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Duplex Routing with Reverse Channels in WDM Lightwave ShuffleNet

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Duplex Routing with Reverse Channels in WDM Lightwave ShuffleNet

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The links in the logical ShuffleNet for a WDM lightwave network can be made duplex at the cost of adding an additional transmitter or receiver in each node. The so called Duplex ShuffleNet or D-ShuffleNet is proposed with two new routing algorithms, *Unidirectional and Shortest Path* routing algorithms. The mean hop delay results and thus channel efficiency are analyzed when these two algorithms are applied to the D-ShuffleNet. A closed form solution for mean hop delay is found when using the proposed unidirectional routing algorithm. Performance measures such as throughput , blocking probability, packet loss probability and total delay are also compared to those from original ShuffleNet. Results show the improvements in these measures arising from the introduction of the reverse channel are significant.

Keywords: WDM, ShuffleNet, D-ShuffleNet Channel Efficiency
Unidirectional Routing Shortest Path Routing

1. Introduction

Fiber optic technology is widely used in the traditional architectures for telecommunication networks. One problem though is the electro-optic bottlenecks in the electronic front ends of each network node. This constraint is at odds with the emerging demand for bandwidth intensive services such as high-definition television (HDTV) and medical imaging. Networks with the above constraint can not support a few hundred or a few thousand such high-bandwidth-demand end users. To overcome the bottleneck that each end user can only access the network at a restricted data rate, new architectures and protocols have been proposed to invoke the concurrency among multiple-user transmissions into the network [1, 2].

The concurrency can be invoked by using Wavelength Division Multiple Access (WDMA). With WDM each wavelength in the huge optical bandwidth can be operated at peak end user speed. It also achieves large scale concurrency. WDM-based local lightwave networks can have two different architectures: single-hop and multihop. In a single-hop system the requirements of wavelength-agile transmitters or receivers and the pretransmission coordination between two users which wish to communicate are serious drawbacks. While a multihop system will not have these two problems the delay in the network is a concern. Among the varieties of multihop lightwave networks ShuffleNet [3] was proposed and shown to achieve high efficiency for uniform traffic loads. However the ShuffleNet has a disadvantage in the asymmetric transmission distance between two nodes [4]. This can be solved if the link in ShuffleNet is duplex which means a reverse channel is added to each link.

A reverse channel augmented multihop ShuffleNet was introduced in [5]. A comparison using three metrics was shown in [5] for ShuffleNet and the Reverse-Channel ShuffleNet. The superiority of introducing the reverse channel was verified. However the routing algorithm in [5] is computationally inefficient. In addition, the broadcast algorithm in [5] has a drawback of bandwidth waste since several copies of the original packet will be routed via the network to its destination.

The approach in [5] develops a logical ShuffleNet with extra logical links for each node. In this paper a duplex approach is used which provides a logical connection similar to the original ShuffleNet. The proposed ShuffleNet using reverse channels will be called the Duplex ShuffleNet or the D-ShuffleNet. Two new routing algorithms for the D-ShuffleNet are proposed. Each routing algorithm will use self routing and unlike in [5] each routing algorithm will achieve computational efficiency. Furthermore, no copies of the original packet will be allowed in the network under these two routing algorithms.

A closed form solution is found for the network mean hop delay when using one of the above routing algorithms. Results show that the channel efficiency can be improved at the expense of doubling the number of transmitters and receivers in each node while keeping the degree of each node unchanged. Other gains from using the D-ShuffleNet compared to original ShuffleNet are that throughput increases more than two times, blocking probability is decreased and total delay is dramatically reduced.

The paper is organized as follows. Section 2 reviews ShuffleNet. The routing algorithms are proposed in section 3 while another known algorithm is also mentioned for comparison. Simulation method is used to obtain those performance measures. The simulation model will be explained in section 4. Performance results and discussion appear in section 5. Finally a brief conclusion is given in section 6.

2. ShuffleNet

ShuffleNet was first proposed in [6] for use as an interconnection network in a multiprocessor system. It was introduced as a virtual topology superimposed upon a physical network topology for multihop lightwave networks in [3]. To create this virtual topology one needs an appropriate assignment of transmit and receive wavelengths to each user on the network. In general a (p,k) ShuffleNet consists of kp^k nodes which are arranged in k columns with p^k nodes in each column. The last column will be connected back to the first column in a cylindrical fashion.

Both dedicated channels and shared channels can be used in a WDM multihop network. In this paper only the ShuffleNet with shared channels will be studied. An example of ShuffleNet with shared channels when each node has a single transmitter and receiver is shown in Figure 1 and 2. For the ShuffleNet using shared channels the multiple users which try to transmit on a common channel will use TDMA access [3, 5, 7, 8].

Several routing algorithms were proposed for the ShuffleNet [8, 9, 10, 11]. In [8] a routing algorithm which will achieve uniform loading of the channels when the source-destination traffic pattern is uniform was proposed and the mean hop delay was obtained for that routing algorithm. The expected number of hops between two randomly selected nodes is given by [8]:

$$E\left[\text{number of hops}\right] = \frac{kp^k(p-1)(3k-1)-2k(p^k-1)}{2(p-1)(kp^k-1)}$$

The above result is for a logical ShuffleNet with simplex logical links. A disadvantage of the original ShuffleNet, pointed out in [4], stems from the asymmetric transmission distance between two nodes. This disadvantage can be eliminated and the mean hop delay in the network can be reduced if one can route in both directions on each link.

