



Load balancing in integrated optical wireless networks Igorithms and evaluation

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LOAD BALANCING IN INTEGRATED OPTICAL WIRELESS NETWORKS: ALGORITHMS AND EVALUATION

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ABSTRACT

In this paper, we tackle the load balancing problem in Integrated Optical Wireless Networks, where cell breathing technique is used to solve congestion by changing the coverage area of a fully loaded cell tower. Our objective is to design a load balancing mechanism which works closely with the integrated control scheme so as to maximize overall network throughput in the integrated network architecture. To the best of our knowledge no load balancing mechanisms, especially based on the Multi-Point Control Protocol (MPCP) defined in the IEEE 802.3ah, have been proposed so far. The major research issues are outlined and a cost function based optimization model is developed for power management. In particular, two alternative feedback schemes are proposed to report wireless network status. Simulation results show that our proposed load balancing mechanism improves network performances.

1. INTRODUCTION

A hybrid optical wireless network is an attractive candidate for the next generation broadband access network architecture. Optical networks offer greater bandwidth and reliability while wireless networks can support greater coverage and mobility. In the integrated architecture, an optical access network, e.g. the Ethernet Passive Optical Network (EPON), provides high bandwidth capacity as a backhaul network, and a wireless network, e.g. Worldwide Interoperability for Microwave Access (WiMAX), locates at the front end to offer both fixed and mobile broadband wireless access. In hybrid network architectures, the resource management mechanism plays a key role in ensuring an efficient usage of both optical link and radio spectrum [1-4]. This is of particular importance for next generation broadband access networks which support data, voice and multimedia services (triple-play services) to multiple users simultaneously. A system level control platform for integrated resource management is required to be considered since most of research efforts in this field have been focused in either optical networks or wireless networks solely.

Recently, there are increased interests in converging optical and wireless networks to exploit the complementary characteristics of the two networking technologies. These papers

primarily focus on the architectures for integrated access networks and offer examples of enhancement over obliviously connected networks. K. Yang et al. [5] propose traffic mapping and hybrid scheduling method in integrated EPON and WiMAX network. Shaw et al. [6] present a novel integrated routing method to achieve load balancing through the use of load-aware routing in multi-hop network. The approach is applicable to mesh network, but it does not provide the mechanism to achieve load balancing in single hop Point to Multiple Point (PMP) network. To the best of our knowledge, load balancing method has not been proposed in this area. This paper takes a look at the challenging yet interesting multi-cell load balancing problem in view of network capacity maximization, by utilizing the integrated EPON backbone to make cooperative and centralized decisions for traffic distribution and power assignment.

The integrated network architecture is illustrated in Figure 1, which shows a mapping between clients and AGs. In the hybrid optical wireless network, the Optical Network Unit (ONU) functions and the Base Station (BS) functions are integrated into a single device, namely an *Access Gateway (AG)*, which handles connections within the wireless network (single-domain connections), or cross both EPON and WiMAX (multi-domain connections). Clients associate with an AG with the strongest Received Signal Strength Indicator (RSSI) of the AG's beacon. Studied in previous work [7][8], client service demands are highly varied in terms of both time of a day and location. Thus, traffic loads are often distributed unevenly among AGs, which results in congestions at popular locations. As shown in the figure, AG^l can become overloaded while nearby AGs are lightly loaded.

In an integrated optical wireless network, coordinated resource management could be accomplished through the use of the integrated control framework. There are many opportunities to exploit the interworking between integrated EPON and WiMAX networks. The principles of the hybrid network architecture allow the Optical Line Terminal (OLT) to operate as a central control office, which distributes downstream data and allocates upstream bandwidth among connected multiple wireless networks. To take advantage of the centralized system and the integrated control scheme, we propose a load balancing algorithm together with the optical

downlink scheduler, which is able to manage the transmit power and distribute traffic load among wireless networks dynamically. In load balancing cells are assigned with proper power values to avoid overload situations if a collocated system still has sufficient resources. A centralized power allocation control is implemented in the OLT unit. This is done by exploiting a set of suitable power profiles that derive the maximum network throughput and user quality of service. Our goal is to propose a novel integrated load balancing scheme, which utilizes a cooperative signalling protocol to collect WiMAX network information and makes centralized power assignment decisions in the EPON.

