Hash-Based Wavelength Path Selection Algorithm for Statistical Lambda Multiplexing Network (SLAMNet)

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SUMMARY: This paper proposes a hash-based wavelength path selection algorithm for statistical lambda multiplexing network (SLAMNet) that provides dynamic path assignment capabilities without signaling between nodes. The proposed algorithm facilitates to resolve the conflicts of wavelength path assignment due to the asynchronous and distributed control scheme of the SLAMNet. The performance of the proposed algorithm is analyzed and the applicability to a large-scale DWDM networks is discussed.

1. Introduction

In order to support the rapidly growing traffic demand in the IP backbone networks, Dense Wavelength Division Multiplexing (DWDM) technologies will be used for the expansion of the transmission capacity in a backbone portion of networks. In DWDM networks, multiple wavelengths can be used by a pair of routers to transmit a large amount of traffic volume. On the other hand, the traffic demand between a router pair is likely to change widely over time, and the peak load may be much higher than its average. In such a situation, it is attractive for both customers and carriers that the number of the paths assigned to a router pair should be changed according to its traffic volume, which can enhance the performance, efficiency and flexibility of the networks. Several types of DWDM network architectures for on-demand wavelength path assignment, e.g. the automatically switched optical networks (ASON), have been proposed [1-4]. These architectures commonly require a signaling function for the wavelength path management. Since a signaling process usually takes more than several hundred milliseconds to exchange control messages, the average holding time of an optical path should be longer than several seconds for resource utilization.

The basic concept of a novel architecture called the Statistical Lambda Multiplexing Network (SLAMNet) was proposed to provide on-demand multi-wavelength services in the DWDM network [5]. In comparison with the other architectures proposed for the DWDM network [1-4], the most striking feature is that it is free from the signaling protocol for wavelength path switching. The SLAMNet can dynamically adjust the number of wavelengths according to the traffic volume within a short period.

Taking advantage of the signaling-free wavelength path switching, the SLAMNet can be implemented in a part of any type of optical network maintaining its scalability in a simple and economical way and responding quickly to the traffic variation regardless of the round trip time necessary for signaling. The major features of the SLAMNet are as follows: (1) The architecture can be implemented as an overlay network independent of the functionality of the DWDM network. No signaling capability is required of the infrastructure and any legacy backbone networks can be utilized for the SLAMNet. (2) The set up time for a wavelength path will be shorter than that in a signaling-based system. This feature becomes a great advantage especially for wide area networks, because a signaling delay may be larger than several hundred milliseconds. (3) The SLAMNet is scalable with the number of routers and wavelengths. (4) The SLAMNet can harmonize with signaling-based wavelength path switching such as Generalized Multi Protocol Label Switching (G-MPLS) [6-7].

This paper aims to propose a new wavelength path selection algorithm that facilitates to resolve the conflicts of wavelength path assignments due to the asynchronous and distributed control scheme of the SLAMNet. An asynchronous control system has an essential problem of the inconsistency of actions in the both end nodes due to noises, errors, drifts of timing, etc. It results in a mismatched wavelength path allocations between the two optical path switches (OPSWs). In order to solve this problem, we propose a hash-based wavelength path selection algorithm for the SLAMNet. We analyze the performance of the proposed algorithm and discuss the applicability to a large-scale DWDM network that multiplexes a lot of wavelengths into an optical link.

This paper is organized as follows. The next section digests the basic concept of the SLAMNet proposed in [5]. Section 3 describes the detail of the proposed algorithm. The performance analysis is presented in Section 4. The final section contains the conclusions.

2. Basic Concept of SLAMNet

The basic concept of the SLAMNet is illustrated in Fig. 1 [5]. A pair of routers uses two types of optical paths, referred to as initial paths and additional paths. The initial paths are always established between the router pair, while the additional paths are temporarily set up and released according to the amount of traffic. The wavelength resources between a pair of optical path switches (OPSWs) are shared among all the pairs of routers. One typical application of the SLAMNet is an overlay network on wavelength-rich environment using link aggregation [8]. The Link aggregation function is widely used to logically bind multiple links into a single large-pile from the viewpoint of users. Traffic load is distributed among available paths by the link aggregation function to utilize the total capacity of the multiple paths assigned to the router pair. It also provides fast recovery capabilities against a link failure within a few hundreds milliseconds. We assume that the wavelength assignment problem between OPSWs has been already solved and a certain number of wavelengths are statically allocated for the SLAMNet.

Figure 2 shows the control sequence of the SLAMNet. A monitor measures the amount of traffic transmitted on the initial and additional paths. If the traffic volume exceeds the predetermined threshold, the controller requests the OPSW to set up an additional path. If there is an available optical path, the OPSW sets up an additional path for the router. After the additional path is established between the pair of OPSWs, the routers begin to transmit packets to the path. On the other hand, if the traffic volume becomes less than another predetermined threshold, the OPSW finds the most recently added optical path for the router and releases it. This process runs in both the source and destination sides separately and independently of each other.

