Performance Analysis of Shufflenet with Deflection Routing[†]

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Abstract

Multi-hop communication networks are drawing increasing interest recently. Shufflenet is a multi-hop communication network which achieves high performance while overcoming the current shortcomings in device technology [1]. In this paper, we present a new and comprehensive analysis for shufflenet. By making use of the connectivity properties of any (p, k) shufflenet, we characterize the probabilistic behavior of a typical packet in the network in terms of a simple discrete-time Markov chain with only $2k$ states, one of which is an absorbing state. We then derive analytic expressions for several important network performance parameters such as hops distribution, average delay for a packet to travel to its destination and the probability of don't care in each hop that the packet takes. The expressions derived can be applied to any (p, k) shufflenet. The calculation of throughput of the shufflenet can then be obtained by finding the relationship between ne! twork packet generation probabili

1 Introduction

Optical fiber provides a tremendous amount of bandwidth for communication. By using its low-loss low-dispersion "window" at 1.2μm-1.6μm, a bandwidth of tens of terabits per second is available for information transmission. Because of the enormous usable bandwidth offered by optical fiber, any communication scheme that utilizes only a small fraction of the bandwidth can provide substantial capacity. If a network makes use of only 1% of the bandwidth, the throughput of the system can be very impressive. Therefore, optical fiber holds promise for the future wideband communication [2].

Current high-performance optical Local Area Network/Metropolitan Area Network (LAN/MAN) such as Fiber Distributed Data Interface (FDDI) and the IEEE802.6 Distributed Queuing Dual Bus (DQDB) are systems in which every node has access to only a single channel at a time. As a result, the performance of the networks falls off for each additional user in the networks. To increase the throughput, parallel or concurrent transmission has to be provided. If different users in the network can transmit packets at the same time through a number of channels, the throughput of the network can be increased. Shufflenet is a Wavelength Division Multiple Access (WDMA) network making use of this principle of concurrency to achieve high throughput performance [3].

In this paper, we report the performance analysis of shufflenet. We first describe some important network parameters and topologies of shufflenet. Then the performance of the network with deflection routing is analyzed. By using the topological properties of shufflenet, we can model the routing behavior of a packet in the network as a single Markov chain with an absorbing state. The simple Markov chain representation enables us to obtain close form solutions for important performance measures of the network. Finally, we present the throughput analysis for shufflenet with hot-potato and store-and-forward routing algorithms. Our analyses agree excellently with the simulation data of the network.

2 Shufflenet System

2.1 Shufflenet with Deflection Routing

Shufflenet is a multi-hop network [1]. Each user in the shufflenet accesses the network through the Network Interface Unit (NIU). Each NIU has a number of lightwave receivers and transmitters. A shufflenet is characterized by two numbers p and k. A $(p,\ k)$ shufflenet consists of kp^k nodes arranged in k columns, and each column consists of p^k NIUs. Figure 1 shows a (2, 3) shufflenet. All the NIUs are interconnected as a perfect shuffle, with the last column being "wrapped-around" to the first column like a completed cylinder. In this way, packets can be continuously circulated around the network until they reach their destinations.

Packets are transmitted within shufflenet in a store-and-forward fashion, if there is storage in the NIUs. A packet will

*The work was supported in part by the New Jersey Commission on Science and Technology's Innovative Partnership Program FY 1993, and in part by the Ogasawara Foundation for the Promotion of Science and Technology.

[†] *Proceedings of IEEE GLOBECOM'93*, Vol. 2, pp. 854-859.