This paper will only study the ShuffleNet with shared channels when the links are duplex. Figure 3 illustrates an example of channel assignment for each node so that ShuffleNet will have duplex logical links. Here λ_i and λ_i' operate at different frequencies. In a Duplex ShuffleNet each node will need twice the number of transmitters and receivers compared to the original ShuffleNet. In the following section two new routing algorithms will be proposed for the proposed D-ShuffleNet.

3. Routing Algorithm

Two different types of routing are proposed for the Duplex ShuffleNet:

- Unidirectional Routing
- Shortest Path Routing

3.1 Unidirectional Routing

In this type of routing, each link in the logical ShuffleNet will be considered to be duplex. However, the duplex link will use different wavelengths for the transmitter and the receiver at each node as seen in Figure 3. The source node will broadcast its packet by using the channel decided by the policy introduced below. Succeeding nodes receiving the message will repeat the packet using the transmitter which is not at the same side of the switching element where the message was received. Since the intermediate nodes can only use the transmitter on the other side of the switching element where the packet arrives, the routing algorithm will be called *Unidirectional Routing.* The decision of which node will repeat the packet is made by the routing algorithm.

If the traffic is uniformly distributed and the destination address of a newly arriving packet from a source node is randomly distributed in the network, then the number of new users h hops away from any source node for a (p,k) ShuffleNet when k is larger than 2 appears in Table 1 and Table 2.

Table 1. Case I: k is odd

h	Number of New Users h Hops From Source Node
1	2p
2	$2p^2$
$\vdots$	$\vdots$
$\frac{k-1}{2}$	$2p^{\frac{k-1}{2}}$
$\frac{k+1}{2}$	$2(p^{\frac{k+1}{2}} - 1)$
$\vdots$	$\vdots$
k-1	$2(p^{k-1}$-1)
k	p^k-1
k+1	$2(p^k - p^{k-1} - p + 1)$
k+2	$2(p^k - p^{k-2} - p^2 + 1)$
$\vdots$	$\vdots$
k+$\frac{k-3}{2}$	$2(p^k - p^{k-\frac{k-3}{2}} - p^{\frac{k-3}{2}} + 1)$
k+$\frac{k-1}{2}$	$2(p^k - p^{\frac{k+1}{2}} - p^{\frac{k-1}{2}} + 1)$

Table 2. Case II: k is even

h	Number of New Users h Hops From Source Node
1	2p
2	$2p^2$
$\vdots$	$\vdots$
$\frac{k}{2}-1$	$2p^{\frac{k}{2}-1}$
$\frac{k}{2}$	$2p^{\frac{k}{2}}$-1
$\frac{k}{2}+1$	$2(p^{\frac{k}{2}+1}$-1)
$\vdots$	$\vdots$
k-1	$2(p^{k-1}$-1)
k	p^k-1
k+1	$2(p^k - p^{k-1} - p + 1)$
k+2	$2(p^k - p^{k-2} - p^2 + 1)$
$\vdots$	$\vdots$
k+($\frac{k}{2}$-1)	$2(p^k - p^{k-(\frac{k}{2}-1)} - p^{\frac{k}{2}-1} + 1)$
k+$\frac{k}{2}$	$p^k - (2p^{\frac{k}{2}} - 1)$

From the above tables one can compute the mean number of hops between two randomly selected users. The mean hop delay for k larger than 2 becomes:

- Case I: k is odd

  E[number of hops]=

  $$\frac{p^2(4k+p^k(5k^2-1)+2(k^2-1))-k^2(2p-1)(5p^k+2)+8p^{\frac{k}{2}}(p^{\frac{3}{2}}+p^{\frac{1}{2}})-p^k(14p+1)-4(k-p)-2}{4(p-1)^2(kp^k-1)}$$

- Case II: k is even

  $$E[number\ \ of\ \ hops] = \frac{(p-1)^2k^2(5p^k+2) - 16p^{k+1} + 16p^{\frac{k}{2}+1} + 4kp^2 - 4k}{4(p-1)^2(kp^k-1)}$$

For a (p,k) D-ShuffleNet each node can be represented by (c,r) where c is the column number the node is located in and r in p-ary digits stands for the row position counted from 0 to p^k-1 in column c. Let (c^d, r^d) be the destination node address of a message sent by source node (c^s, r^s). The source node will send out the packet using the channel on basis of the following policy:

Channel Selection Policy for Source Node

let $(c^s, r^s) = (c^s, r^s_{k-1}r^s_{k-2}\cdots r^s_1r^s_0)$

and $(c^d, r^d) = (c^d, r^d_{k-1}r^d_{k-2}\cdots r^d_1r^d_0)$

Define:

Forward Distance $D_f = (c^d - c^s)_{mod\ k}$

Backward Distance $D_b = (c^s - c^d)_{mod\ k}$

1. $r^s_{k-1-D_f}r^s_{k-2-D_f}\cdots r^s_1r^s_0 = r^d_{k-1}r^d_{k-2}\cdots r^d_{D_f+1}r^d_{D_f}$

2. $r^s_{k-1}r^s_{k-2}\cdots r^s_{D_b+1}r^s_{D_b} = r^d_{k-1-D_b}r^d_{k-2-D_b}\cdots r^d_1r^d_0$

If either only condition 1 or condition 2 is satisfied, the channel in the right hand side or left hand side of the source node will be used respectively.

