Collision-less Scheduling Algorithms with Arbitrary Transceiver Tuning Latencies in Broadcast DWDM Networks

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Abstract

To achieve high bandwidth in the high-speed communication network is available for fiber-optical networks. Wavelength Division Multiplexing （WDM） increases the usage of bandwidth by partitioning the bandwidth into many, more manageable high-speed channels. Many scheduling algorithms are proposed to bring out channel reusing in a limited bandwidth to increase system performance. Unfortunately, from the practical point of view, the proposed scheduling algorithms did not consider some factors such as the *data packet collision* （multiple data packets use the same channel to transmit simultaneously）, *transceiver conflict* （transceiver transmits or receives multiple data packets simultaneously） and *tuning latency* （the time transceiver needs to tune to the dedicated channel）. In this paper, we propose a novel collision-less scheduling algorithm embedded with arbitrary transceiver tuning latencies in single-hop passive star coupler based WDM

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network for different transceiver models （TT-TR, TT-FR and FT-TR）. In addition, the proposed scheduling algorithm also supports multi-transmission behavior （point-to-point, multicast and broadcast）. The simulation model can be developed to analyze the system performance in terms of average packet delay, channel utilization and network throughput with the variations of the number of nodes, the number of data and the number of channels for TT-TR, TT-FR and FT-TR transceiver models.

Key Words： WDM, Data packet collision, Transceiver conflict, Tuning latency, Collision-less scheduling algorithm, System performance.

任意傳收器調諧延遲光纖網路中無碰撞排程演算法

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摘　要

由於網路的蓬勃發展，加上多媒体（multimedia）技術的應用，使得現有的頻寬已逐漸不敷使用，透過光纖網路可以提供較多的頻寬，故得在固定的頻寬中，使用良好的排程演算法，來增進頻道的重覆使用率，和網路的整體效率。就目前波長分割多工（WDM） 的排程演算法而言，大略可分成三種主要方式:Random access-based protocol 、Pre-allocation-based protocol 以及 Reservation-based protocol，本文裡，首先概述個別的工作原理。接著描述所摘錄下來，以 Reservation-based protocol 爲主的六個排程演算法工作原理。而本文所提出的無碰撞（collisionless）排程演算法是以廣播式被動星形隅合器（Passive Star Coupler （PSC））連結的光纖網路架構爲主，不但能夠解決之前六個演算法在單一對資料頻道的傳收器中，單次跳躍傳輸可能發生封包碰撞與傳收器困擾的問題，同時我們也考慮收發器的轉換延遲（tuning latency）對整個系統的影響，甚至可適用於 Multi-transmission behavior 之機制。我們利用模擬程式來評估演算法對於三種不同傳收端（transceiver）架構；評估演算法於 multi-transceiver model 的效能，包括以節點數、封包數與頻道數爲操縱變因的

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頻道使用率（channel utilization）、平均封包延遲（average packet delay）與輸出率（throughput）。以提供此演算法對不同網路架構。

關鍵字： multimedia、random-access based protocol、pre-allocation based protocol、reservation based protocol、PSC（Passive Star Coupler）、multi-transceiver model: TT-TR 、 FT-TR 、 TT-FR 、 Multi-transmission behavior ： point-to-point、Multicast、Broadcast

I、Introduction

In recent years, network flow increases due to dynamic development of the network, where network users and application services are increasing, such as multimedia systems, Video on Demand （VOD）, video conference, … , etc [1]. To achieve Terra bits per second（Tbps）high bandwidth in the high-speed communication network is available only with fiber-optical network. Wavelength Division Multiplexing（WDM）[2][3] increases the usage of bandwidth by partitioning the bandwidth into many, more manageable high-speed channels. However, the increasing of network traffic will raise the collision and congestion of the data packets. There are two possible ways to resolve such problems: 1、Reducing the packet flow of traffic（including the compression techniques）. 2、Increasing network bandwidth and channel utilization that the important issues will be the discussed in this paper. Many scheduling algorithms [4][5][6] are proposed to bring out channel reusing in a limited bandwidth to increase channel utilization. The efficiency of channel assignment and packet allocation will affect the system throughput. But, from the practical point of view, the proposed scheduling algorithms did not consider data packet collision, transceiver conflict （Collision means multiple data packets use the same channel to transfer simultaneously; conflict means a transceiver transmits or receives multiple data packets simultaneously） and tuning latency [6][15] （tuning latency is the time transceiver needs to tune a channel before the packet is transmitted or received）. Thus, in this paper, a new collision-less scheduling algorithm is proposed to support channel assignment and packet allocation with arbitrary transceiver tuning latencies based on the single-hop WDM passive star-coupled network architecture [6][14]. In addition, the proposed scheduling algorithm also supports point-to-point, multicast, and broadcast of transmission behaviors.

Scheduling algorithm is used to solve the problem that how to efficiently put many data packets sequentially into data channels to obtain the optimum throughput. So far, the proposed scheduling algorithms can be divided into three categories；1、Random-access-based scheduling algorithm [7][8], 2、Pre-allocation-based scheduling algorithm [9] [10] [11] [12], and 3、Reservation-based scheduling algorithm [4][5][6][13]. In Random-access-based protocol, all optical network channels are assigned to data packet transmissions, while channels are allocated by contention vulnerably. In Pre-allocation-based protocol, all optical network channels are also assigned to data packet transmissions, while particular channels are allocated to predefined data packet statically. In Reservation-based protocol, one channel is assigned as a control channel broadcasting global information to internal nodes in the system, where each node performs the same distributed scheduling algorithm to determine when particular nodes can use dedicated data channels to receive/transmit data packet. Reservation-based protocol is appropriate for dynamic scheduling algorithm, and is applied in this paper to obtain the optimum throughput. Table 1 summarizes the characteristics of the existing scheduling algorithms. Those existing scheduling algorithms not only have the transceiver conflict problems but also have no support multicast and broadcasting of transmission behaviors.

Table 1. Characteristics of the existing scheduling algorithms.

Scheduling algorithm	Average delay	Conflict-less	Multicast/ Broadcast
EATS/FCPFSS [1][2]	VERY LONG	NO	NO
Frame Scheduling [1][2]	LONG	NO	NO
Frame-and-Queue Scheduling [1][2]	MIDDLE	NO	NO
Scheduling with receiver-grouping [3]	MIDDLE	NO	NO
Balance scheduling with cut-off concept [2]	SMALLEST	NO	NO
Multiple-Messages-per-Node Scheduling [1]	SMALL	NO	NO

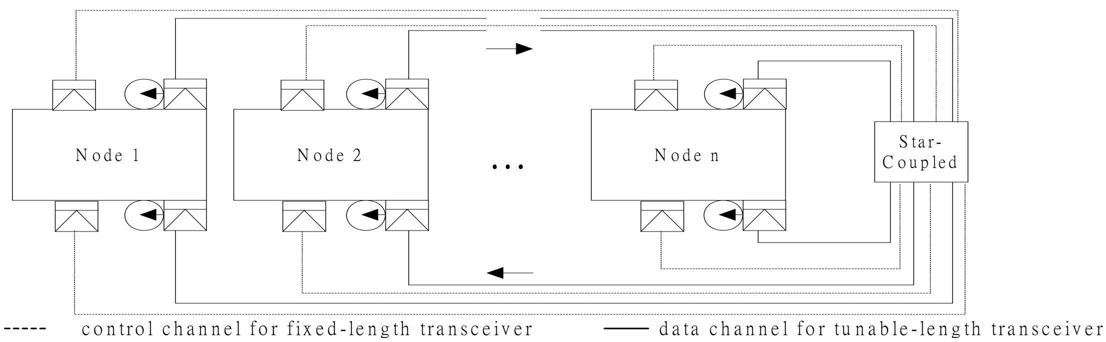
The passive star coupler of the single-hop WDM passive star-coupled network architecture is used to broadcast data packets. In reservation-based protocol, each node has a pair of fixed-channel transceiver, served as control channel. Control channel expanded with one of the three transceiver models act as transceiver's data channel: TT-TR（tunable transmitter–tunable receiver）, FT-TR（fixed transmitter–tunable receiver）or TT-FR（tunable transmitter–fixed receiver）. In this paper, collision-less scheduling algorithms for variable-length and fixed-length data packet are proposed and compared with transceiver tuning latency （0~1 μs） for TT-TR, FT-TR and TT-FR transceiver models, respectively. For data packet sorting, Shortest Job First（SJF）algorithm is used to obtain the optimum sequencing for average packet delay. Furthermore, the proposed scheduling algorithms are suitable for multi-transmission behavior [17][23]（point-to-point, multicast and broadcasting）. One exception is that TT-FR model does not support multicast and broadcasting since fixed-receiver model is not adapted to tune the channel in the receiver end. The simulation model can be developed to analyze the system performance with the variations of the number of nodes, the number of data and the number of channels for different transceiver models （TT-TR, TT-FR and FT-TR）.