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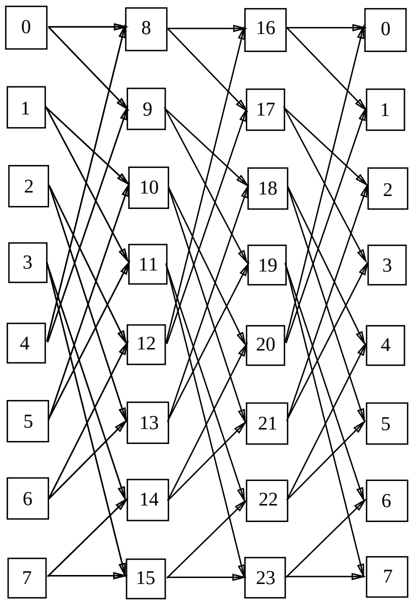

Figure 1: An example of a (p, k) shufflenet, with $p = 2$ and $k = 3$.

hop through the nodes until it reaches its destination, where the packet will be absorbed. Shufflenet is internally blocking in the sense that different packets destined to different destinations may suffer collision with each other for an output channel during the process of routing. In this case, one of the packets will be routed correctly while the rest of them will be either stored if storage is available, or "deflected" temporarily to the wrong channels. Therefore, in deflection routing, packets are never lost due to buffer overflow. In a (p, k) shufflenet, for each deflection it suffers, a packet simply takes k more hops to reach its destination. In this way, a shufflenet with deflection routing is a packet-switched network in which packets are continuously circulated around until they get absorbed.

In a (p, k) shufflenet, each NIU can be identified by an address (c, r), where $c \in \{0, 1, ..., k-1\}$ and $r \in \{0, 1, ..., p^k - 1\}$. For a given packet at node (c, r), let D be the number of columns between the source (c, r) and destination (c^d, r^d). We clearly have:

$$D = \begin{cases} (c - c^d) \bmod k & \text{if } c^d \neq c, \\ k & \text{if } c^d = c. \end{cases}$$

D represents the lowest bound on the number of hops the packet must take to go from (c, r) to (c^d, r^d). In shufflenet, a packet at a node is said to be "don't care" with respect to its destination if the destination cannot be reached within k hops by the packet under no deflection. A node is said to be a "don't care" node for a packet if the packet at the node can go from this node to its destination with the minimum number of hops by taking any link emanating from this node. Therefore, if a packet is at a "don't care" node, it will never suffer deflection. It should be noted that if a packet is in a "don't care" node, it is not possible for the packet to be routed in D steps; it takes $D+k$ steps. This is an important property of shufflenet which will greatly reduce the state space when we analyze the network.

2.2 Topological Properties

In dealing with multi-hop communication networks, there are three important topological performance parameters [6]:

• Diameter – the maximum distance, d_{max}, between any two nodes in a network is called the diameter of the network. This parameter shows how compact a network is and how fast a packet can go to its destination. For a (p, k) shufflenet, $d_{max} = 2k - 1$. Let N be the total number of nodes in the shufflenet, $N = kp^k$, then $k \approx \log_p N$. Therefore, for large N, $d_{max} \approx 2\log_p N$ for shufflenet.

• Deflection cost – the maximum increase in the number of hops due to a deflection is the deflection cost. For a (p, k) shufflenet, deflection cost is $k \approx \log_p N$, for large N. This parameter indicates the delay of a packet once the packet is deflected, thus it also indicates how well the network performs with deflection routing.

• Number of "don't care" nodes – High fraction of "don't care" nodes helps to keep the deflection probability low, thus implies high performance of the network. In a (p, k) shufflenet, all the nodes that are within k hops from a packet's destination are "care" nodes. Since a shufflenet is symmetric with respect to all the N nodes, we may specify any node as a destination. The total number of "care" nodes, n_c, with respect to the destination node can be written as:

$$\begin{aligned} n_c &= \sum_{i=1}^{k} p^i \\ &= \frac{p(p^k - 1)}{p - 1}. \end{aligned}$$

Therefore, the fraction of "don't care" nodes in a shufflenet, p_{dc}, is:

$$\begin{aligned} p_{dc} &= 1 - \frac{n_c}{N} \\ &= 1 - \frac{p^k - 1}{kp^{k-1}(p-1)}. \end{aligned} \tag{1}$$

The fraction increases with the size of the shufflenet and approaches unity as $k \to \infty$. This is an important and attractive property of shufflenet because a packet at a "don't care" node will never contend for an output link. It means that a large shufflenet will have a lower deflection probability than a smaller one for a given load.