In this paper, we explore an integrated load balancing scheme using the cell breathing technique. The concept of cell breathing is used in conventional cellular networks to dynamically change the coverage area of cell towers [9][10]. Fully loaded cells contract their coverage area whereas the lightly loaded cells expand their coverage area. Basic idea of load balancing is to relocate users in overlapping region from fully loaded cells to lightly loaded cells. The proposed cell breathing mechanism is based on interworking between AG and OLT to dynamically adjust the number of subscriber stations (SS) associated to each wireless network.

The remaining parts of this paper are structured as follows. We introduce the system model and formulate the optimization power management problem in Section 2. In Section 3, we discuss our proposed load balancing mechanism as an extension and modification of traditional MPCP scheme. In Section 4, we present and discuss our simulation results. Finally, we conclude this paper in Section 5.

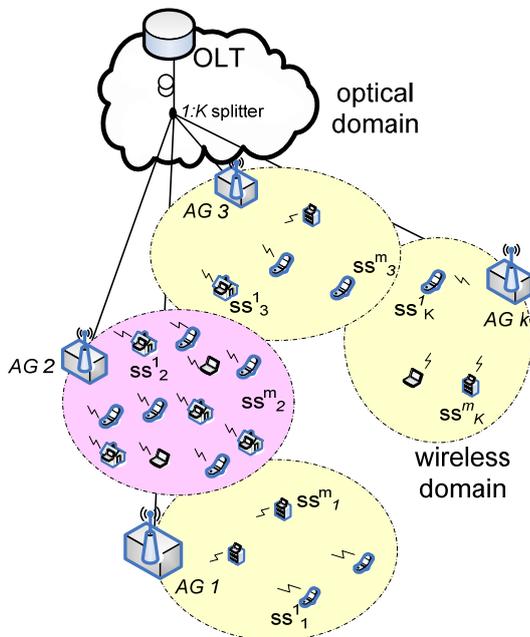


Figure 1 - Illustration of imbalance load distribution among AGs in the hybrid network. AG2 becomes heavily loaded as indicated in red colour, while neighbouring cells have sufficient resources.

2. SYSTEM MODEL AND PROBLEM FORMULATION

2.1. System Model

We consider the hybrid architecture with multiple WiMAX cells as frond-end networks, where K AGs that connect to a central control station, OLT, via the optical link. There is one AG in each cell. As shown in Figure 1, the wireless network consists of a set of $k = \{1, 2, \dots, K\}$ of cells and a set of $m = \{1, 2, \dots, M\}$ users in each cell. The service area is partitioned so that each client connects to only one AG at any given time.

For simplicity of presentation, a system consisting of two cells is used to illustrate the cell breathing technique as shown in Figure 2. Cell operation area is modelled by a circle with a coverage radius (R_c). At any given time slot n , the cell coverage, the number of connected SSs, and the offered data rates to SS are varied by allocating different transmitting power levels (P_t) to the AG. For instance, AG^1 initially is assigned with power P_t^1 and covers SS_{1-4}^1 . After AG^1 is reported as overloaded, R_c^1 is contracted and its neighbouring cell (R_c^2) is expanded in order to accommodate and serve additional SS_{3-4}^1 . Thus, the traffic load is balanced between AG^1 and AG^2 with minimized packet loss.

Within a WiMAX cell all users share the common channel by using a Time Division Multiple Access (TDMA) radio interface. The delivery of the packets to subscriber users is performed on a TDM frame consisting of N slots. Mobility is not considered in our simulation scenario, only stationary (e.g. fixed terminals) or quasi stationary users (e.g. pedestrian) are assumed. The handover procedure is out of the scope of this work. We assume that fast handover is supported to minimized delay and delay jitter. In order to optimize the system and ensure overall QoS, we use the backlogged queue size and delay merit to determine whether or not a cell is overloaded. A cell overloading is said to occur, if 1) the total queued data for all traffic classes at that instant exceeds a threshold, Q_{thr} , or 2) delay to transmit the queued real-time traffic is violated to the requirement, D_{thr} . In the former case, the cell cannot take more traffic due to the buffer size limitation. In the latter case, the cell cannot guarantee real-time traffic with satisfied QoS requirements.