This paper is organized as follows. Section 2 describes the single-hop WDM passive star-coupled network architecture, transceiver tuning latency and channel mechanism of scheduling algorithm to avoid data packet collision and transceiver conflict for each TT-TR, FT-TR and TT-FR transceiver model and multi-transmission behavior （point-to-point, broadcasting and multicast, respectively）. Section 3 defines the performance metrics （channel utilization, throughput and average packet delay）, compares the relative performance through simulation with system parameters（the number of nodes, the number of packets and the number of channels）. The Conclusion is made in Section 4.

II、Novel Scheduling Algorithms

1、Network Architecture

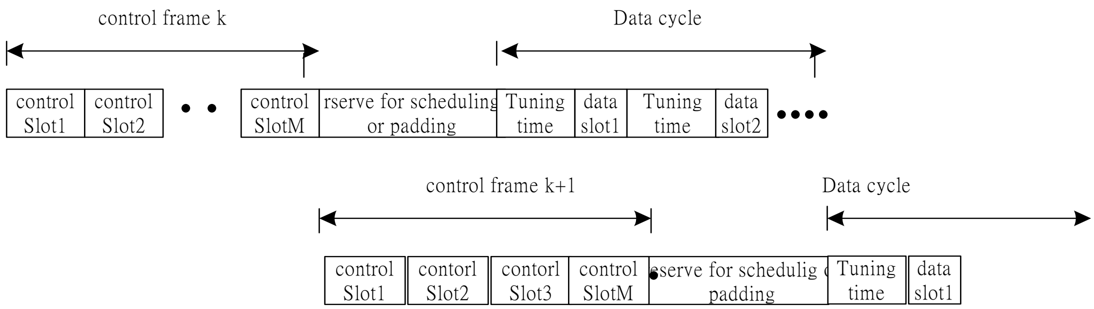
Fig. 1. Star-coupled configuration based WDM network.



The system with star coupler network [14][15] is shown in Fig. 1, and each node has a pair of fixed wavelength transceiver served as control channel device. Control channel expanded with one of the three transceiver models act as transceiver's data channel: TT-TR （tunable transmitter–tunable receiver）, FT-TR（fixed transmitter–tunable receiver）or TT-FR（tunable transmitter–fixed receiver）. Transceiver that choose one of the three data channel devices for variable-length and fixed-length data packet and its control channel broadcasts global information to internal nodes in the system, where each node performs the same scheduling algorithm to determine when particular nodes can use the dedicated data channel to receive/transmit data packet. In this paper, we propose three scheduling algorithms for each transceiver models.

2、Packet Allocation

Fig 2. Timing sequence of control channel and data channel.



Scheduling algorithm [19][22][24] based on reservation-based protocol [23], allocates a channel as control channel and the others as data channels. Each node retrieves/loads information to be transmitted/received that sends global information to each node of the entire system. Each node performs dynamic scheduling algorithm to determine when the particular node may transmits/receives data packet through a dedicated data channel. It uses TDM scheme to define control channel frame. Data can be variable-length packet or fixed-length packet [18]. Variable-length packet uses SJF to determine its precedence, while the fixed-length packet uses packet ID. Variable-length packet takes more delay cycle to avoid packet collision and transceiver conflict, where P_{ij} is the *j*th time slot of the *i*th node—eg. P_{11} is the 1^{st} time slot of the 1^{st} node of control frame. Packet P_{ij} contains two arguments, destination node and packet length. After all time slots are loaded, global information is sent to each node in the network, while each node performs the algorithm simultaneously to determine when the data packet is loaded into data channel. From timing sequence chart shown in Fig. 2, information of each time slot of control frame is collected, then each node performs distributed scheduling algorithm or appends to waiting cycle until one of the data cycle ends—（after each control slot collected into control frame is divided into N（N-1）types of packet P_{sd}, the scheduling algorithm performed for sorting collected data）. After a transceiver tuning delay, sorted packet is added into data slot. Time sequence of packet includes reserve for scheduling, wait for previous data cycle padding and each transceiver's tuning time. The sequence of data packet is based on the sequence generated from scheduling algorithm. The initial point of the next control frame is where the previous control frame ends and the initial point of the next data cycle is where previous data cycle ends.

In the next section, we define packet collision, transceiver conflict and propose scheduling algorithms to avoid packet collision, transceiver conflict, and provide multi-transmission behavior （point-point, broadcast, and multicast）.

3、Definition of Packet Collision and Transceiver Conflict

Packet collision is defined as when two different transmitters use the same channel to transfer data. Transmitter conflict is defined as when a transmitter transmits two data packets simultaneously. A node receives data packet from different channels at the same time is called receiver conflict. Existing scheduling algorithms have solved collision problems on transmitter, since it allocates only one data packet to a channel at one time. The definition of transmitter conflict and receiver conflict are defined as follows and shown in Table 2:

（1） efinition 1: Packets that have transmitter conflict with packet P_{ab} at the same time as $TCP_{ab}\{P_{a1}, P_{a2}, P_{a3}, P_{a4}\}$; define P_{aa} as null.

（2） Definition 2: Packets that have receiver conflict with packet P_{ab} at the same time as $RCP_{ab}\{P_{1b}, P_{2b}, P_{3b}, P_{4b}\}$; define P_{bb} as null.

（3） Definition 3: Packets that have transceiver conflict from node a to node b, c through multicast transmission are defined as （$TCP_{ab}\{\ldots\} \cup RCP_{ab}\{\ldots\}$）$\cup$（$TCP_{ac}\{\ldots\} \cup RCP_{ac}\{\ldots\}$）, where （$TCP_{ab}\{\ldots\} \cup RCP_{ab}\{\ldots\}$） and

b *and* $(TCP_{ac}\{\ldots\} \cup RCP_{ac}\{\ldots\})$ and node to a to node c respectively denote that transmitter and receiver conflicts from node *a* to node *c*.

4、Fundamental Principle

In this section, we propose the novel scheduling algorithm to avoid packet collision and transceiver conflict in one of the transceiver models and to provide multi-transmission behavior. Besides, we try to obtain the minimum average packet delay time to optimize the system throughput.

First, we describe the fundamental principle of collision-less scheduling algorithm. Then, we prove that the proposed scheduling algorithm is collision-less for three models under considerations: (1) TT-TR, (2) FT-TR and (3) TT-FR. We will give an example to explain more precisely the algorithm we propose, not only the solutions for point-to-point but also for the broadcast and multicast of transmission behaviors. Moreover, we make comparison with the existing algorithms.

Table 2. Packet set

	d_1	d_2	d_3	d_4
s_1		P_{12}	P_{13}	P_{14}
s_2	P_{21}		P_{23}	P_{24}
s_3	P_{31}	P_{32}		P_{34}
s_4	P_{41}	P_{42}	P_{43}	

the number of elements = $N(N\text{-}1)$

To generate collision-free and conflict-less scheduling algorithm, first, information of each time slot of control frame is collected, then each node performs distributed scheduling algorithm. After each time slot A_{sn} shown in Fig. 3 collected into control frame is divided into $N(N\text{-}1)$ types of packet P_{sd} shown in Table 2, the scheduling algorithm we proposed is performed to sort. A_{sn} is the n^{th} control slot of node *s* of the control frame, where A_{sn} contains two arguments: destination node and packet length. P_{sd} is the collection of packets from source node s to destination node d. N is the total number of nodes. After a transceiver tuning delay, the sorted packets are added into data slot shown in Fig. 4. Time sequence of a packet includes delay time for scheduling, wait for previous data cycle padding and each transceiver's tuning time. The sequence of data packet is based on the sequence generated from scheduling algorithm. The initial point of the next data cycle has to wait for transceiver's tuning latency.

Fig. 3 Collision-less Scheduling Algorithm.