3 Analysis of Shufflenet

3.1 Descriptions

There are several parameters that are important when the performance of shufflenet is considered. They are:

• Normalized throughput (throughput per node) – It is defined as the average number of packet absorbed (or generated) by each node in the steady state of the network in each clock cycle. Note that in shufflenet with deflection routing, the normalized throughput can be lower than the offered load as the packets may suffer deflections and continuously circulate around the network without reaching their destinations.

• Hops distribution and average number of hops – The probability distribution of the number of hops that a packet makes before being absorbed is important when we deal with time-sensitive information, such as voice or video packets. The hop distribution and the average number of hops are appropriate indicators of the delay performance. With deflection routing, the delay increases and distribution tail broadens with the deflection probability.

• Probability of deflection in the "care" node, P_{def} – A packet can be deflected only when it is in a "care" node with respect to its destination. The deflection probability critically determines how well a shufflenet performs. The higher the deflection probability, the lower the throughput of the network and the longer the packets take to reach their destinations. Deflection probability, P_{def}, generally increases with the the packet generation probability in each node, which is called the offered load, g.

• Probability of don't care, P_{dc} – It is defined as the probability that a packet enters one of its "don't care" nodes in a given hop that it takes in the network. Except for its last hop, a packet in the shufflenet is always put into a "don't care" node for each deflection it suffers. Note that in order to route a packet to its destination in the minimum number of hops [9], a packet is always directed to go to its "care" nodes. Therefore, in any shufflenet, the higher the probability of don't care, the worse the performance of the network. Let N^{dc} be the random variable that represents the number of "don't care" nodes that a packet visits on its way to the destination, and let D be the number of hops that the packet takes. Then we have

$$P_{dc} \triangleq \frac{\mathrm{E}[N^{dc}]}{\mathrm{E}[D]}, \qquad (2)$$

where $\mathrm{E}[V]$ is the expected value of the random variable V. Without any deflection, P_{dc} is equal to p_{dc} mentioned in Section 2.2 (Equation (1)). With deflection, P_{dc} is always greater p_{dc}.

3.2 Analysis

We now present analytical relationships among P_{def}, P_{dc}, hops distribution and the expected number of hops, $E[D]$, and obtain the throughputs of shufflenet with hot-potato and store-and-forward routing algorithms. As we remarked earlier, we make use of the special pattern of the "care" nodes in a shufflenet. Using this property, we need to deal with a Markov chain with only $2k$ states, instead of the usual $N(=kp^k)$ states reported by previous investigators [7, 10].

In any (p,k) shufflenet, the "care" nodes for a packet are the nodes within diameter k from its destination. All the other nodes are "don't care" nodes where the packet will not suffer deflection. We assume that the traffic generated in the network is uniform and independent among all the $N(=kp^k)$ nodes in the network. We further assume that the users in the network will not generate any packet to themselves.

Let us select a packet arbitrarily and observe the behavior of the "tagged" packet. Let our state space $S = \{0, 1, ..., 2k-1\}$ be a collection of possible distances between the current position of the tagged packet and its destination. Here the distance is defined as the minimum number of hops that the packet must make to travel to its destination in the absence of deflection. Let

$$\begin{aligned} D_i \;=\; & \mathrm{E}[\text{number of hops when the tagged packet is at} \\ & \text{distance } i \text{ from its destination} \mid \text{probability} \\ & \text{of deflection} = P_{def}], \quad \forall i \in S. \end{aligned} \qquad (3)$$

We model the network as an absorbing Markov chain with state space S, and state 0 is the absorbing state. As in a (p,k) shufflenet, each deflection increases the packet's hops by k, we have

$$D_i = P_{def} D_{i-1+k} + (1-P_{def})D_{i-1} + 1, \quad 1 \le i \le k. \qquad (4)$$

When the packet is at a distance more than k hops from its destination, it is in its "don't care" node and therefore will not suffer deflection (i. e. $P_{def} = 0$) until it is k hops from its destination. Hence,

$$D_i = \; D_k + (i-k), \quad k+1 \le i \le 2k-1. \qquad (5)$$

Since state 0 is the destination of the tagged packet, we have D_0=0. Solving Equations (4) and (5), we get

$$D_j = \begin{cases} j + \frac{k}{(1-P_{def})^k}[1-(1-P_{def})^j], & 1 \le j \le k, \\ D_k + (j-k), & k+1 \le j \le 2k-1. \end{cases} \qquad (6)$$

Note that Equations (4)-(6) hold for any (p,k) shufflenet and do not depend on the parameter p.