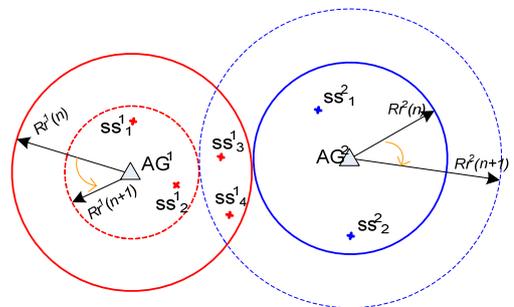


Figure 2 - Cell breathing in wireless network. The solid circles represent initial coverage areas (at time n) and the dashed circles represent adjusted coverage areas (at time $n+1$).

2.2. Wireless Air-interfaces and Service Queues

The size of cell coverage depends on transmit power, noise and path loss. The received signal at the m th user in the k th AG, SS_m^k , is an attenuated version of the transmitted power level. The propagation model includes path loss, shadowing and fading [11]. The mean received power (P_r) is the difference between the sum of the transmit power (P_t) and the antenna gains (G_a) and the path loss (P_n). The Signal to Interference plus Noise Ratio (SINR) is the ratio of received signal power to the interference signal power (I_n), which is computed using Eq. (1). There is a minimum acceptable SINR ($SINR^{thr}$) for receiving a quality satisfied signal.

$$SINR (dB) = P_r - I_n = P_t + G_a - P_n - I_n \quad (1)$$

Where I_n denotes the total interference received at each user, which consists of two parts: intra-cell interference and inter-cell interference. The intra-cell interference is caused from other SSs within the cell and the inter-cell interference is caused from the neighboring BSs. In this scenario, TDMA scheme is applied and only one SS transmits during the assigned slot time. It is assumed that there is no mutual interference among SSs in a cell. On the other hand, the initial cell coverage of AG^1 and AG^2 are non-overlapping by assigning proper transmission power values in order to avoid cross-cell interference. Our analysis is restricted to a static scenario, where we assume that all channel gains are constant. The system throughput of a Single Input Single Output (SISO) system, AG^k , can be derived from the well-known Shannon capacity using the expression below (2):

$$T_{total}^k = \sum_{i=1}^K \log_2(1 + SINR^i), k \in K \quad (2)$$

Clearly, the throughput is determined by the interference level, the channel condition, applied transmitting power and the distance between the AG and SSs.

To present the queuing states in this integrated cell breathing problem, we define $r^i(N)$ as the residual queue length in AG^i at the beginning of period N . $\alpha^i(N)$ is total arrived traffic in AG^i from OLT during period N . $d^i(N)$ represents total departed traffic from AG^i to the SS during period N and $Q^i(N)$ is the notation of downlink queue size in AG^i at the beginning of period N . At the beginning of period N , a burst of packets $\alpha^i(N)$ arrive at the AG^i from the OLT and a control message may also be sent to the AG^i with the power assignment if power control is issued. At the beginning of period N , AG^i holds $r^i(N-1)$ amount of data in the queue from previous period $N-1$. During this period N , the AG^i is expected to transmit $E[d^i(N)]$ to its SS. $E[d^i(N)]$ is denoted as $\hat{d}^i(N)$ in the following discussion and the difference between $E[d^i(N)]$ and $\hat{d}^i(N)$ are reconciled when the actual queue length, $R^i(N)$, is reported. Thus, the equation for the AG^i backlogged queue size is:

$$Q^i(N+1) = r^i(N+1) + \alpha^i(N+1) = Q^i(N) - d^i(N) + \alpha^i(N+1) \quad (3)$$