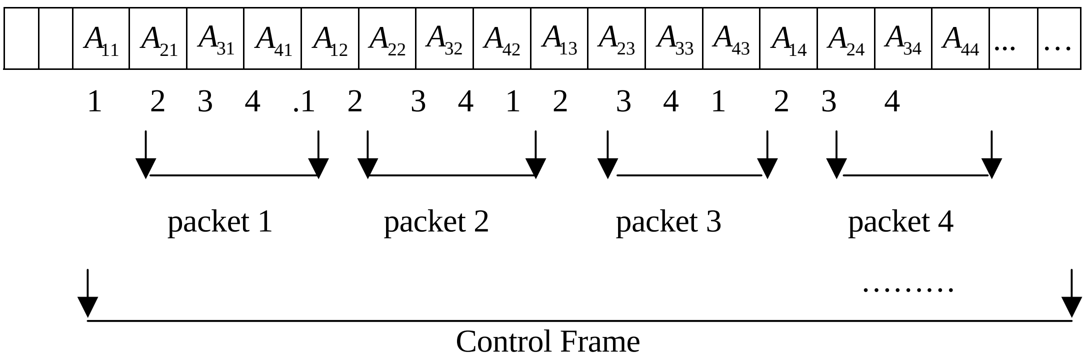
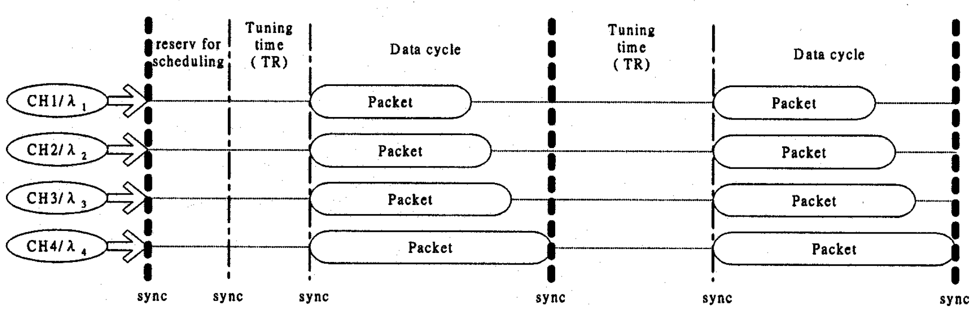


Fig. 4 Timing sequence chart of data channels.



We first define the symbols of tuning latency shown in Fig. 4, then, we will describe how to calculate the values.

Tuning latency Symbol Definitions

T_{ia} : Time needed to tune from previous channel to channel *i* while node *a* is ready to transmit data.

R_{ib} : Time needed to tune from previous channel to channel *i* while node *b* is ready to receive data.

T_i : Tuning time of each channel. $T_i = \max\{T_{ia}, R_{ib}\}$, *i* : number of channels.

T_r : Tuning time of each round. $T_r = \max\{T_1, T_2, \ldots, T_c\}$.

c: Total number of channels, $i = 1$ to *c*.

One round: Process to append packets into channel 1 to *c* under collision-less assumption.

After the algorithm is performed, the dedicated channel can be used by transceiver node has been determined. We find the maximum value of transceiver's tuning time of each node $T_i = \max\{T_{ia}, R_{ib}\}$, and then, tuning time of each round $T_r = \max\{T_1, T_2, T_i \ldots, T_c\}$. T_r is the tuning latency of that round.

5、Collision-less Algorithm

Timing sequence chart of data channel is shown in Fig. 4. The initial point of data packet transmission is determined after the synchronization of each node, delay time for scheduling and tuning delay （T_r）.

（1） rom existing scheduling algorithms, we learn that SJF algorithms to sort packets has the optimum average packet delay time. Thus, for any types of data packets, we get the packet with minimum packet length P_{ab} as the first element.

（2） The remaining packets, excluding Transmitter Conflict $TCP_{ab}\{\ldots\}$（Definition 1）and Receiver Conflict $RCP_{ab}\{\ldots\}$（Definition 2）of P_{ab}, are the following sample space.

（3） By analogy, by taking the total number of data channel as the number of elements, add selected packets to channel sequentially. If no elements match, add to delay cycle until a round process ends.

（4） Each packet of data channel initiates after synchronization, while the next synchronization initiates at the point where present longest data packet finishes. The rest are padding cycle.

（5） In multicast transmission or broadcasting, excluding fixed receiver mode, deleting packets that generate transmission conflict and receiver conflict （Definition 3） will work as well.

***Proof*:** Let the Sample space as $S_{s0}\{\ldots\}$, P_{xy} as packet type.

- Retrieve the first element P_{ab} of $S_{s0}\{\ldots\}$
- Let $S_{s1}\{\ldots\}=S_{s0}\{\ldots\}-TCP_{ab}\{\ldots\}-RCP_{ab}\{\ldots\}$
- By analogy, the next element is P_{cd}
- $S_{s2}\{\ldots\}=S_{s1}\{\ldots\}-TCP_{cd}\{\ldots\}-RCP_{cd}\{\ldots\}$
- Since $a\neq c\neq$ any one element x of $S_{s2}\{\ldots.\}$, no transmitter conflict occurs. And $b\neq d\neq$ any one element y of $S_{s2}\{\ldots.\}$, no receiver conflict occurs. Thus, it is conflict-less.
- Since then, all the processes are conflict-less. Furthermore, by scheduling algorithm, since on the same channel only one packet is allocated at one time, packet collision on transmitter has been solved.

Thus, it was proved that the proposed scheduling algorithm is **Conflict-less** and **Collision-free**.

Three models of collision-less algorithms

Next, the proposed algorithm is applied to each of three transceiver models: FT-TR, TT-FR and TT-TR and examples are used to describe transmission behaviors: point-to-point, multicast, and broadcast transmission, respectively. In the examples, we emphasize on the sequence of the scheduled packets, and ignore the delay for scheduling and tuning latency. In our simulation, we will take the delay of scheduling and tuning latency into consideration to get a more precise result.

（1）FT-TR model （Fixed Transmitter–Tunable Receiver）

Let four nodes share four data channels simultaneously:

- The set of all elements, its sample space is
  $S_{s0}\{P_{12}, P_{13}, P_{14}, P_{21}, P_{23}, P_{24}, P_{31}, P_{32}, P_{34}, P_{41}, P_{42}, P_{43}\}$
- Node n's transmitter use Channel n; n ranges from 1 to 4
- Sample space of Channel *1* is $C_{s1}\{P_{12}, P_{13}, P_{14}\}$,
  Sample Space of Channel *2* is $C_{s2}\{P_{21}, P_{23}, P_{24}\}$
  Sample Space of Channel *3* is $C_{s3}\{P_{31}, P_{32}, P_{34}\}$
  Sample Space of Channel *4* is $C_{s4}\{P_{41}, P_{42}, P_{43}\}$

Algorithm:

1、Take Min$\{C_{s1}\{\ldots\} \cap S_{s0}\{\ldots\}\}$as P_{ab}, add to Channel *1*
$S_{s1}\{\ldots\} = S_{s0}\{\ldots\}\text{-}TCP_{ab}\{\ldots\}\text{-}RCP_{ab}\{\ldots\}$. According to Definition 1, 2.

2、Take Min$\{C_{s2}\{\ldots\} \cap S_{s1}\{\ldots\}\}$as P_{cd}, add to Channel *2*
$S_{s2}\{\ldots\} = S_{s1}\{\ldots\}\text{-}TCP_{cd}\{\ldots\}\text{-}RCP_{cd}\{\ldots\}$. According to Definition 1, 2.

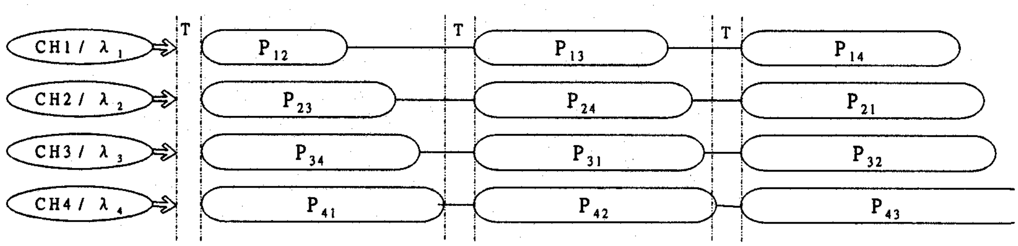
3、Take Min$\{C_{s3}\{\ldots\} \cap S_{s2}\{\ldots\}\}$as P_{ef}, add to Channel *3*
$S_{s3}\{\ldots\} = S_{s2}\{\ldots\}\text{-}TCP_{ef}\{\ldots\}\text{-}RCP_{ef}\{\ldots\}$ According to Definition 1, 2.

4、Take Min$\{C_{s4}\{\ldots\} \cap S_{s3}\{\ldots\}\}$ as P_{gh}, add to Channel *4*
$S_{s4}\{\ldots\} = S_{s3}\{\ldots\}\text{-}TCP_{gh}\{\ldots\}\text{-}RCP_{gh}\{\ldots\}$ According to Definition 1, 2.

5、Packet allocation of a round finishes, sample space after synchronization is
$S_{s \longrightarrow next}\{\ldots\} = S_{s0}\{\ldots\}\text{-}P_{ab}\text{-}P_{cd}\text{-}P_{ef}\text{-}P_{gh}$
Substitute the new Sample Space into 1 and repeat.

Ex. Fig. 5 shows the result of point-to-point of transmission behaviors for FT-TR model for packet length $P_{12} < P_{13} < P_{14}$, $P_{23} < P_{24} < P_{21}$, and $P_{34} < P_{31} < P_{32}$, $P_{41} < P_{42} < P_{43}$.

