PMR) industry had specialist manufacturers of control room equipment, the majority of which differed in the way they interfaced to PMR networks. Similarly, the TETRA network architecture of manufacturers also differed adding to the complexity of providing a universal interface. For these reasons only TETRA manufacturer specific interface specifications are available to support the many voice and data applications requiring access to TETRA infrastructures.

*5) PSTN/ISDN/PABX (6):*This standardized interface enables TETRA to interface with the PSTN, the ISDN and/or a PABX.

*6) Inter-System Interface (7):*This standardized Inter-System Interface (ISI) allows infrastructures supplied by different TETRA manufacturers to inter-operate with each other allowing interoperability between two or more networks. There are two methods of interconnection in the standard, one covering information transfer using circuit mode and the other using packet mode.

7) Network Management Interface (8): Like the local dispatcher interface, it was recognized during standardization activities that a common network management interface was impractical. Fortunately, this early standardization was not wasted as it was later turned into a comprehensive guide to assist users in defining network management requirements.

Besides these network element standards, the many services and facilities available on TETRA are also standardized. The most significant of these being:

- Advanced and fast group call services - clear and encrypted
- Individual calls - clear and encrypted
- Short Data Services - clear and encrypted
- Packet Data Services - clear and encrypted

Each TETRA carrier is spaced at 25 kHz intervals and supports 4 calls. In a typical 400 MHz system there is 10 MHz duplex spacing between the transmit and receive frequencies (45 MHz for 800 MHz systems). Each TETRA carrier is divided into four time slots as shown in Fig. 3. A TETRA call is allocated one of four time slots on a particular downlink carrier frequency for mobile station (MS) reception, and the corresponding time slot on the corresponding uplink carrier frequency for MS transmission. Each time slot can be occupied by a burst which contains traffic in two fields and a number of bits which aid the terminal in synchronizing to the air interface signal.

At the base station the burst signals for four separate calls are assembled into one TDMA frame and these TDMA frames are organized into a structure of multi-frames and hyper-frames. Radio performance testing is concerned with the bursts in the timeslots. Terminals use the timing information from the received signal to judge when they should transmit to the base station in their allotted time slot.

We assume that the channel bit rate is 5Mbps and N operators can share the cell radio resource (channel rate). Each operator has number of MS. The transmission rate of each operator's MS is scheduled on time-slot basis. For each slot, the scheduler allocates adequate service rates to the N operators, using M-TDGPS scheduling procedures, to guarantee the capacity share requirements of all the operators in a fair manner.

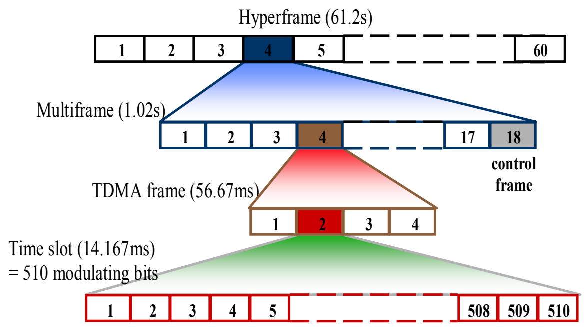

Figure 3. TETRA TDMA

After assigning each operator j its fair service rate, its local scheduler allocates adequate service rates to its flows to guarantee the QoS requirements of all the traffic classes within operator j in a fair manner. The scheduler within each operator can be designed independent of other operator scheduler. Each operator implements its own call admission control, which attempts to control its own arrival traffic.

The new RRM system model is shown in Fig. 4. When a mobile terminal wants to connect, it needs to send a connection requests using the random access channel (RACH). When this request is received at the base station (BS), the multi-operator call admission control (CAC) scheme is first used to check the admission of the connection request of an operator. If the result is positive, the connection request belonging to this operator is accepted and becomes ready for traffic transmission. This is called the admitted connections. When packets for an operator are available for transmission, they need to be scheduled according to their QoS and bit error rate (BER) requirements as a second phase using the uplink scheduler. However, how the packets of this operator's connections are transmitted in each frame is determined by our proposed M-TDGPS scheduling scheme. Therefore, the M-TDGPS scheme employs the dynamic rate allocation among operators in order to increase the overall system utilization and use the GPS model in order to insure the fairness amongst operator when allocating the shared resource. After allocating each operator its resource the TDGPS is then used within each operator to schedule its traffic class.