As for $1 \le j \le k-1$, there are p^j nodes at j hops away from a given node, and for $0 \le j \le k-1$, there are $(p^k - p^j)$ nodes at $k+j$ hops away, the expected number of hops, $\mathrm{E}[D]$, for any packet in the network is therefore given by

$$\begin{aligned} \mathrm{E}[D] &= \frac{1}{kp^k-1}\left[\sum_{j=1}^{k-1} p^j D_j + \sum_{j=0}^{k-1}(p^k-p^j)D_{k+j}\right] \\ &= -\frac{kp(1-p^{k-1}(1-P_{def})^{k-1})}{(kp^k-1)(1-P_{def})^{k-1}(1-p+pP_{def})} \\ &\quad + \frac{kp^k}{kp^k-1}\left(\frac{k-1}{2}\right) + \frac{k}{(1-P_{def})^k}. \end{aligned} \qquad (7)$$

With no deflection, $\lim_{P_{def}\to 0} \mathrm{E}[D] = 4.6349$.

To find the probability distribution of the number of hops, we form a $(2k)\times(2k)$ transition matrix, $\mathbf{T}$, where the entry

$t_{i,j}$ is the one step transition probability:

$$t_{i,j} \triangleq \Pr[\text{The tagged packet at distance } j \text{ from its destination hops to distance } i \text{ in the next time epoch}], \quad (8)$$

$\forall i, j \in S$. Then we have

$$\begin{aligned} t_{0,0} &= 1, \text{ (absorbing state)}, \\ t_{i+k-1,i} &= P_{def}, \quad \text{for } 1 \le i \le k, \\ t_{i-1,i} &= \begin{cases} 1 - P_{def}, & \text{for } 1 \le i \le k, \\ 1, & \text{for } k+1 \le i \le 2k-1, \end{cases} \\ t_{i,j} &= 0, \quad \text{elsewhere.} \end{aligned} \quad (9)$$

Clearly $t_{i,j}$'s satisfy

$$\sum_{i \in S} t_{i,j} = 1, \quad \forall j \in S.$$

Let Q_n be the probability that a packet (first) reaches its destination at the nth hop. $\{Q_n, n = 1, 2, 3, ...\}$ is then the probability distribution of the number of hops taken by a packet in the network and is given by:

$$\sum_{i \le \min(n, 2k-1)} \Pr[\text{Packet generated at distance } i \text{ reaches its destination exactly at the } n\text{th hop.}] \quad (10)$$

Let $\mathbf{P}_0$ and $\mathbf{P}_n$ be column vectors. The ith element of $\mathbf{P}_0$ is the initial probability that a packet is generated at distance i and the ith element of $\mathbf{P}_n$ is the probability that the packet visits state i in its nth hop, where $i \in S$. Then, $\mathbf{P}_n = \mathbf{T}\mathbf{P}_{n-1} = \mathbf{T}^n\mathbf{P}_0 = \mathbf{S}\mathbf{\Lambda}^n\mathbf{S}^{-1}\mathbf{P}_0$. where $\mathbf{\Lambda}$ is the diagonal matrix formed by the eigenvalues of $\mathbf{T}$ and $\mathbf{S}$ is the corresponding matrix formed by the eigenvectors of $\mathbf{T}$.