In the proposed integrated cell breathing problem, the AG load is seen as the aggregate load contributed by its associated users. During a given network state, a subset of the AGs

that suffer from maximal load is called the congested AGs. The optimal controller would move the congested AGs into un-congested states and minimize the impact of the transfer loads to neighbouring AGs. In Eq. (3), variables $\alpha^i(N+1)$ and $d^i(N)$ to denote the traffic to be allocated to AG^i (control variable) and expected amount of departed traffic during current period N (measurement variable). The second parameter is not exact and in this formulation, the inexactness between $E[d^i(N)]$ and the actual $d^i(N)$ is considered as a source of noise. The expected amount of departed data can be estimated using theoretical system throughput.

2.3. Problem Format

After the definition of the air-interfaces and service queues including the constraint, we now formulate the optimization problem. The cost that an AG suffers from assigned resources can be measured. System cost merits contain the system throughput, delay, and the backlogged data size. From the operator's perspective, the profit increment represents minimizing the total cost over all possible resource assignments, in our work, meaning power management.

Given a finite horizon of N period, an optimal cell breathing controller will minimize the cost function defined as Eq. (4). Each AG^k attains its individual fixed transmitting power lever during a time slot, P_t^k , to provide services with satisfied QoS constraints of each user, while optimizing the global multi-cell system throughput through balancing traffic load between AGs. Define $p = [p_1, \dots, p_{max}]$ as a vector of discrete power levels assigned to AGs by the OLT.

$$\begin{aligned} & \text{Minimize} && \sum_{i=1}^K T_i(p_i) && (4) \\ & \text{Subject to} && p_i \leq p_i \leq p_{max} && \forall i \in K, \\ & && SINR_{ij} \geq SINR_{ij}^{thr} && \forall i \in K, \forall j \in M, \\ & && Q_i < Q_{thr} && \forall i \in K. \end{aligned}$$

The first constraint indicates that each AG is assigned within a maximum power p_{max} . The second constraint shows that quality transmission is ensured with assigned power. The last constraint represents that the expected traffic load is less than a pre-determined congestion level.

3. PROPOSED LOAD BALANCING MECHANISM IN THE INTEGRATED NETWORK

As specified in IEEE 802.3ah, EPON relies on multi-point control protocol (MPCP) that bases on GATE and REPORT messages to grant and request for uplink bandwidth [12]. The GATE message is broadcasted to all ONUs and target ONU receives the packets based on the labelled link layer identification (LLID). The REPORT message is reported to the OLT by ONU within its uplink transmission window. OLT allocates upstream bandwidth based on either fixed bandwidth allocation or dynamic bandwidth allocation (DBA) algorithms. Here in the hybrid architecture, ONU functions are implemented into the AG unit.

The load balancing mechanism is implemented based on the traditional MPCP framework. In order to decide optimal power assignment and achieve load balancing, the traditional MPCP is extended and new fields are added into the GATE and REPORT control messages. We define the control messages deployed in the load balancing mechanism as *GATE-p* and *REPORT-p*. The *GATE-p* message is used for both assigning power information and allocating upstream bandwidth allocation information. *REPORT-p* is a modification with additional network information, such as the residual queue length (Q_{res}) and Residual Expected Wireless Transmission Time (*REWTT*) to the message. *GATE-p* and *REPORT-p* messages incorporate and provide feedback network information for intelligently distributing traffic load among multi-cell network.

In order to collect network status from all connected AGs, we develop two cell information feedback disciplines and compare their performances in the MPCP based load balancing mechanism. The first of two feedback disciplines is called Polling Period Report (PPR) scheme, where cells update their network status whenever they are polled by the OLT. We show that without increment of complexity compared to traditional MPCP, the scheme attains improved performances in terms of network throughput and delay. The second feedback discipline is called Short Period Report (SPR) scheme, which is an extension to the PPR scheme. We describe these two feedback schemes in the following subsections and then illustrate their performances by simulation results.