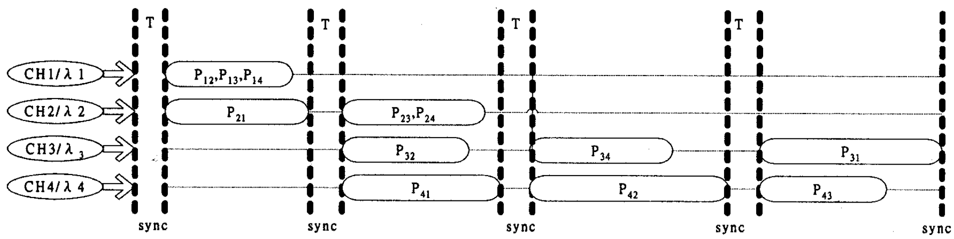
Fig. 5 Point-to-point of transmission behaviors for FT-TR model.



Ex. Fig. 6 shows the result of multi-transmission behavior（point-to-point, multicast and broadcast） for FT-TR model. Suppose node 1 broadcasts to node （2,3,4）, and node 2 multicasts to node （3,4）.

Let （P_{12}, P_{13}, P_{14}）$< P_{32} <$（P_{23}, P_{24}）$< P_{43} < P_{21} < P_{41} < P_{34} < P_{31} < P_{42}$

Fig. 6 Multi-transmission behavior for FT-TR model.



（2）TT-FR model （Tunable Transmitter – Fixed Receiver）

There are no multicast and broadcast of transmission behaviors provided in fixed-receiver model due to fixed-receiver model is not adapted to tune the channel in receiver end. Let four nodes share four data channels simultaneously.

- The set of all elements, its sample space is
  $S_{s0}\{P_{12}, P_{13}, P_{14}, P_{21}, P_{23}, P_{24}, P_{31}, P_{32}, P_{34}, P_{41}, P_{42}, P_{43}\}$
- Node *n*'s transmitter use Channel *n*; *n* ranges from *1* to *4*
- Sample space of Channel *1* is $C_{s1}\{P_{21}, P_{31}, P_{41}\}$

  Sample Space of Channel *2* is $C_{s2}\{P_{12}, P_{32}, P_{42}\}$

  Sample Space of Channel *3* is $C_{s3}\{P_{13}, P_{23}, P_{43}\}$

  Sample Space of Channel 4 is $C_{s4}\{P_{14}, P_{24}, P_{34}\}$

Algorithm:

1、Take Min{$C_{s1}\{\ldots\} \cap S_{s0}\{\ldots\}$}as P_{ab}, add to Channel *1*

$S_{s1}\{\ldots\} = S_{s0}\{\ldots\} - TCP_{ab}\{\ldots\} - RCP_{ab}\{\ldots\}$. According to Definition 1, 2.

2、Take Min{$C_{s2}\{\ldots\} \cap S_{s1}\{\ldots\}$}as P_{cd}, add to Channel *2*

$S_{s2}\{\ldots\} = S_{s1}\{\ldots\} - TCP_{cd}\{\ldots\} - RCP_{cd}\{\ldots\}$. According to Definition 1, 2.

3、Take Min{$C_{s3}\{\ldots\} \cap S_{s2}\{\ldots\}$}as P_{ef}, add to Channel *3*

$S_{s3}\{\ldots\} = S_{s2}\{\ldots\} - TCP_{ef}\{\ldots\} - RCP_{ef}\{\ldots\}$. According to Definition 1, 2.

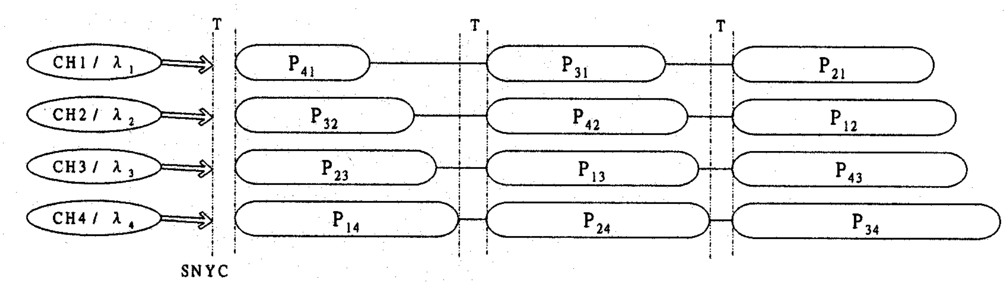
4、Take Min{$C_{s4}\{\ldots\} \cap S_{s3}\{\ldots\}$}as P_{gh}, add to Channel *4*

$S_{s4}\{\ldots\} = S_{s3}\{\ldots\} - TCP_{gh}\{\ldots\} - RCP_{gh}\{\ldots\}$. According to Definition 1, 2.

5、Packet allocation of a round finishes, sample space after synchronization is
$S_{s\longrightarrow next}\{\dots\}=S_{s0}\{\dots\}-P_{ab}-P_{cd}-P_{ef}-P_{gh}$
Substitute the new Sample Space into 1 and repeat.

Ex. Fig. 7 shows the result of point-to-point of transmission behaviors for TT-FR model for packet length $P_{14}<P_{24}<P_{34}, P_{23}<P_{13}<P_{43}, P_{32}<P_{42}<P_{12}, P_{41}<P_{31}<P_{21}$

Fig. 7 Point-to-point of transmission behaviors for TT-FR model.



（3）**TT-TR model** （**Tunable Transmitter–Tunable Receiver**）

Let four nodes share four data channels simultaneously. Sample space of the set of all elements is $S_{s0}\{P_{12}, P_{13}, P_{14}, P_{21}, P_{23}, P_{24}, P_{31}, P_{32}, P_{34}, P_{41}, P_{42}, P_{43}\}$.

Algorithm:

1、Take Min{ $S_{s0}\{\dots\}$} as P_{ab}, add to Channel *1*
$S_{s1}\{\dots\}=S_{s0}\{\dots\}-TCP_{ab}\{\dots\}-RCP_{ab}\{\dots\}$. According to Definition 1, 2.

2、Take Min{ $S_{s1}\{\dots\}$} as P_{cd} , add to Channel *2*
$S_{s2}\{\dots\}=S_{s1}\{\dots\}-TCP_{cd}\{\dots\}-RCP_{cd}\{\dots\}$. According to Definition 1, 2.

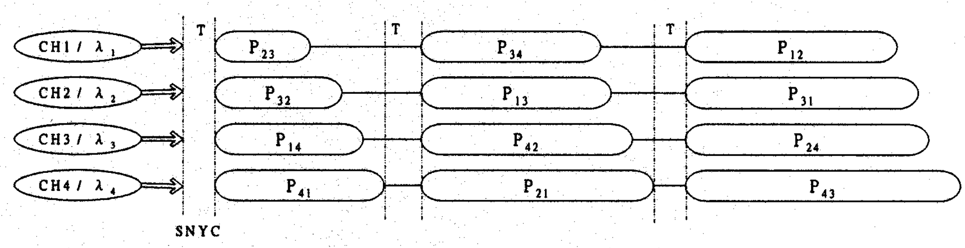
3、Take Min{ $S_{s2}\{\dots\}$}as P_{ef} , add to Channel *3*
$S_{s3}\{\dots\}=S_{s2}\{\dots\}-TCP_{ef}\{\dots\}-RCP_{ef}\{\dots\}$. According to Definition 1, 2.

4、Take Min{ $S_{s3}\{\dots\}$} as P_{gh}, add to Channel *4*
$S_{s4}\{\dots\}=S_{s3}\{\dots\}-TCP_{gh}\{\dots\}-RCP_{gh}\{\dots\}$. According to Definition 1, 2.

5、Packet allocation of a round finishes, sample space after synchronization is
$S_{s\rightarrow next}\{\dots\}=S_{s0}\{\dots\}-P_{ab}-P_{cd}-P_{ef}-P_{gh}$
Substitute the new Sample Space into 1 and repeat.

Ex. Fig. 8 shows the result of point-to-point of transmission behaviors for TT-TR model for packet length $P_{23} < P_{32} < P_{14} < P_{41} < P_{34} < P_{13} < P_{42} < P_{21} < P_{12} < P_{31} < P_{24} < P_{43}$.

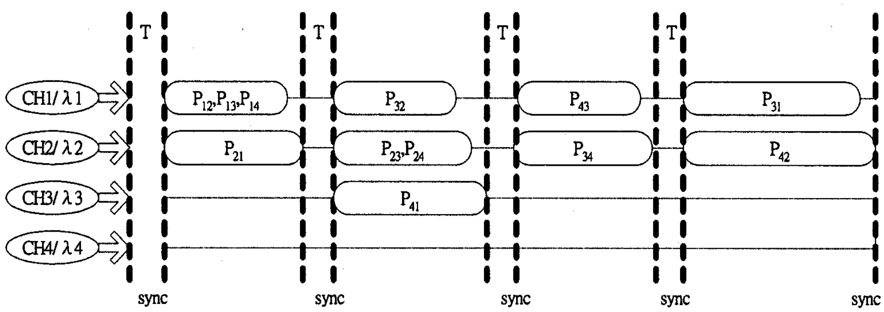
Fig. 8 Point-to-point of transmission behaviors for TT-TR model.