As the destination of a packet just generated is randomly distributed among all the other $(N-1)$ users in the network, the initial probability distribution for the distance of a packet can be written as

$$\mathbf{P}_0 = \frac{1}{kp^k - 1} \begin{pmatrix} 0 \\ p \\ . \\ . \\ p^{k-1} \\ p^k - 1 \\ p^k - p \\ . \\ . \\ p^k - p^{k-1} \end{pmatrix}. \quad (11)$$

Note that the underlying Markov chain has one absorbing state (i. e., state 0) and all the other $(2k-1)$ states are transient (see Figure 2). Therefore it is known that only one eigenvalue of the transition matrix $\mathbf{T}$ is unity, $\lambda_0 = 1$, and the magnitudes of all the other eigenvalues are strictly less than 1. Therefore in the limit

$$\lim_{n \to \infty} \mathbf{\Lambda} = \begin{pmatrix} 1 & 0 & ... & 0 \\ 0 & 0 & ... & 0 \\ . & . & . & . \\ 0 & 0 & ... & 0 \end{pmatrix}, \quad (12)$$

and from the theory of Markov chain, we can show that

$$\lim_{n \to \infty} \mathbf{P}_n = \mathbf{e}_0, \quad (13)$$

where $\mathbf{e}_0$ is a column vector whose entries are all zero except the first element (corresponds to state 0), which is unity. Therefore the tagged packet reaches its destination with probability one.

Since the state $0 \in S$ is the absorbing state, Q_n is given by the first element of the vector $(\mathbf{P}_n - \mathbf{P}_{n-1})$. Thus, we have

$$Q_n = \mathbf{e}_0^T \cdot (\mathbf{P}_n - \mathbf{P}_{n-1}) \quad \text{for } n = 1, 2, 3, ..., \quad (14)$$

where $\mathbf{e}_0^T$ is the transpose of vector $\mathbf{e}_0$.

The average number of "don't care" nodes which a packet hops through before it is absorbed can be obtained in an analogous way as in the calculation of E$[D]$. Let

$$N_i^{dc} = \text{E[number of "don't care" nodes that the tagged packet at distance } i \text{ visits in its lifetime]}, \quad (15)$$

then we have

$$N_i^{dc} = P_{def} N_{i+k-1}^{dc} + (1 - P_{def}) N_{i-1}^{dc}, \quad 1 \le i \le k, \quad (16)$$

and

$$N_i^{dc} = N_k^{dc} + (i - k), \quad k+1 \le i \le 2k-1. \quad (17)$$

As state 0 is the destination of the tagged packet, $N_0^{dc} = 0$. From Equations (16) and (17), we get

$$N_j^{dc} = \begin{cases} D_j - \frac{1-(1-P_{def})^j}{P_{def}(1-P_{def})^k}, & 1 \le j \le k, \\ N_k^{dc} + (j-k), & k+1 \le j \le 2k-1. \end{cases} \quad (18)$$

The expected number of "don't care" nodes that the packet hops through can then be obtained as

$$\begin{aligned} \mathrm{E}[N^{dc}] &= \frac{1}{kp^k - 1} \left[\sum_{j=1}^{k-1} p^j N_j^{dc} + \sum_{j=0}^{k-1} (p^k - p^j) N_{k+j}^{dc} \right] \\ &= \mathrm{E}[D] - \frac{p}{P_{def}(kp^k - 1)} \left[\frac{p^{k-1} - 1}{p - 1} - \frac{1 - p^{k-1}(1 - P_{def})^{k-1}}{(1 - P_{def})^{k-1}(1 - p + pP_{def})} \right] - \\ &\quad \frac{1 - (1 - P_{def})^k}{(1 - P_{def})^k P_{def}}. \end{aligned} \quad (19)$$

The probability that the node which the tagged packet visits is a "don't care" node is then given by Equation (2) with the use of Equations (7) and (19). We obtain $\lim_{P_{def} \to 0} P_{dc} = 0.2123$.