3.1 Polling Period Report (PPR) feedback scheme

After receiving bandwidth requests from registered AGs, the OLT schedules the upstream transmission without conflict. Using the *GATE-p* message, granted bandwidth and start time are assigned to AGs. AGs are polled in sequence based on the scheduling police used in the OLT. In this example, AGs are polled in an increased order of their LLID number using Round Robin (RR) scheduling. The following load balancing procedure is carried out (illustrated in Figure 3):

- At time t_1 , the OLT broadcasts power assignments to its connected AGs via *GATE-p* message. Each AG adjusts its transmitting power and associates SSs.
- After receiving the *GATE-p* message, AG^l is polled and starts its uplink transmission at t_2 . Along with data, the current Q_{res} and *REWTT* information of the AG^l are reported to the OLT. Upon receiving the *REPORT-p* message at t_3 , the initial entry table is updated at the OLT.
- If the AG^l is sufficiently crowded, the OLT reduces the assigned power to AG^l ($Pt^l_2 < Pt^l_1$) and increases its neighboring cell powers ($Pt^k_2 > Pt^k_1$). The *GATE-p* message is broadcasted along with the *GATE-p* message at t_4 , and all AGs adjust their transmission power levels. Since the subscriber device chooses the base station with the strongest Received Signal Strength Indication (RSSI) among all received signals from AGs. When the cell coverage changes, some subscribers in

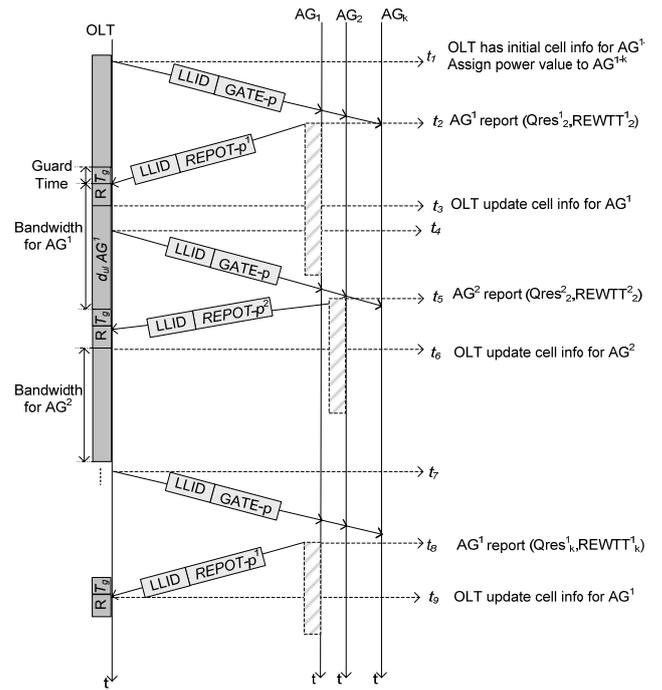


Figure 3 – Load balancing mechanism with the Polling Period Report (PPR) feedback scheme.

the overlapping region (e.g. SS^l_3, SS^l_4 in Figure 1) will be forced to handover to a less loaded neighboring cell.

- The *GATE-p* message destined to AG^2 contains both information for transmission power adjustment and information for upstream bandwidth allocation. At t_5 , only AG^2 is granted with upstream transmission bandwidth.
- The feedback from AG^l after decreasing its transmission power and contracting its region will be reported to the OLT at its next polling time, t_8 .

As explained above, in the PPR scheme, an AG reports its current traffic load and channel conditions to the OLT only when the time the AG is polled. For example, the AG^l changes its power at time t_2 , and the consequence of power adjustment is learnt at the OLT at time t_3 . The length of the interval to update the cell information depends on the signaling mechanism in MPCP. The AGs reply to the OLT with a *REPORT-p* message, when the AGs receive the *GATE-p* message with the bandwidth assignment. Therefore, different bandwidth allocation mechanisms results in different polling intervals, which are the interval for updating the cell status:

- When the fixed upstream bandwidth allocation (for example, TDM) is used, the polling interval for an AG is fixed, so that the interval for each AG to report is also a fixed amount of time.
- When the dynamic upstream bandwidth allocation (for example, IPACT [15]) is employed, *REPORT-p* message and the embedded downlink load information is feedback to the OLT aperiodically.