Ex. Fig. 9 shows the result of multi-transmission behavior（point-to-point, multicast, broadcast）for TT-TR model. Suppose node 1 broadcasts to node（2,3,4）, and node 2 multicasts to node （3,4）.

Let packet length as （P_{12}，P_{13}，P_{14}）$<$ P_{32} $<$ （P_{23}，P_{24}）$< P_{43} < P_{21} < P_{41} < P_{34} < P_{31} < P_{42}$.

Fig. 9 Multi-transmission behavior for TT-TR model.



6、The Algorithms Comparison

Table 3 summarizes the characteristic comparisons of the three algorithms we propose with other existing scheduling algorithms on packet collision, multicast/broadcast. We learn that collision will occur on single transmission based on other existing algorithms. In addition, multicasting/broadcasting is not provided in the existing algorithms and fixed receiver configuration does not provide multicasting/broadcasting. Collision-less and multicasting/broadcasting provided by our proposed scheduling algorithms are our main contribution in this paper.

Table 3 Characteristic comparisons of algorithms.

Scheduling Algorithm	Collision-free & Conflict-less	Multicast /Broadcast
Scheduling with receiver-grouping	NO	NO
Balance scheduling with cut-off concept	NO	NO
Multiple-Messages-per-Node Scheduling	NO	NO
FT-TR model	YES	YES
TT-FR model	YES	NO
TT-TR model	YES	YES

III、Simulations

Our simulation is accomplished on different transceiver models （TT-TR, TT-FR, and FT-TR） with the variations of tuning latency （0~1*u*s）[6][15]. The model developed in the previous section is now used to analyze the behavior of the system. The performance of the system is analyzed in terms of average packet delay, channel utilization, and network throughput with the variations of the number of nodes, the number of data packet [20][21], and the number of channels.

Since other existing scheduling algorithms fit only one of the transceiver models（TT-FR, FT-TR, TT-TR） and single transmission behavior （point-to-point, multicast or broadcast） without considering the effect of conflict and tuning latency. Our algorithm performance evaluation and comparison is modified due to the following reasons:

- Conflict occurs on other algorithms, thus ignoring conflict will reduce the precision of our estimation. On the other hand, considering conflict will modify the original idea of others.

- Since other algorithms assume single transceiver model and single transmission behavior, the estimation is subjective and general evaluation is not obtained.

1、Performance Metrics

The network architecture considered in our simulation is single-hop passive star coupler based network, in order to estimate the system performance, such as channel utilization, average packet delay and network throughput for each of the three models TT-TR, FT-TR and TT-FR. Time complexity of the algorithm or propagation delay of network transmission is ignored in this simulation. The terms used in our system are the number of nodes（M）, the number of wavelengths （W）, packet length, the total number of packets （P）, bandwidth （C） and tuning latency（T）. We assume OC-48 as transmission speed for each channel, 2.5G as channel capacity, Standard Gigabit Ethernet 64byte~1518 bytes as packet sizes, and tuning latency [6][15] ranges from 0~1000ns. Random Distribution is used to generate source node, packet length, destination node and the performance metrics of our system is defined as the follows:

- Channel utilization: percentage of channel usage during transmission
- Average packet delay: average value of packet transmission time

Average packet delay={W •[M •（frame1）+（M-1）•（frame2）+…+frameN]}/ P.

- Throughput: output rate of data packet per second（bps）

Network throughput=Total channel capacity • Channel utilization.

Figure 10 shows the scenarios of the simulations that consist of Simulation I, II and III.　More detail for each simulation is described below:

- Simulation I

Comparing the channel utilization, average packet delay, and network throughput for varying the number of nodes, M=4, 8, 12, 16, 20, 24, 28, 32, 36, 40, where P=1600, W=4, C=2.5G bps, T=0, 10ns, 50ns, 100ns, 500ns, 1000ns.

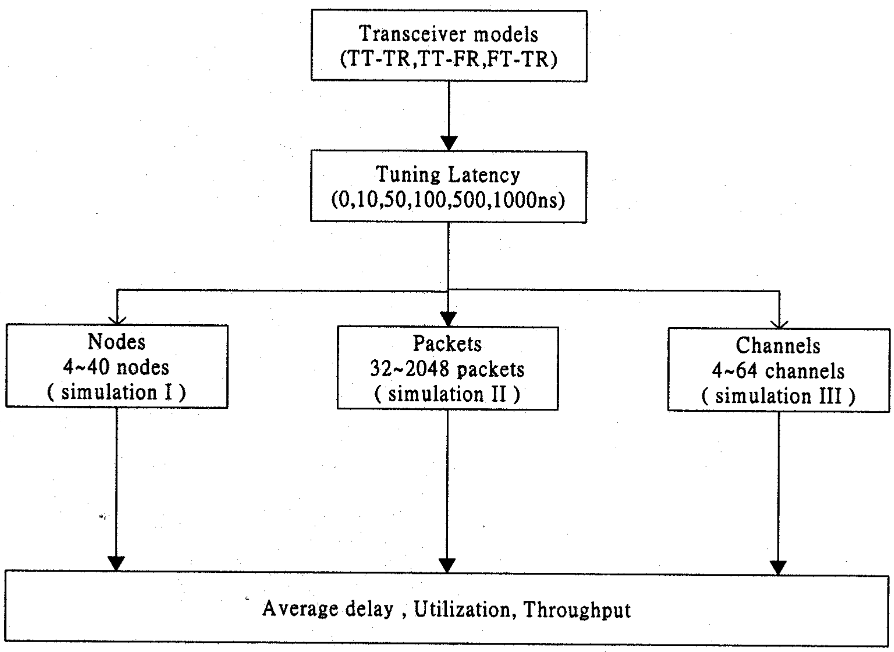
- Simulation II

Comparing the channel utilization, average packet delay and network throughput for varying the sizes of packet, P=32, 64, 128, 256, 512, 1024, 2048, where M=32, W=4, C=2.5G bps, T=0, 10ns, 50ns, 100ns, 500ns, 1000ns.

- Simulation III

Comparing the channel utilization, average packet delay and network throughput for varying the number of channels, W=4, 8, 16, 32, 64, where P=2048, M=64, C=2.5G bps, T=0, 10ns, 50ns, 100ns, 500ns, 1000ns.

Figure 10. Simulation flow chart



2、Simulation I

Comparing the channel utilization shown in Fig. 11（a）, average packet delay shown in Fig. 11（b）, and network throughput shown in Fig. 11（c） for varying the number of nodes M=4, 8, 12, 16, 20, 24, 28, 32, 36, 40, where P=1600, W=4, C=2.5Gbps, T=0, 10ns, 50ns, 100ns, 500ns, 1000ns.

Fig. 11（a） Channel Utilization for varying the number of nodes M=4, 8, 12, 16, 20, 24, 28, 32, 36, 40.

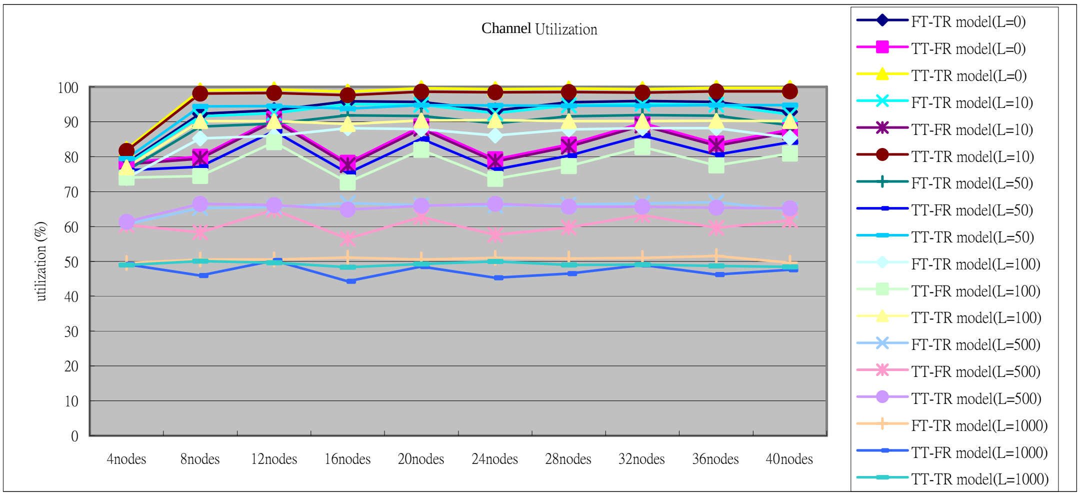


Fig. 11（b） Average packet delay for varying the number of nodes M=4, 8, 12, 16, 20, 24, 28, 32, 36, 40.