Two types of services are considered in this study. These two types are: 1) Real-time traffic (RT) such as voice or video, 2) non-real-time traffic (NRT) such as data traffic. The required QoS in terms of delay and BER are different for each of these traffic types. In the next sections, the detail descriptions of the proposed scheme are presented.

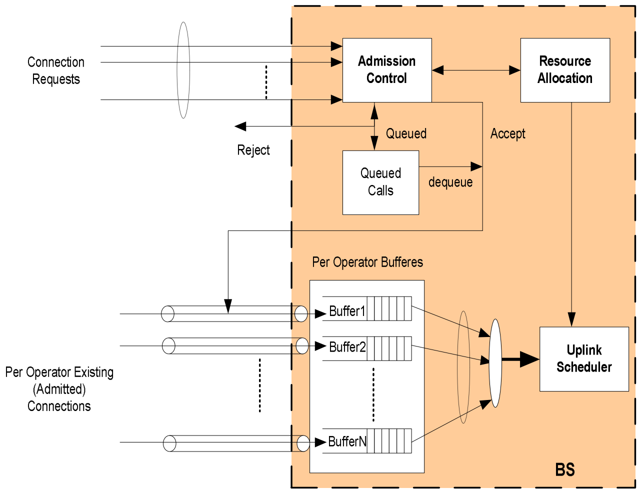

Figure 4. RMM Model for RAN sharing

III. PROPOSED M-TDGPS SCHEMES

The shared resources will be the TETRA channel rate, C, assumed here to be equal to 5 Mbps. We have N operators sharing the same channel. The queuing model of the proposed M-TDGPS scheme is shown in Fig. 5, where the link capacity C is shared by N operators. Each operator has its own assigned soft capacity defined based on the SLA. The assigned weight for operator j is g_j, where $j = 1, 2,\ldots N$. Therefore the total cell capacity in terms of channel rate is divided into N groups. The j^{th} operator maintains two of connections with link rate $C_j(k)$ during the k^{th} medium access control (MAC) slot with capacity $g_j C$.

It is assumed that the traffic characteristic of each input traffic input or stream of the M-TDGPS model is shaped by a Leaky-Bucket regulator [4] in order to achieve a bounded delay and bounded buffer size for traffic queue. Leaky Bucket characterization of a traffic stream is based on specifying two parameters (σ_{ij}, ρ_{ij}) where σ_{ij} and ρ_{ij} are token buffer size and token generate rate, respectively of the leaky bucket. In M-TDGPS scheduling schemes, the allocated resources to an operator $C_j(k)$ during the k^{th} slot can be fixed or adaptive as follows.

A. *Fixed rate M-TDGPS*

Let c_j is the minimum assigned rate for j^{th} operator such that;

$$c_j = g_j C \quad , j = 1,.., N \tag{1}$$

where g_j is defined based on SLA such that; $\sum_{j=1}^{N} g_j = 1$ and $\sum_{j=1}^{N} c_j \le C$. With this mechanism and at each time slot, an operator j is given $C_j(k) = c_j$ share if there it has a backlogged session. If no packet is ready, then $C_j(k) = 0$ and the unutilized capacity of an operator is not allowed to be used by other backlogged operators. This scheduling called fixed rate (FR) M-TDGPS scheduling and the system can be viewed and multi-independent TDGPS systems. Therefore, the assigned rate for each operator is based on (1).