The problem with the PPR feedback scheme is realized as the long update interval. Along with increasing the number of AGs, waiting a polling cycle to update the cell status may either result in a congestion that can not be discovered on time, or, alternatively, yield improper power adjustment due to out-of-date information. Particularly, to account for random wireless channel fluctuations, the feedback mechanism is important to attain real-time cell status.

3.2 Short Period Report (SPR) feedback scheme

Although the implementation of PPR scheme is simple, the load balancing may be not optimized and effective because precise network status can not be attained, especially when the polling interval for an AG is increased. Therefore, a feedback scheme with short updating period is proposed. The scheme can be implemented by coordinating the upstream bandwidth allocation at the OLT and AGs.

The basic idea of SPR scheme is to grant AGs upstream bandwidth to report their cell information after an AG is polled. As indicated in Figure 4, the OLT broadcasts the GATE-p control message to all AGs and assigns transmission power value according to the cell breathing algorithm to attain global network throughput optimization (at t_1). Upon receiving the GATE-p message, all AGs are required to inform their network conditions by transmitting the REPORT-p message (during t_2 to t_3). The OLT allocates a period for receiving REPORT-p messages from all AGs and then upstream transmission period for the polled AG. Different to the PPR scheme, the entry table maintained in the OLT is updated every granted slot time (at t_4 and t_7) to each AG instead of after all AGs are granted.

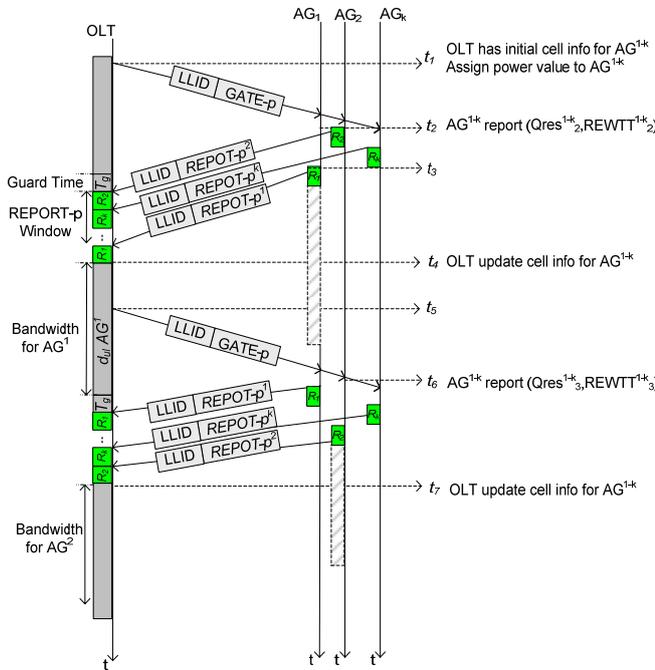


Figure 4 – Load balancing mechanism with the Short Period Report (SPR) feedback scheme.

Compared to PPR scheme, the period that the OLT receives network updating information is decided by the granted upstream transmission bandwidth to each AG using SPR scheme. Cell status is updated more frequently, so that the power management decisions are made according to nearly real-time network conditions. The period that the OLT allocates for receiving REPORT-p messages from all AGs is defined as the REPORT-p window. It is worth noting that the length of the REPORT-p window is determined by the number of connected AGs and the size of REPORT-p message. Obviously, the upstream link utilization is reduced by introducing the overhead of REPORT-p window. In the next section, we will show the increment on network performance as a trade-off of introducing more control message overhead in the SPR feedback scheme.

4. SIMULATION RESULTS

In this section, we evaluate the integrated load balancing using cell breathing scheme in OPNET simulation environment [13]. The integrated system is similar to Figure 1 and consists of K AGs ($K=16, 32, 64, \text{ or } 128$). The downlink optical transmission rate is 1 Gbps and downstream data are broadcasted from the OLT to AGs. There are up to 200 SSs connected into a wireless network. Traffic arrival process follows a Poisson distribution and the mean arrival rate varies from 0.01 to 0.1 Mb/s per SS. The guard time is 5 μ s and the AG buffering queue size is 50 MB. In the WiMAX system, network parameters are configured as in [14]. For simplicity there is one AG per wireless cell and SSs are distributed randomly over the cell region.