If none of the above conditions exists or both are satisfied, the right hand side channel will be used if $D_f < D_b$ or the left hand side channel will be used if $D_f > D_b$.

If $D_f = D_b$ and both conditions are either satisfied or neither is satisfied, a channel will be randomly selected.

After the source node sends out the packet, the decision as to whether an intermediate node will repeat the packet after it receives it will be determined by the following self routing algorithm.

Routing Algorithm

- Forward Routing: If the packet comes from the left hand side channel, the algorithm in [8] will be used. From [8],

  1. If (c,r)=(c^d, r^d), then (c,r) is the destination, and the packet is not repeated.
  2. If $(c, r) \neq (c^d, r^d)$, then the packet is repeated if, and only if, $r_0 = r^d_{(k+c^d-c)_{mod\ k}}$.

- Backward Routing: If the packet comes from a right hand side channel,

  1. If (c,r)=(c^d, r^d), message reaches destination. No users will repeat the packet.
  2. If $(c, r) \neq (c^d, r^d)$, only the node with $r_{k-1} = r^d_{k-1-(c-c^d)_{mod\ k}}$ will repeat the packet.

The channel selection policy and self routing algorithm will route the packet through the shortest and unique path in either forward or backward direction. The channel will be well balanced. That is,

Proof of Channel Balance: Define a *directed spanning tree* rooted at a source node as a tree which includes all the minimum-hop paths from the given source node to each destination in the network.

For a (p,k) ShuffleNet kp^k directed spanning trees rooted at each user in the network can specify all the routing of packets in the network. When using the proposed channel selection policy and routing algorithm for a source and destination pair, a unique shortest path exists in the spanning tree rooted at the source node. However because ShuffleNet has a regular structure all the above spanning trees are actually a one to one mapping (isomorphism [12]). That is every tree can be formed by using a permutation of vertices of the other tree. By this property if the unique shortest path exists for any source and destination pair in a tree there will also exist a pair of source and destination nodes in the other trees with the same shortest and unique path. Since the traffic is uniformly distributed and the destination address of a newly arriving packet from a source node is randomly distributed in the network, the number of destination nodes which can be reached via forward channel will be equal to those via backward channel for a source node. Because of this and because of the isomorphism property of the directed spanning tree for the Duplex ShuffleNet, the channel will be well balanced.

3.2 Shortest Path Routing

A link in the ShuffleNet will still be considered to be duplex as in the previous section. The source node and the following nodes can broadcast the packet to all of its channels in spite of which side of the receiver the message arrives on.

The number of new users h hops away from the source node was found by using a computer program. The mean hop delay can be computed from the results by the program.

The diameter of the ShuffleNet when using this routing method is:

- k is odd: Diameter=$k+\frac{k-1}{2}$
- k is even: Diameter=$k+\frac{k}{2}$

This is the shortest diameter one can have for a (p,k) ShuffleNet.

The Shortest Path Routing algorithm consists two parts. The first part is for a source node to create information concerning the routing direction and concerning whether a packet has to be retransmitted ("transmission"). This information will be placed in two fields in the packet header. The second part involves intermediate nodes. It defines how an intermediate node can determine the routing direction and which node has to transmit an arriving packet. This shortest path routing algorithm will provide the optimal shortest path one can have for a Duplex ShuffleNet.

Header Information from Source Node

A source node will find the shortest path to the destination first, and the information will be included in the header of the packet to be sent. The information consists of two fields, a directional field and a transmission field. The directional field indicates in which direction a node should transmit a packet. The transmission field is used by intermediate nodes to determine whether a received packet should be repeated.

The fields are formed in the way explained below. The links are labeled as 0 to p-1 from top to bottom for a node in both directions in a Duplex ShuffleNet. Since each node can use its forward and backward transmitters, a source node can create a tree similar to a directed spanning tree and find the shortest path. When the shortest path is found the path direction information and link label used in each node will be collected to form the directional and the transmission fields. If there is more than one shortest path, one will be randomly chosen. After forming the field information, the source node will read the least significant bit of the directional field. The packet will be sent to the forward direction if the bit is 1 and to the backward direction if it is 0. Before the packet is sent out the node will move the direction header one bit to the right.

Figure 4 shows an example of how a source node can form the header field information by creating a tree similar to a directed-spanning-tree for a (2,3) Duplex ShuffleNet. The source node, 0, has a packet destined for node 4. The source node will first use a program to create a tree down to the level where it finds destination node 4. The letter in the label beside the tree link indicates which direction the node will route the packet in. The number in the label indicates which link label defined in the above for a node the packet should go through. Then the directional field information will be formed by tracing the path from source to the destination. The information will be written from the lowest significant bit to the highest significant bit. A 1 will indicate the forward direction and a 0 will indicate the backward direction. Since the diameter is 4, the directional field will be of length 4 bits. After collecting the bit data by tracing the path, the rest of the higher bits will all be set to 0. In a similar manner the transmission field information is written using the bit number in the label beside the link in the tree.

The result for the above example if the randomly selected path is via node 8 will be 0001 and 0010 for directional and transmission fields respectively. Since the least significant bit of the directional field is 1, node 0 will send out the packet using the forward (R.H.S.) channel after shifting 0001 to be 0000.

It should be pointed out that the field information for both direction and transmission can be stored in the source node as a table. In this case, the extra memory cost will save a great deal of processing time in forming the field information.