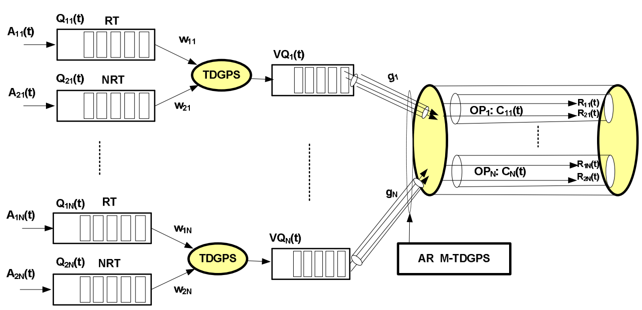

Figure 5. Queuing detail mode for M-TDGPS Scheme

B. Adaptive rate M-TDGPS

In case of an adaptive rate (AR) M-TDGPS scheduling, for each time slot, T, first the j^{th} operator is given its minimum c_j as in (1). The unutilized resources, if any, are then specified by;

$$C_r = C - \sum_{j=1}^{N} c_j \geq 0 \tag{2}$$

Then the excess resources are divided amongst the backlogged operator such that

$$c_e = \frac{g_j C_r}{\sum_{\forall \text{ i such that operator } i \text{ has backlog}} g_i} \tag{3}$$

$$C_j(k) = c_j + c_e \tag{4}$$

The sum of $C_j(k)$ over all the operators should not exceed C in case of adaptive rate and should not exceed $g_j C$ in case of fixed rate allocation. The assigned capacity share to each operator j, $C_j(k)$, is also shared by K traffic classes or flows. Each traffic class i within each operator j has its arrival rate (A_{ij}), queue (Q_{ij}), and maintain a connection with link rate $R_{ij}(k)$ during the k^{th} MAC slot. The sum of $R_{ij}(k)$ over all classes of one operator j should not exceed $C_j(k)$. The procedure used to assign the link rate is explained in the next subsection.

C. The M-TDGPS Procedure

The M-TDGPS procedure is defined as follows. Consider a queuing system of TETRA uplink channel rate with link transmission rate of C. Let $W_j(\tau, t)$ be the amount of operator j traffic served during interval of $(\tau, t]$. Each operator j link is associated with a positive real weight, g_j, j=1,.., N.

Let $S_{ij}(k)$ be the amount of session i traffic of operator j served during the time slot k out of the $W_j(\tau, t)$ that was assigned to its operator. Each traffic i of operator j link is associated with a positive real weight, w_{jj}, i=1,.., K selected based on QoS requirement of this traffic class. Let the scheduling period of M-TDGPS scheme, i.e. the slot length, be T. The M-TDGPS server will allocate each $C_j(k)$ and $R_{ij}(k)$ for each operator j and its individual traffic i, respectively using the following steps.

- Let $OB_j(k)$ be the total amount of backlogged traffic for operator j during the time-slot k, and $B_{ij}(k)$, be the total amount of backlogged traffic of class i of operator j during the time-slot k, such that $OB_j = \sum_{i=1}^{K} B_{ij}(k)$.
- Using $OB_j(k)$, the $W_j(k)$ and $S_{ij}(k)$ are determined as follows. If $OB_j(k)$=0, then $W_j(k)$=0 and $S_{ij}(k)$=0 for all i. If $OB_j(k)$> 0, then $W_j(k)$= c_iT and $S_{ij}(k)$= r_{ij}T for all $B_{ij}(k)$>0, where c_i is the minimum capacity share guaranteed to operator j, and r_{ij} is the minimum rate guaranteed to traffic i form the assigned capacity share of its corresponding operator j. c_i and r_{ij} are calculated as follows:

$$c_i = \frac{g_i C}{\sum_{j=1}^{N} g_j} \tag{5}$$

$$r_{ij} = \frac{w_{ij} C_j(k)}{\sum_{i=1}^{K} w_{ij}} \tag{6}$$

  The session i with $B_{ij}(k)$=0 will have $S_{ij}(k)$= 0 and $w_{ij}(k)$=0.
- After assigning each operator its $W_j(k)$ then , in case of adaptive rate scheduling if $\sum_j W_j(k) < CT$, then the remaining unused resource is distributed to the operators who need more than their guaranteed service c_iT. The distribution of the remaining unused resource should be in proportion to each operator's weight g_j, according to the M-TDGPS service discipline as shown in (4). When an operator j receives part of the unused capacity, it will be distributed to its traffic who need more than their guaranteed service r_{ij}T in proportion to each traffic's (session) weight w_{ij}.
- Finally the allocated channel rate to each operator j and to each backlogged operator traffic i can be determined by $C_j(k)$= $W_j(k)$/T and $R_{ij}(k)$= $S_{ij}(k)$/T, respectively.