For the simulation study, we consider one heavily loaded cell at AG^1 . Few traffic arriving are designating to the neighbouring cells of AG^1 and thus its neighbour cells are available to assist AG^1 with hosting traffic from boundary SSs. The simulation compares the performances of the load balancing (LB) solution against without using load balancing (NLB). In addition, two alternative feedback schemes are implemented in the load balancing mechanism and their performances are analyzed and discussed.

4.1. Comparison of LB and NLB schemes

We first simulate the network throughput rate vs. input traffic amount (shown in Figure 4a). As expected, when the load balancing scheme is applied, overloaded traffic in the AG^1 can be shared by neighbouring cells, and therefore, the overall network throughput increases. The LB solution increases the network throughput in excess of 30% at best and the improvements become more obvious when the input traffic load increases. In the case of NLB, AG^1 continues to serve the boundary SS, which overloads the AG while demanding relatively longer transmission time due to low SINR available at the crowded cell boundary. Hence it is advantageous to balance traffic load among cells.

Then we investigate the average transmission delay in the overloaded cell (shown in Figure 4b). Because sufficient optical resource is assumed and high speed optical link is

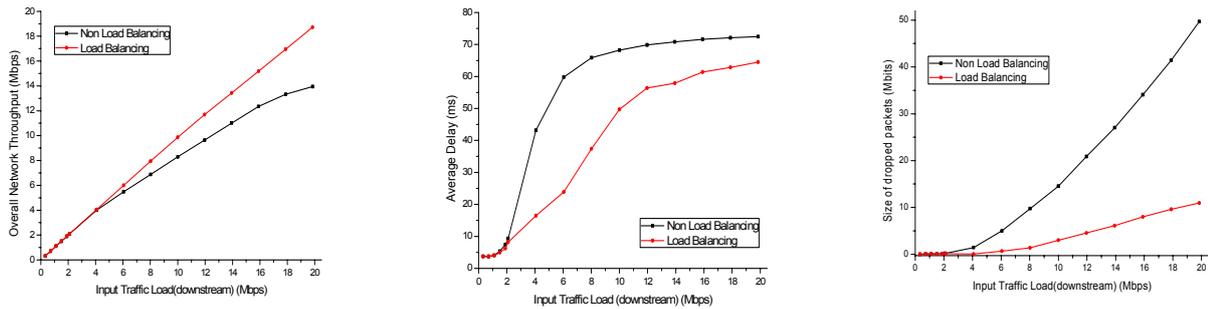


Figure 4 – Comparison of LB and NLB mechanism (a) overall network throughput (b) average delay (c) size of dropped packets.

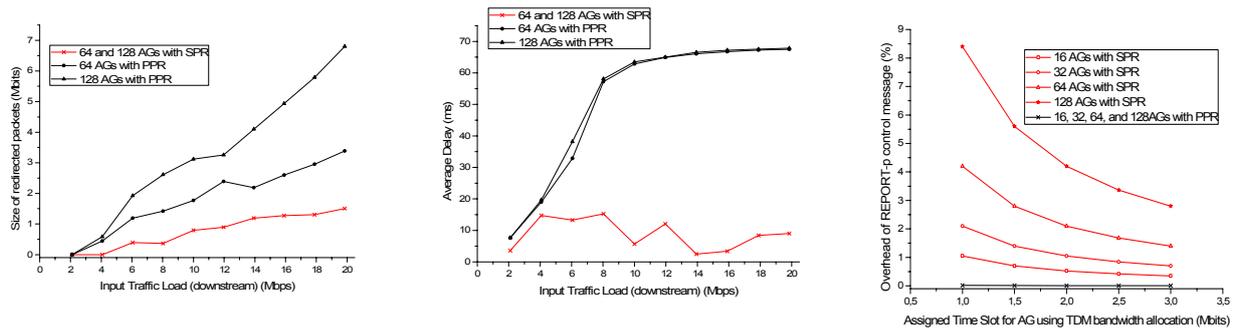


Figure 5 – Comparison of PPR and SPR feedback scheme (a) size of redirected packets (b) average delay (c) overhead of REPORT-p control messages