Routing Algorithm

let $(c^s, r^s) = (c^s, r^s_{k-1}r^s_{k-2}\cdots r^s_1 r^s_0)$

and $(c^d, r^d) = (c^d, r^d_{k-1}r^d_{k-2}\cdots r^d_1 r^d_0)$

For Intermediate Node (c,r):

1. If (c,r)=(c^d, r^d), then (c,r) is the destination, and the packet is not repeated.

2. If $(c, r) \neq (c^d, r^d)$, an intermediate node will repeat the packet on basis of the following algorithm:

   If the packet comes from the left hand channel, then the packet is repeated if, and only if, r_0 = the least significant bit of the transmission field.

   If the packet comes from the right hand channel, then the packet is repeated if, and only if, r_{k-1} = the least significant bit of the transmission field.

If an intermediate node finds it has to repeat the packet it will check the least significant bit of the directional field to determine which direction it should send the packet in. The decision method is the same as mentioned above for a source node. Before the packet is sent out, both the direction and transmission fields will be moved one bit to the right.

When using the *Shortest Path Routing* algorithm the routing path for a source and destination pair will be shortest and unique. The channels will also be well balanced. The proof will be similar to the arguments mentioned previously for unidirectional routing.

4. Simulation Model

Simulation programs were written to simulate a (2,5) original ShuffleNet and Duplex ShuffleNet. The routing algorithm used in the original ShuffleNet is the same as in [8] which will route a packet through the shortest path and achieve channel balance. The unidirectional and shortest path routing algorithms are used in the Duplex ShuffleNet.

In the program each node in the Duplex ShuffleNet has 10 node buffers and 10 buffers for local incoming traffic. In the D-ShuffleNet, the buffers will be partitioned into two sets with 5 buffers in each. All the packets for routing in the same direction will be put into the same set of buffers. For the original ShuffleNet there are 5 buffers each for the node buffer and the local buffer. This will make a packet go through the same queueing size of the local buffer and the node buffer for the original ShuffleNet and the D-ShuffleNet.

The local traffic arrival probability is assumed to be Bernoulli distributed in each TDMA cycle and arrivals occur in the beginning of each cycle. A newly generated packet's destination is assumed to be uniformly distributed among the network. No self-directed traffic is generated. No cut through occurs in the local buffers and the node buffers. The head of the line packet in the local buffers can only be moved into the node buffers in the beginning of a cycle if there is no packet inside the node buffers at the end of the previous cycle. The reason for using this protocol is to minimize the packet loss in the network.

The simulation is run for 10,000 TDMA cycles with the first 1000 discarded as a transient period. Performance results such as blocking probability in local buffers, cell loss rate in node buffers, throughput, and total delay were collected. The total delay will be in the unit of cycle time. The propagation delay is assumed to be one cycle time which is the most conservative assumption.

5. Comparison of Performance Result and Discussion 5.1 Channel Efficiency

The channel efficiency, η, can be defined as that in [8] under the condition that the traffic loads will balance the channel utilization:

$$\eta = \frac{1}{E[number\ \ of\ \ hops]}$$

Figure 5 and 6 illustrate the channel efficiency of a ShuffleNet with different total column numbers when the degree of each node, p, is the same.

Using duplex links in the virtual ShuffleNet can increase the channel efficiency. The largest improvement results when the total column numbers and the total numbers of transmitters and receivers are kept as low as possible for a fixed numbers of total nodes. These improvements are of a marginal nature but as seen below the improvement in throughput and delay are substantial.

5.2 Throughput and Delay

Figure 7 shows the comparison result of throughput for each node. It can be seen the throughput in the D-ShuffleNet using *Shortest Path Routing* can achieve more than two times that in the original ShuffleNet.

Using another criteria to view the improvement in throughput, one can find the maximum throughput for each node under different routing algorithms when no packets are lost internally [7]:

$$\gamma_{maximum} = \eta f C$$

where γ : Throughput

η : Channel Utilization Efficiency

f : Number of Physical Ports in/out of a node

C : Capacity of each transmitter

Here f equals to 2 and 1 for the (2,5) D-ShuffleNet and the original (2,5) ShuffleNet respectively. Here C is 1 packet in each cycle and η can be found from figure 5. Thus the maximun throughput can be computed. It can be seen the maximum throughput for each node in the (2,5) D-ShuffleNet is 0.39 and 0.46 when using *Unidirectional Routing* and *Shortest Path Routing* algorithm respectively. It will be 0.16 for the original (2,5) ShuffleNet which is less than one half of those in the D-ShuffleNet case.

In addition to the increase of throughput by using the Duplex ShuffleNet, the throughput in the original ShuffleNet gets saturated much earlier than that in the D-ShuffleNet when the local traffic load becomes heavier.

Total delay is defined as end-to-end delay through local buffers, node buffers and network hop delay. The results are shown in figure 8. The total delay in the D-ShuffleNet is dramatically reduced. The delay in the original ShuffleNet increases a great deal even under a light traffic load. Naturally if the propagation delay from node to star coupler and back to every other node is more than one cycle, the total delay under the D-ShuffleNet will show a greater improvement.

A delay versus throughput curves can be found in figure 9. It can be seen that a large improvement in performance results from adding one more transmitter and receiver in each node.