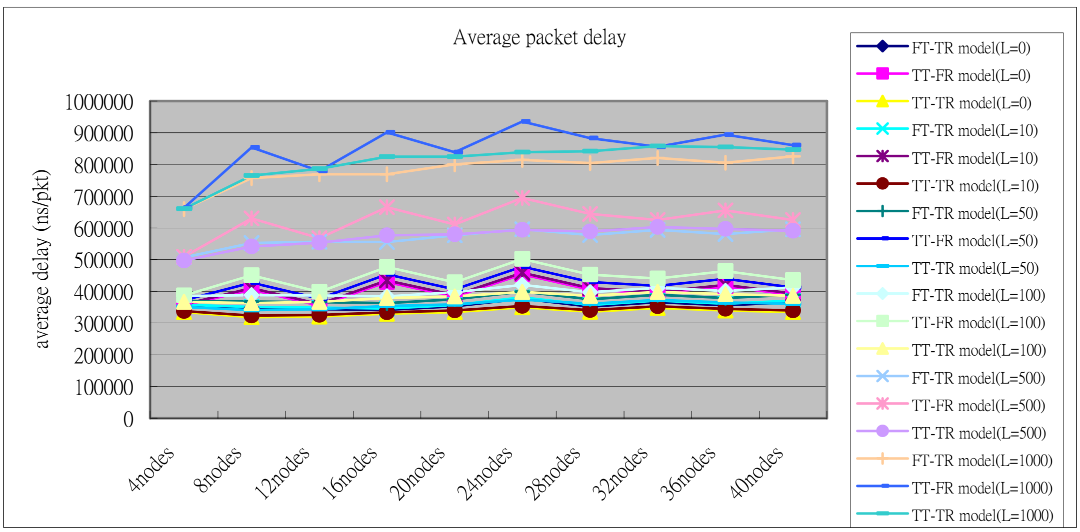
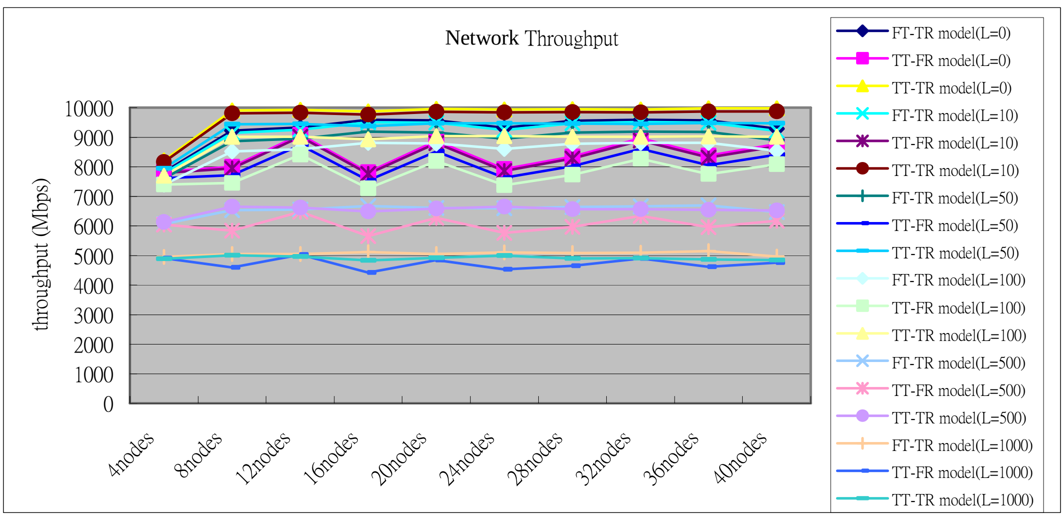


Fig. 11（a） shows that the channel utilization for three models is （TT-TR）>（TT-FR）>（FT-TR） as M=W and the channel utilization increasing rate is （TT-TR）>（FT-TR）>（TT-FR） when M≧2W. In （FT-TR） model, for 3W ≦M≦9W, higher channel utilization is reached, more than 93%. In （TT-FR） model, for M=3W, higher channel utilization is more than 90%. In（TT-TR）model, when M≧2W, channel utilization reaches 99%. For M=W, tuning latency ranges from 0 to 1000ns, channel utilization decreases about 40%. For M>2W, tuning latency ranges from 0 to 1000ns, channel utilization decreases about 40%~50%. Fig. 11（b）shows that the average packet delay for three models is（TT-FR）>（FT-TR）>（TT-TR） as T≦500ns and the average packet delay is （TT-FR）>（TT-TR）>（FT-TR） when T=1*us*. When tuning latency ranges from 0 to 1000ns, average packet delay increases about 180%~250%. Fig. 11（c） shows that the network throughput for three models is （TT-TR）>（FT-TR）>（TT-FR） as T≦500ns and the network throughput is （FT-TR）>（TT-TR）>（TT-FR） when T=1*us*. When tuning latency ranges from 0 to 1000ns, network throughput decreases about 48%~63%.

Figure 11（c） Network throughput for varying the number of nodes M=4, 8, 12, 16, 20, 24, 28, 32, 36, 40.



3、Simulation II

Comparing the channel utilization shown in Fig. 12（a）, average packet delay shown in Fig. 12（b）, and network throughput shown in Fig. 12（c）for varying the number of sizes of packet, P=32, 64, 128, 256, 512, 1024, 2048, where M=32, W=4, C=2.5G bps, T=0, 10ns, 50ns, 100ns, 500ns, 1000ns.

Fig. 12（a） shows that the channel utilization for three models is （TT-TR）>（FT-TR）>（TT-FR） as T≦500ns and the channel utilization is （FT-TR）>（TT-TR）>（TT-FR） when T=1*us* and P≦256. When tuning latency ranges from 0 to 1000ns, channel utilization decreases about 49%~65%. Fig. 12（b） shows that the average packet delay for three models is （TT-TR）<（FT-TR）<（TT-FR）. As number of packets and the tuning latency increases, average delay increases accordingly. Fig. 12（c） shows that the network throughput for three models is （TT-TR）>（FT-TR）>（TT-FR） as T≦500ns and the network throughput is （FT-TR）>（TT-TR）>（TT-FR） when T=1*us* and P≦256. When tuning latency ranges from 0 to 1000ns, network throughput decreases about 49%~65%.

Fig. 12（a） Channel utilization for varying the number of sizes of packet, P=32, 64, 128, 256, 512, 1024, 2048.

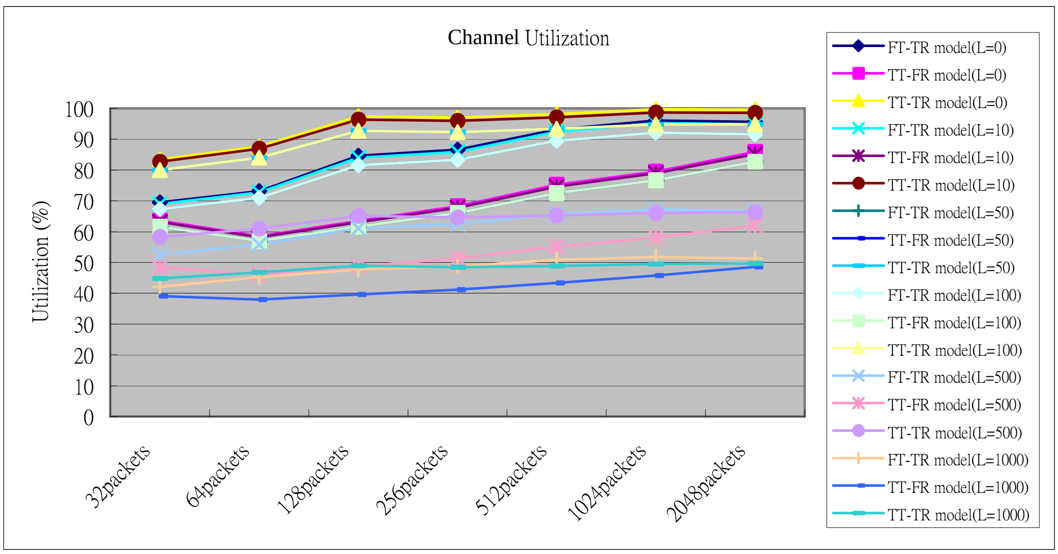


Fig. 12（b） Average packet delay for varying the number of sizes of packet, P=32, 64, 128, 256, 512, 1024, 2048.