The throughput of $(2, k)$ shufflenet has been presented by Forghieri, Bononi and Prucnal [7]. Let the normalized throughput be λ. Then,

$$\lambda = 2 \frac{\sqrt{\alpha^2 + g^2(1 - \alpha)^2} - \alpha}{g(1 - \alpha)^2} \alpha, \quad (20)$$

where

$$\alpha \triangleq \frac{1}{\mathrm{E}[D]}. \tag{21}$$

Our analysis presented above shows that the average number of hops, hops distribution, probability of deflection and throughput of the network can all be analytically obtained, once the probability of deflection, P_{def}, is specified. The analysis of the shufflenet is then reduced to the problem of finding the relationship between the offered load, g, and the deflection probability, P_{def} [6, 8]. The relationship depends on the routing algorithm and buffer architecture used in the network [5]. With independence assumptions, P_{def} is obtained by solving a nonlinear equation in hot-potato routing for each offered load, g, and $P_{def} \equiv 0$ in store-and-forward routing for all offered load, g [7].

3.3 Results

As an illustrative example, the performance of $(2,4)$ shufflenet has been analyzed for both hot-potato and store-and-forward routing algorithms. Figure 2 shows the state transition diagram for the $(2,4)$ shufflenet. From Equation (9),

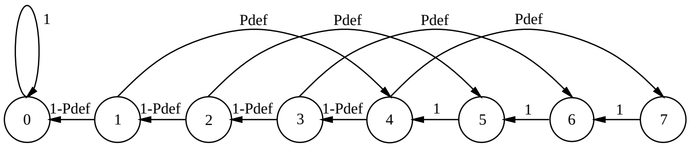

Figure 2: State transition diagram for $(2,4)$ shufflenet. The state number represents distance $i, 0 \leq i \leq 2k-1$, i. e., the number of hops that a packet must take from the current node to its destination without deflection.

the transition matrix $\mathbf{T}$ is given by:

$$\begin{pmatrix} 1 & 1-P_{def} & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1-P_{def} & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1-P_{def} & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1-P_{def} & 0 & 0 & 0 \\ 0 & P_{def} & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & P_{def} & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & P_{def} & 0 & 0 & 0 & 1 \\ 0 & 0 & 0 & 0 & P_{def} & 0 & 0 & 0 \end{pmatrix} \tag{22}$$

and, from Equation (11),

$$\mathbf{P}_0 = \frac{1}{63}\begin{pmatrix} 0 \\ 2 \\ 4 \\ 8 \\ 15 \\ 14 \\ 12 \\ 8 \end{pmatrix}. \tag{23}$$

We present in Figure 3 the curve of Equation (7), i. e., the average number of hops that the packets make in the network versus the deflection probability, P_{def}. We also plot our earlier results based on simulations [4]. As we can see, both analyses and simulation results agree very well. Figure 4 shows the corresponding hops distribution (i. e. $Q_n, n = 1, 2, 3, \ldots$ of Equation (14)) for hot-potato routing for three different values of traffic load, $g = 0.1, g = 0.3$ and $g = 0.5$. We verify the exponential tail of the hop distributions reported by others [7, 10] based on simulation and numerical analysis of $N \times N$ matrices, where $N = kp^k$. The simulation and analytic result for the probability of don't care, P_{dc}, (see Equations ((2), (7) and (19)) against deflection probability, P_{def}, is shown in Figure 5, while the complete analysis for hot-potato and store-and-forward routing is shown in Figure 6. We see close agreements between the analytic and simulation results. The good agreement between analysis and simulation clearly verifies that the independence assumptions made in are justifiable [7].

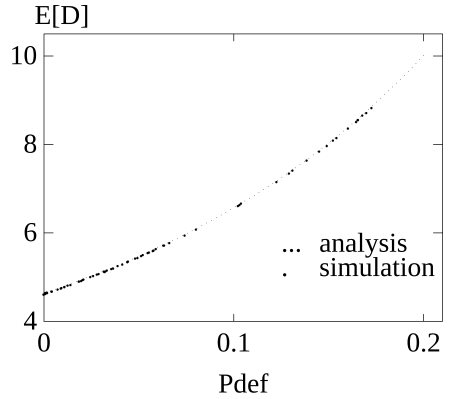

Figure 3: Simulation and analytic results of average number of hops, $\mathrm{E}[D]$, versus probability of deflection, P_{def} for a $(2,4)$ shufflenet.