5.3 Blocking Probability and Loss Probability

Figure 10 and 11 illustrate the blocking probability for the local buffers and loss probability for the node buffers. Packet loss probability is defined as the probability that a packet finds the node buffers of a node which is its next stop full.

As seen in figure 10 the blocking probability for the local buffers in original ShuffleNet increases a great deal even under a light traffic load.

Figure 11 shows that the packet loss probability in the D-ShuffleNet is lower than that in the original ShuffleNet. The network mean hop delay when using the shortest path routing algorithm will be the smallest. That means the packets in the network will reach its destinations more quick than those do under unidirectional routing or original routing algorithm. Thus the loss probability when using the shortest path routing algorithm will be the lowest under the condition that there are the same amount of packets inside the network.

However the loss probability under the shortest path routing algorithm is higher than that under the unidirectional routing algorithm when the arrival probability is higher than 0.5. The reason is because the throughput under the unidirectional routing algorithm will be less than that under the shortest path routing algorithm when the arrival probability is higher than 0.5. This can be found in figure 7. When the traffic load becomes heavier, there will thus be more packets on the network when using the shortest path routing algorithm than when using the unidirectional routing algorithm. This will result in higher loss probability.

6. Conclusion

A ShuffleNet variation called the Duplex ShuffleNet is proposed as a multihop lightwave network. Two new routing algorithms for the D-ShuffleNet are also introduced. A closed form solution of the mean hop delay and channel efficiency for the unidirectional routing algorithm is presented in this paper. It was pointed out that the channel efficiency can be improved at the cost of adding one more transmitter and receiver in each node. By doing so, performance metrics such as throughput, total delay, blocking probability and loss probability can be improved. The improvements are significant.

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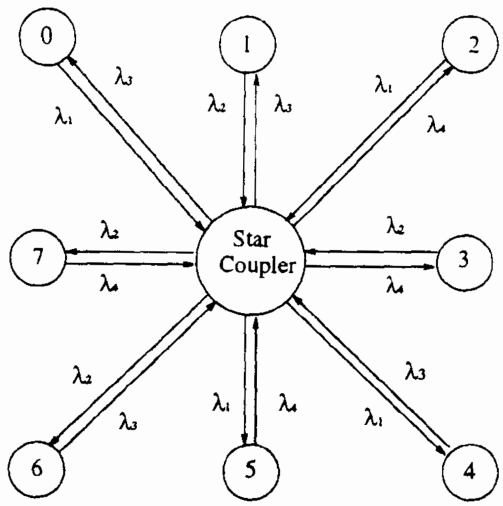


Figure 1 : An example of a physical lightwave network

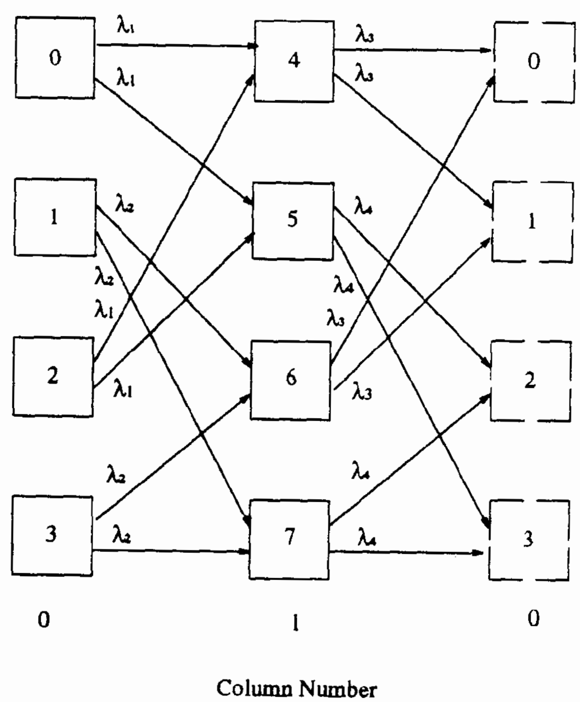


Figure 2: A (2,2) shared channel logical ShuffleNet from figure 1.