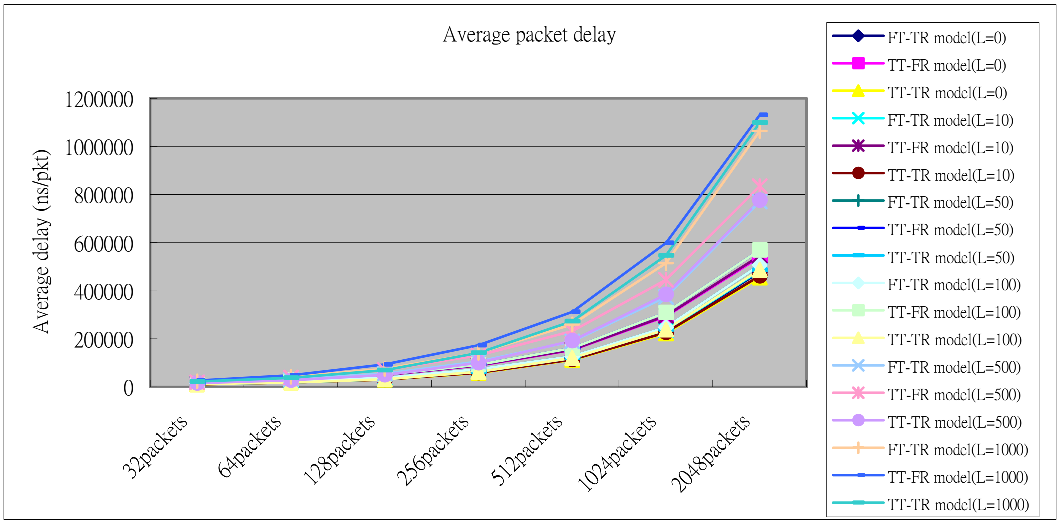
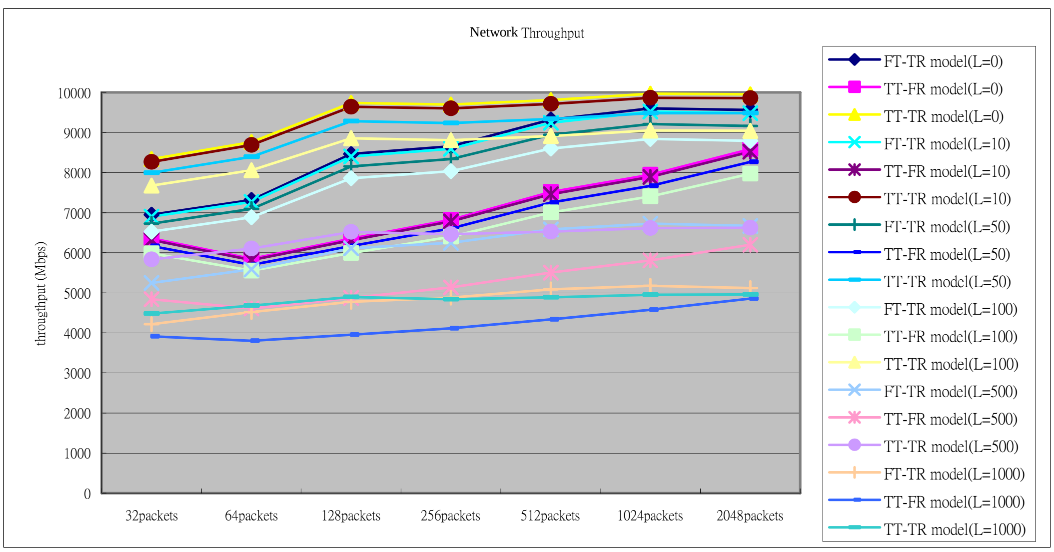


Fig. 12（c） Network throughput for varying the number of sizes of packet, P=32, 64, 128, 256, 512, 1024, 2048.



4、Simulation III

Comparing the channel utilization shown in Fig. 13（a）, average packet delay shown in Fig. 13（b） and network throughput shown in Fig. 13（c） for varying the number of channels, W=4, 8, 16, 32, 64, where P=2048, M=64, C=2.5G bps, T=0, 10ns, 50ns, 100ns, 500ns, 1000ns.

Fig.13（a） Channel Utilization for varying the number of channels, W=4, 8, 16, 32, 64.

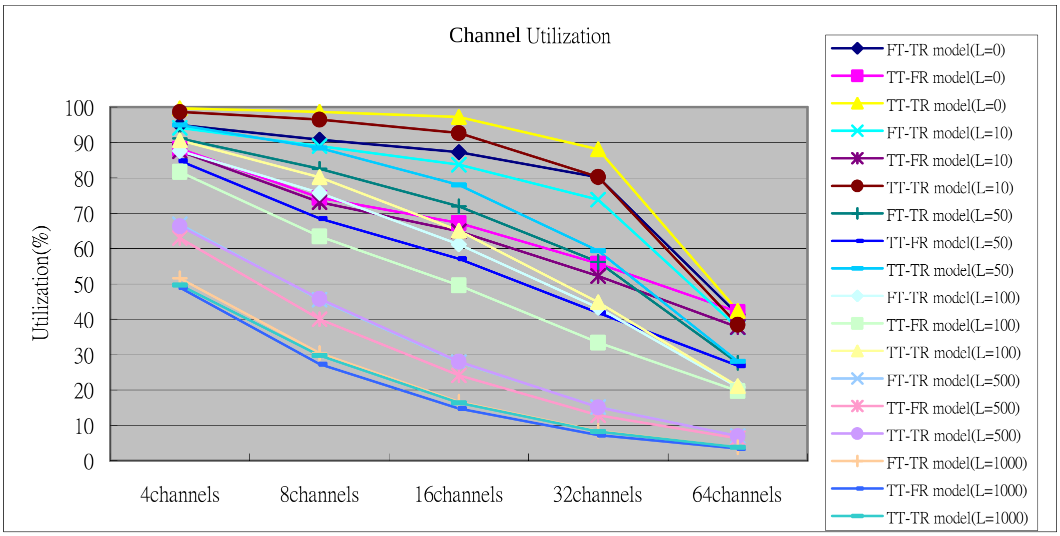


Fig. 13（a） shows that channel utilization decreases rapidly when tuning latency<100ns and number of channels increases, decreasing of channel utilization becomes slower when tuning latency>100ns, and channel utilization decreases rapidly when W/M>1/2 and tuning latency>100ns.

Fig. 13（b） Average packet delay for varying the number of channels, W=4, 8, 16, 32, 64.

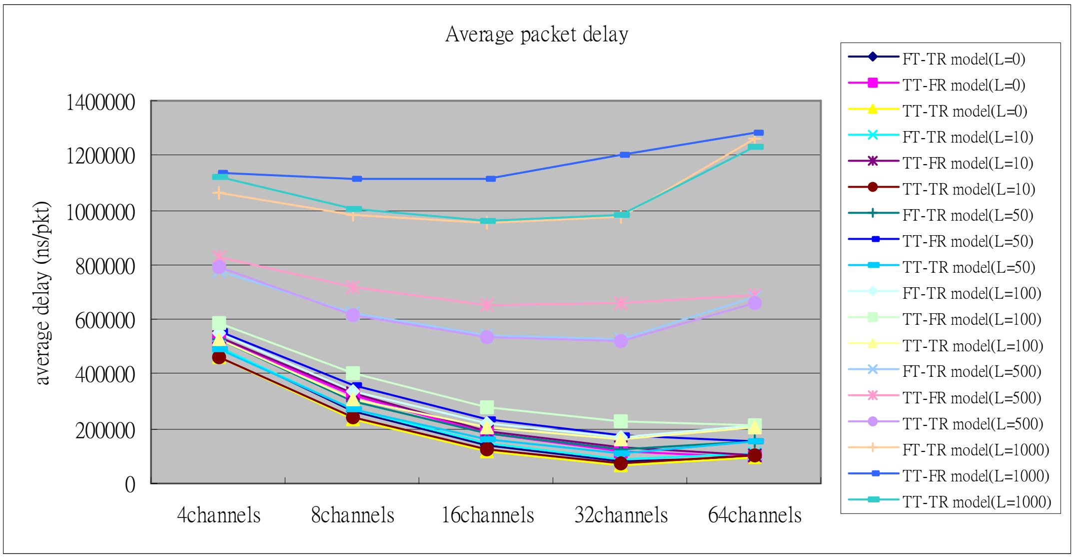


Fig. 13（b）shows that as tuning latency and the number of channel increase the average packet delay increases. The optimum average packet delay is achieved at 1/4W/M to W/M.

Fig. 13（c）Network throughput for varying the number of channels, W=4, 8, 16, 32, 64.