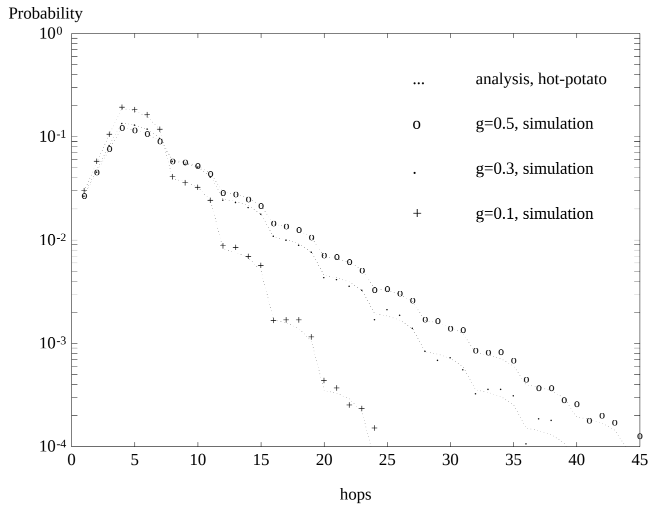

Figure 4: Probability distribution of the number of hops for $(2,4)$ shufflenet with hot-potato routing for the offered offered load $g = 0.1, g = 0.3$ and $g = 0.5$.

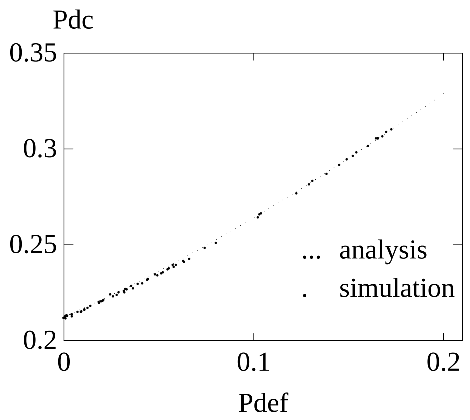

Figure 5: Probability of don't care plotted against probability of deflection, P_{def} for a $(2,4)$ shufflenet.

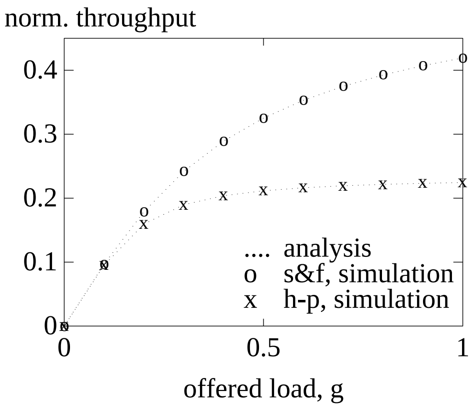

Figure 6: Normalized throughput for $(2,4)$ shufflenet with hot-potato and store-and-forward routing algorithms.

4 Conclusion

We have presented a complete performance analysis of (p,k) shufflenet with hot-potato and store-and-forward routing algorithm. By using the symmetric connectivity pattern of shufflenet, we are able to model the behavior of an arbitrary chosen packet in the network as a discrete time Markov chain with $2k$ states, one of which is an absorbing state and the remaining $(2k-1)$ states are transient. Several important network parameters and performance measures can then be analytically derived. Both analysis and numerical evaluation are greatly simplified compared with earlier results, in which the network is modelled as a Markov chain with $N(=kp^k)$ states, where N is the total number of users in the network. This simplification enables us to put some performance measures in closed forms. The parameters we obtained – average number of hops, hops distribution and probability of don't care – hold for any (p,k) shufflenet. The throughput analysis of shufflenet is simply reduced to finding the relationship between the offered load, g, and the probability of deflection, P_{def}. The relationship depends on the parameters of the shufflenet, routing algorithms, buffer designs and memory capacity [5, 6, 8]. We finally present numerical results together with the simulation data for a $(2,4)$ shufflenet with hot-potato and store-and-forward routing algorithms. The analyses agree very well with our previous simulation results [4].

Acknowledgement
We wish to thank Mr. Alberto Bononi for introducing the problem to us, and for the valuable discussions and comments he provided.

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