available, the queuing delay in OLT and the optical downstream transmission delay are neglected. In this test case, the First-In First-Out (FIFO) scheduler is deployed for downstream transmission in wireless networks. When the input traffic load is moderate, using the load balancing algorithm achieves nearly half reduced queuing delay. This is because AG¹ is relieved from excess loads after load balancing and can more efficiently handle the remaining queued data despite reducing data rate due to reduced transmission rate as a result of reduced transmission power.

Next shown in Figure 4c, the size of dropped packets at AG¹ is evaluated under different input traffic load. Under light traffic load, the dropping probability of LB solution is zero, which performs better than the NLB solution. However, when the input traffic load continues to increase, neither LB nor NLB can meet the delay requirement or the maximum buffer size.

4.2. Comparison of PPR and SPR schemes

In this test case, we compare performance of PPR and SPR feedback schemes. We consider a network scenario with 64 and 128 AGs. Figure 5a shows the size of redirected SSs as a function of the input traffic load of the overall network. As expected, the network performances are degraded when the number of AGs is increased due to long interval to update cell status. We can see that the SPR scheme outperforms the PPR scheme in terms of resource utilization especially when the traffic load is high. The reason is that when the system load is high, the network status, such as queue size, is changed within shorter period compared to the case when

system load is low. SPR scheme makes sure that the congestion in a cell can be reported and discovered on time, so that the OLT can adjust the power value of the overloaded cell and the size of redirected SSs is decreased. A relatively long interval to update cell status increases the buffer size, so that more SSs are reallocated. In other words, using SPR scheme, a cell serves more traffic and generates better network utilization.

Figure 5b shows the average transmission delay experienced by the data in the overloaded cell. Since the heavily loaded situation can not be solved on time, using PPR scheme the cell experienced high delay. On the other hand, with SPR scheme, we observe that the load balancing mechanism is more effective to relieve high traffic load burden from the overloaded cell.

Next, we measure the percentage of the REPORT-p window versus the allocated upstream bandwidth. The smaller percentage is, the lower overhead produced by the REPORT-p window. In this simulation, we use the TDM upstream bandwidth allocation, so that each AG is polled and assigned with fixed upstream transmission period. Figure 5c shows the overhead of the REPORT-p window when the assigned upstream bandwidth for data payload is increased. We can see that when the number of AG grows, the variance of the overhead grows as well, while the overhead in the PPR case remains as the lowest. Using the PPR scheme, only the polled AG needs to transmit REPORT-p message. Therefore, the overhead is much smaller in the PPR case. We conclude that the SPR scheme improves the load balancing efficiency

and results in better network performances, however, at the cost of moderate increased control message overhead.

5. CONCLUSION AND FUTURE WORKS

In this paper, we have considered the cell breathing technique and developed the load balancing mechanism for the integrated optical wireless network. Depending on the feedback cell status from AGs, the OLT choose optimal power assignments and corresponding cell association for SSs. Two feedback approaches are proposed based on modification and extension of traditional MPCP. Verified by simulation results, it demonstrates that the proposed load balancing operation can effectively handle heavy load cell by reduces the transmit power and reallocates boundary SSs. Hence, with the load balancing of network, the congestion of the cell and in turn the whole system is effectively relieved. We have also considered the effect of providing frequent report messages and observed that short period report scheme outperforms in terms of network throughput and delay performances, however, at a cost of additional control message overhead.

Although this paper has discussed the basic idea and provided simulation results for the load balancing mechanism in a hybrid network architecture, as a new and interesting topic for integrated optical wireless networks, advanced signalling protocols may be investigated in the future work.

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