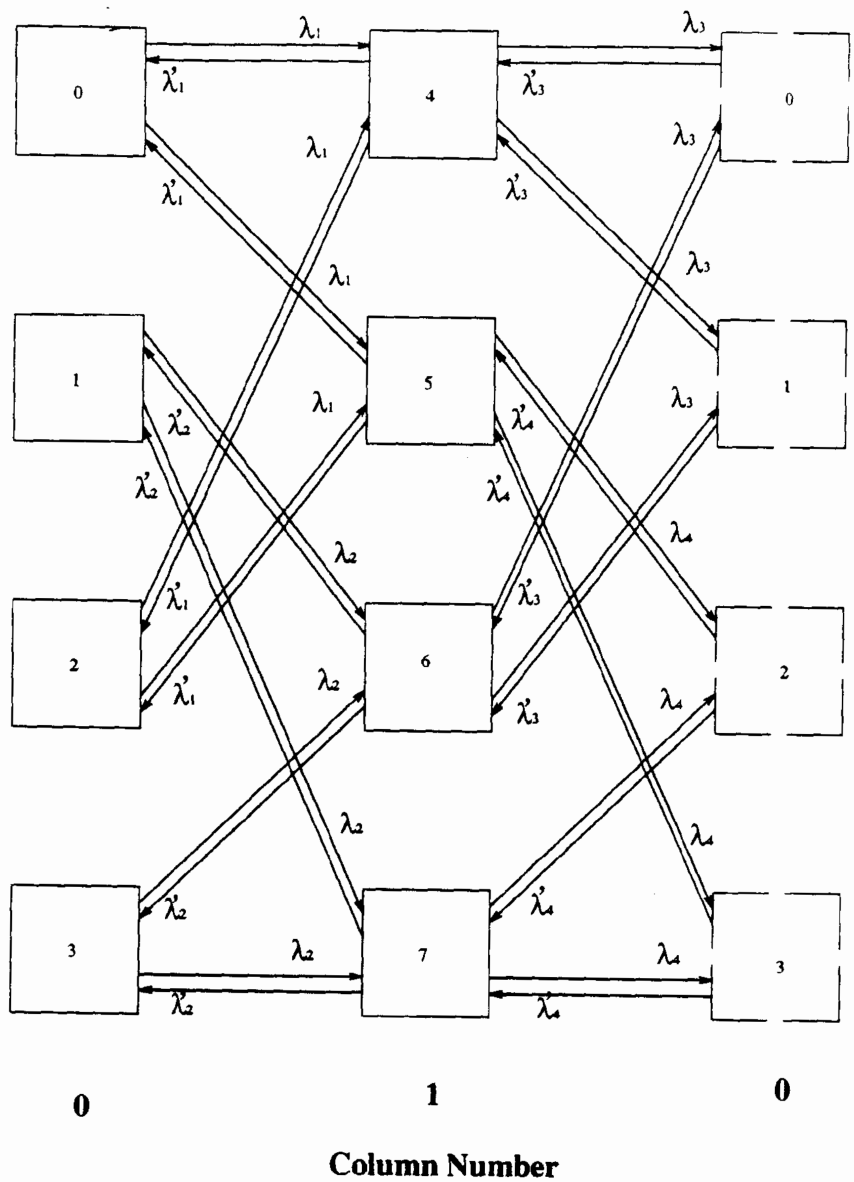
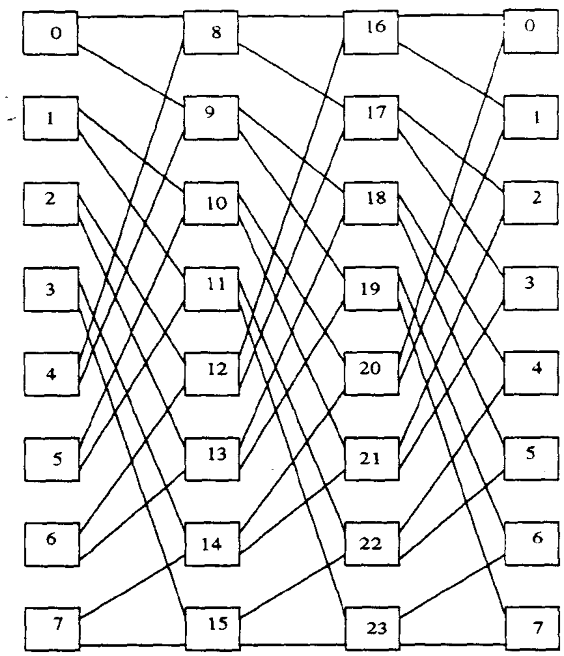