IV. SIMULATION RESULTS

In this section, simulation results are presented to demonstrate the performance of the proposed M-TDGPS scheme in terms of delay and system throughput only due to paper limitation. Throughput is calculated as the average number of served packets per second. C++ is used to build the simulation model. Based on the characteristic of TDMA wireless physical layer, the scheduling period T is 14.167 ms as shown in Fig. 3. In simulation, the M-TDGPS scheme is compared in case of adaptive rate (AR) M-TDGPS and fixed rate (FR) M-TDGPS under heterogeneous traffic environments. The total bandwidth is assumed to be a constant C=5Mbps assuming we have the new generation of TETRA Networks. Three operators are considered (N=3) each operator is assigned different weight based on SLA. We assumed that each operator is given (g_j=1/3) of the bandwidth as a minimum. All operator follows are modeled by a Poisson process with average arrival rate λ and packet length L shaped by a leaky-bucket regulator for providing bounded delay. In this simulation L=512 bits which is the maximum size of data frame, σ_{ij} =100L, ρ_{ij} =C/6, and λ can be varied in order to change the system load.

In the following experiments, the traffic loads of operator 2 (OP2) and operator 3 (OP3) is fixed to 512 Kbps and the traffic loads of operator 1 (OP1) is varied. The system throughputs and the average packet delay versus offered traffic are depicted in Fig. 6 and Fig. 7. The offered traffic is

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calculated as the total of all operators' traffics (Packets per second).

Fig. 6 shows the system throughputs comparison in case of fixed rate (FR) and adaptive (AR) rate M-TDGPS. The traffic loads are the sum of average arrival rates of the 6 data follows (two per operator).

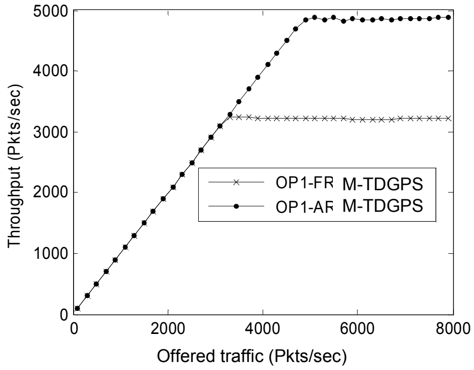

Figure 6. System Throughputs

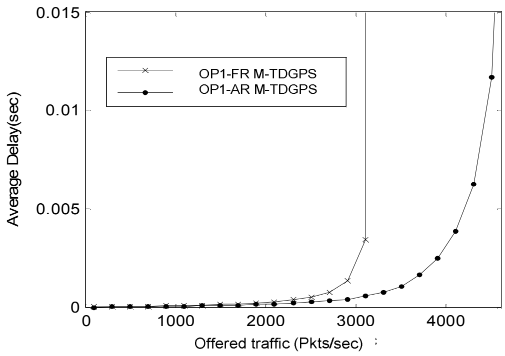

Figure 7. Average packets delay.

As expected the throughputs of adaptive rate M-TDGPS is higher in case of using adaptive rate because of using the concept of utilizing the unused resources of other operators. Hence the system throughputs increase. Fig. 7 shows the average delay with different system loads. In this figure it can be seen that the average delay performance of adaptive M-TDGPS is better than M-TDGPS with a fixed capacity per operator. In adaptive M-TDGPS, the unused resources can be distributed amongst the backlogged flows. Therefore, more packets can be served.

V. CONCLUSION

An efficient adaptive rate M-TDGPS scheme has been proposed for supporting multi-services in the uplink of TETRA networks with multi-operators. The simulation results show that the proposed scheme can improve both system utilization and average delays. The proposed scheme allows for a flexible trade-off between the GPS fairness and efficiency in resource allocation and is an effective way to maximize the radio resource utilization under the fairness and QoS constraints.

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