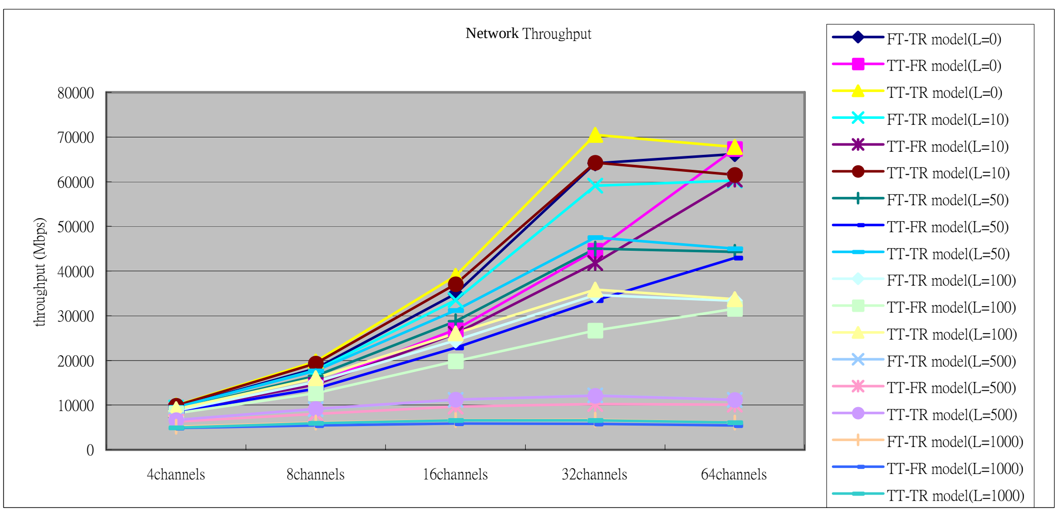


Fig. 13（c） shows that the optimum network throughput and optimum multiplication of network throughput and channel utilization are obtained at W=1/2. Number of packets affects only average packet delay. Network throughput does not depend on the sizes of packet. While tuning latency increases progressively from 0 to 1*u*s, network throughput decreases about 50%.

IV、Conclusions and Future Work

This paper proposed and compared collision-less scheduling algorithms with variable-length and fixed-length packets for FT-TR, TT-FR and TT-TR transmission models. The proposed scheduling algorithms are to avoid data packet collision, transceiver conflict and tuning latency that are ignored in many scheduling algorithms. In addition, the proposed scheduling algorithms are also applicable to multi-transmission behavior （point-to-point, multicast, broadcast）. Simulation model is developed to analyze the system performance in terms of average packet delay, channel utilization and network throughput with the variations of the number of nodes, the number of data and the number of channels. The average packet delay and throughput decreases about 50% as the tuning latency closes to 1us. The effect of tuning latency on the system performance should be significant. Simulation results show that number of nodes does not affect utilization, average packet delay and throughput, but it leads to increase the average packet delay as number of channels increases, utilization decreases. The optimum average packet delay and maximum throughput, channel utilization are achieved when the number of channel is half of the number of nodes. Our future work can be possibly divided into two parts: first, to reduce delay cycle in scheduling algorithm. The variable-length packet cut into smaller fixed-length packet to increase channel utilization and network throughput. Second, to adapt the multimedia trends. Fuzzy theory can be applied to the existing scheduling algorithms to provide dynamically adaptive quality of service and future application trends.

References

K. Hashimoto, Y. Shibata and N. Shiratori, Database and Expert Systems Applications, 1999. Proceedings. Tenth International Workshop on, Page（s）: 662–666, 1999. "Agent-oriented flexible multimedia system considering organization and QoS functions".[1]

C. Guillemot, F. Clerot, M. Henry, A.Le Corre, J. Kervarec, A. Dupas and L. Billes, Optical Communication, 1998. 24th European Conference on Volume: 2, Page（s）: 81-85, 1998. "Optical packet switching for WDM high-speed backbones"[2]

J.R Kiniry, IEEE Internet Computing Volume: 2, Page（s）: 13-15, March-April 1998 "Wavelength division multiplexing: ultra high-speed fiber-optics". [3]

Babak Hamidzadeh, Ma Maode, and Mounir Hamdi, IEEE Journal, pp, 1309-1319, August 1999. "Efficient Sequencing Techniques for Variable-Length Messages in WDM Networks" [4]

Shiann-Tsong Sheu, Yue-Ru Chuang, and Hsuen-Wen Tseng, TANET 2000, pp, 895-902, December 2000 "Balanced scheduling Mechanism for supporting variable-length packets in WDM Networks". [5]

I-Shyan Hwang and Ling-Feng Ku, 2nd International Photonic Conference （IPC 2000）, Hsinchu, Taiwan, pp. 831-835, Dec. 12-15, 2000 "Performance Impacts of tuning latency in passive star-coupled DWDM network". [6]

Jin Seek Choi and Hyeong Ho Lee, The Bridge to Global Integration. IEEE Volume: 4, Page（s）: 2358-2362, 1998 "A dynamic wavelength allocation scheme with status information for fixed- and variable-length messages". [7]

E. Modiano, INFOCOM '98. Seventeenth Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE Volume: 1, Page（s）: 86-93, 1998 "Unscheduled multicasts in WDM broadcast-and-select networks". [8]

Ganz and Y. Gao, IEEE Transactions on Communications, Vol. 42, No. 2, pp.1827-1836, Feb. 1994 "A Time-wavelength Assignment Algorithm for A

WDM Star Network". [9]

K. Bogineni, K. M. Sivalingham, and P. W. Dowd, IEEE Journal on Selected Areas in Communications, Vol.11, pp. 590-604, May 1993 "Low-complexity Multiple Access Protocols for Wavelength-division Multiplexed Photonic Networks". [10]

T. Weller and B. Majek, IEEE/ACM Transactions on Networking, Vol. 56, pp. 813-823, Dec. 1997 "Scheduling Non-uniform Traffic in Packet Switching System with Small Propagation Delay". [11]

George N. Rouskas and V. Sivaraman, IEEE/ACM transactions on networking, Vol. 5, No. 3, pp. 359-370, June 1997 "Packet Scheduling in Broadcast WDM Networks with Arbitrary Transceiver Tuning Latencies". [12]

Hwa-Chun Lin and Chun-Hsin Wang, 2000 IEEE International Conference on Volume: 3, Page（s）: 1645-1649, 2000 "Minimizing the number of multicast transmissions in single-hop WDM networks". [13]

Patrick W. Dowd and I-Shyan Hwang, Journal of Parallel and Distributed Computing, Vol. 25, No. 2, pp. 144-161, Mar. 1995 "Memory and Network Architecture Interaction in An Optically Interconnected Distributed Shared-Memory System". [14]

Leonid G. Kazovsky, Charles Barry, Michael Hickey, Ciro A. Noronha Jr., and Pierluigi Poggiolini, IEEE LTS, pp. 8-15, May 1992 "WDM Local Area Networks". [15]

I-Shyan Hwang and Patrick W. Dowd, Journal of Information Science and Engineering, Vol. 11, No. 3, pp.345-369, Sep. 1995 "Media Access Protocol Impacts on A WDMA Star Photonic Network with Distributed Shared Memory System". [16]

Hwa-Chun Lin and Chun-Hsin Wang, INFOCOM 2001. Proceedings. IEEE, Volume: 1, 2001, Page（s）: 169–178 "A hybrid multicast scheduling algorithm for single-hop WDM networks". [17]

P. Barcaccia, M.A. Bonuccelli and M. di Ianni, Parallel and Distributed Systems, IEEE Transactions on, Volume: 11 Issue: 10, Oct. 2000, Page（s）: 1090–1102 "Complexity of minimum length scheduling for precedence constrained messages in distributed systems". [18]

K.H. Liu, B.J. Wilson and J.Y. Wei, Selected Areas in Communications, IEEE Journal on, Volume: 18 Issue: 10, Oct. 2000, Page（s）: 2041–2050 "A scheduling application for WDM optical networks".[19]

A.C. Kam and Kai-Yeung Siu, Selected Areas in Communications, IEEE Journal on, Volume: 18 Issue: 10, Oct. 2000, Page（s）: 2029–2040 "Supporting bursty traffic with bandwidth guarantee in WDM distribution networks".[20]

Xiong Yijun, M. Vandenhoute and H.C. Cankaya, Selected Areas in Communications, IEEE Journal on, Volume:18 Issue: 10, Oct. 2000, Page（s）: 1838–1851 "Control architecture in optical burst-switched WDM networks".[21]

M.J. Spencer and M.A. Summerfield, Lightwave Technology, Journal of, Volume: 18 Issue: 12, Dec 2000, Page（s）: 1657–1676 "WRAP: a medium access control protocol for wavelength-routed passive optical networks". [22]

Hwa-Chun Lin and Pei-Shin Liu, Networks, 2000. （ICON 2000）. Proceedings. IEEE International Conference on, 2000, Page（s）: 493 "A reservation-based multicast scheduling algorithm with a reservation window for single-hop WDM networks". [23]

M.A. Bonuccelli and S. Pelagatti, Parallel and Distributed Processing Symposium, 2000. IPDPS 2000. Proceedings. 14th International, 2000, Page（s）: 343–352 "Optimal on demand packet scheduling in single-hop multichannel communication systems".[24]

Hsuan-Chih Chen, M.S. Thesis of Dept. of Computer Engineering and Science of Yuan-Ze University, July 2001 "Collision-less Scheduling Algorithms with Arbitrary Transceiver Tuning Latencies in DWDM Networks".[25]