Figure 3: A duplex shared channel logical (2,2) ShuffleNet



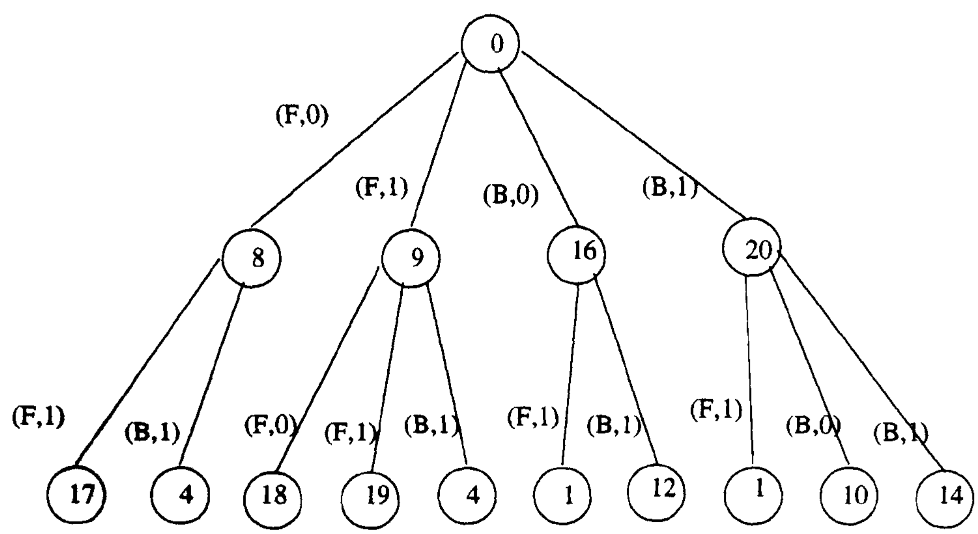


Figure 4: Formation of directional and transmission fields for source node 0

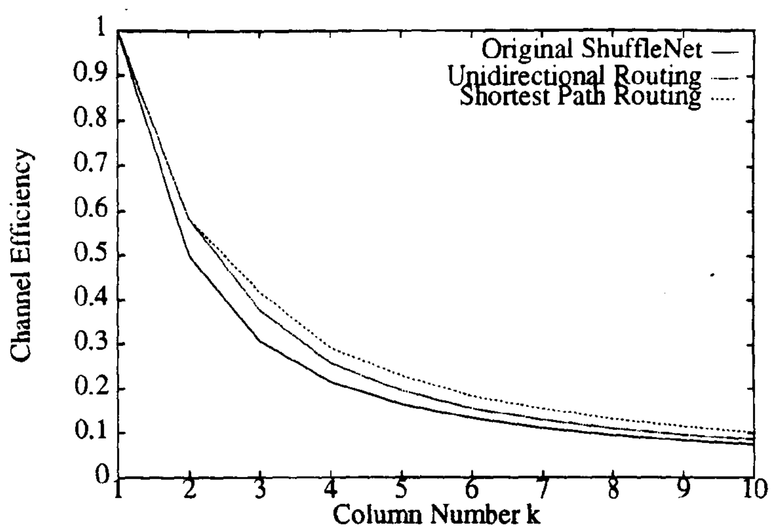


Figure 5: Channel efficiency when p=2

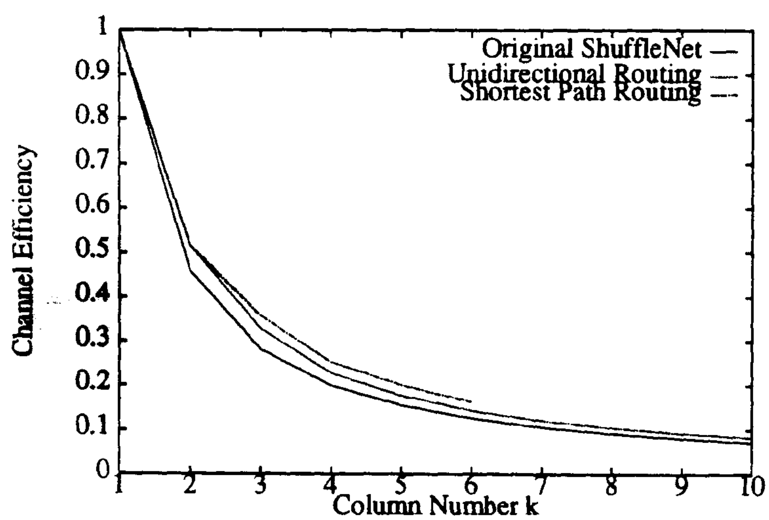


Figure 6: Channel efficiency when p=3

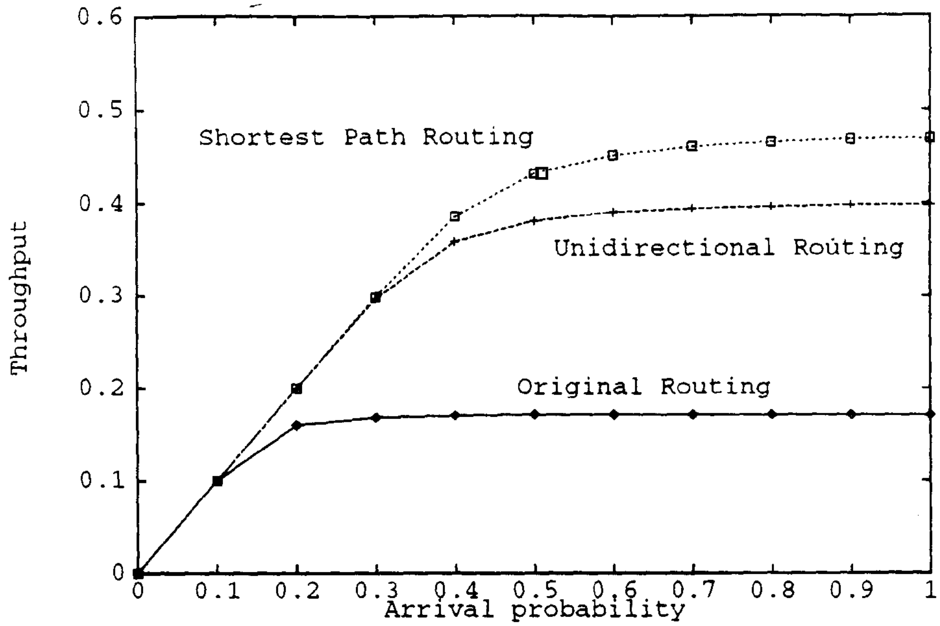


Figure 7: Throughput for a (2,5) ShuffleNet and a D-ShuffleNet

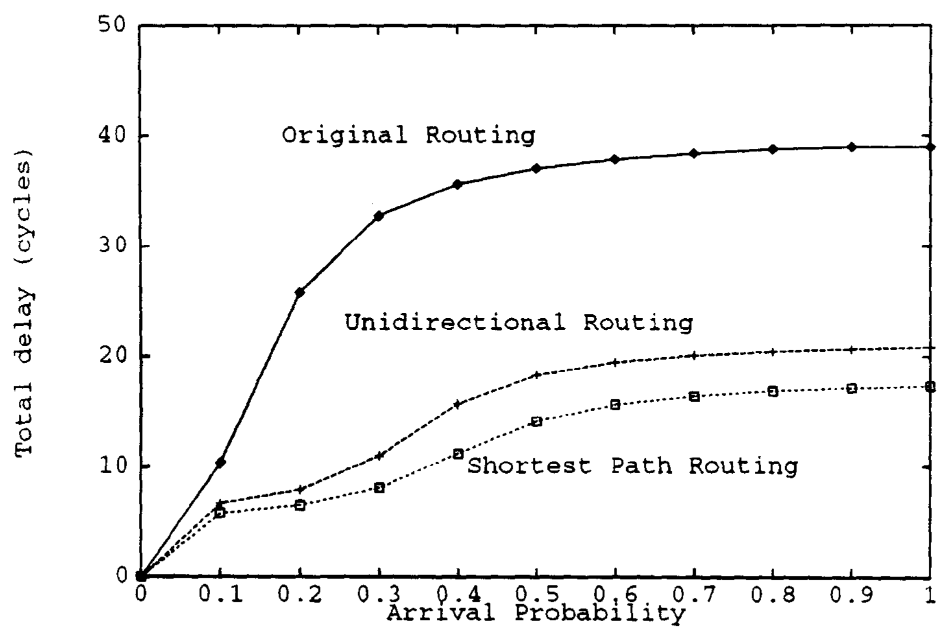


Figure 8: Total delay for a (2,5) ShuffleNet and a D-ShuffleNet

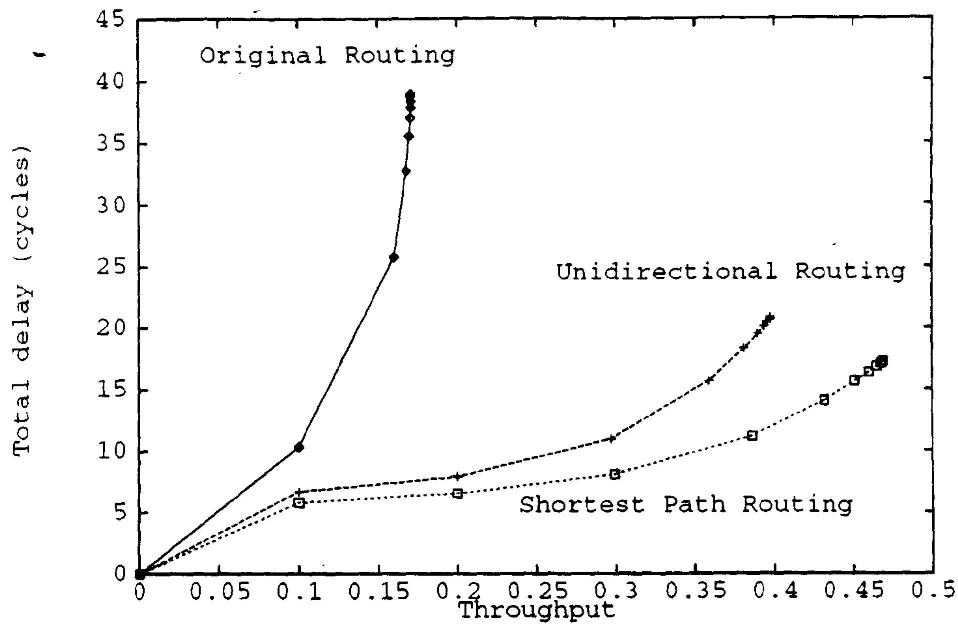


Figure 9: Throughput-Delay performance for a (2,5) ShuffleNet and a D-ShuffleNet

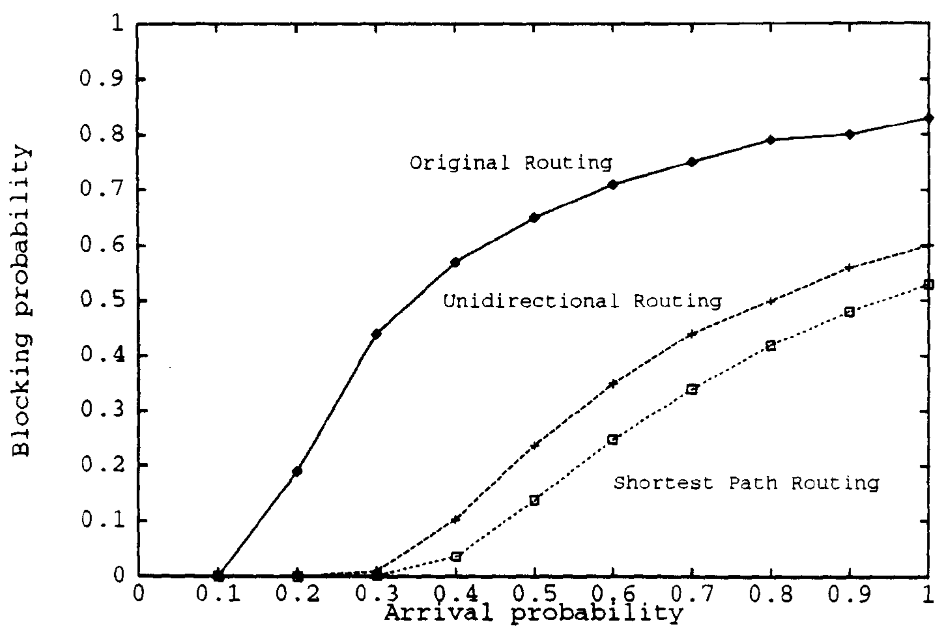


Figure 10: Blocking probability for a (2,5) ShuffleNet and a D-ShuffleNet