The difference in propagation delay among the optical paths is a key point of the path switching mechanism. The propagation delay variation should be limited for guaranteeing the same actions in both controllers and for preventing mis-ordering of the packets transferred by the multiple optical paths. When the initial and additional paths for the same router pair are accommodated in an identical physical route provided by the DWDM facility, the difference in propagation delay among the paths is small enough compared with the transmission time of a packet. Based on the guaranteed difference in propagation delay, additional paths can be managed by the autonomous control mechanism mentioned above. The guard time can be determined as the summation of the switching time and the maximum difference of propagation delay among the initial paths and additional paths. In the DWDM network, the guard time is dominated by the switching time of the OPSW. Since the difference of transmission delay among different wavelengths can be reduced to a negligibly short time by the use of dispersion flattened fibers and dispersion compensating fibers, the geophysical scale of networks is not critical for the SLAMNet. We therefore can apply the SLAMNet to a wide variety size of networks such as local area networks (LAN), metropolitan area networks (MAN), wide area networks (WAN), and international networks. The SLAMNet can be extended to multi-hop networks, and applicable to any network topology such as ring, star, tree, and mesh [9].

A configuration of the prototype system of the SLAMNet is shown in Fig. 3. In this figure

OPSW is composed of a traffic monitor, optical cross connect (OXC), and OXC controller. The traffic monitor measures the total traffic volume in the initial and additional paths on a realtime basis. According to the observed traffic volume, the OXC controller changes the path configuration of the OXC. The algorithms of the path addition and release are exactly the same at the both sides. If both of the two monitors observe the same traffic pattern, the action of the OXC is identical to each other. To avoid the mismatched path assignment due to the error or fluctuation of the control system, we employ the hash-based path selection algorithm described in the next section.

3. Hash-Based Path Selection Algorithm

In SLAMNet, the actions of path setup and release are independently achieved in each node triggered by the traffic load and no signaling messages are exchanged between nodes. Consider that two OPSWs connected by a DWDM link observe exactly the same traffic pattern at the same time. Then the action of the two OPSWs is identical to each other. In reality, however, we have some errors, noises, and drifts of timing in the networks, and it may result in a mismatched path assignment between two OPSWs. Imagine that two requests of path addition occurred in both OPSW within a short time, i.e., clock interval time of hardware. Then two distinct wavelength paths should be assigned for the two requests in one time. A simple strategy to select wavelength paths is First-Come-First-Serve (FCFS) discipline, where an available path is assigned to the first-coming request in the ascending order of wavelength path ID. For the FCFS based method, it may happen that one OPSW selects wavelength paths #1 and #2 for Users 1 and 2, respectively, while the other OPSW may select wavelength path #2 and #1 for Users 1 and 2, respectively, if the arrival order of path setup requests from Users 1 and 2 are reversed due to the limitation of the time resolution or fluctuation of the control system. We call such the mismatched state "path inconsistency". In this case, it is impossible to communicate normally between Users A and B. In order to avoid the path inconsistency between the OPSWs, we propose a hash-based path selection algorithm.

We assume that both two OPSWs have a pre-designed hash-table $H(i, j)$, which specifies a wavelength path as elements $H(i, j)$ to be assigned to User *i* for the *j*-th choice. Each OPSW also has flags $F(i, j)$ of User *i* for the *j*-th choice, which indicates the availability of the wavelengths specified in $H(i, j)$. If $F(i, j) = 0$, the wavelength $H(i, j)$ is idle, otherwise $H(i, j)$ is occupied. When wavelength path *w* is assigned for one of user, elements of *F* are set to be 1 for such (i, j) that satisfies $H(i, j) = w$. Each OPSW has memories $a(i)$ of User *i* that records the assigned wavelength path ID for the user. If $a(i)$ is null, no additional path is established for User *i*. The important point is to use an identical hash-table in the both OPSWs.

Table 1 shows an example of the hash-table. In this table, rows correspond to User *i*, and columns show wavelength path for the *j*-th choice. The elements of the hash-table *H* are arranged at random for each user in the *j*-th choice. In Table 1, wavelength path #2, #3, and #1 are specified for the 1st, 2nd, and 3rd choice of User 2, respectively. When a path setup request for User 2 is arrived and wavelength path #2 is available, then the OPSW sets up wavelength path #2 for User 2 The availability of the wavelength path #2 is judged by the value of $F(2,1)$. If $F(2,1) = 0$, wavelength path #2 is available, otherwise not. In Table 1, since $F(2,1) = 0$, wavelength path #2 is selected and assigned to User 2, and the flags are updated as shown in Table 2. Note that the flags *F* are set to 1 for such element (i, j) that satisfies $H(i, j) = 2$. Furthermore, when a path setup request is generated by User 3, an available wavelength path is scanned from left to right columns of the 3rd row. At the first column, unassigned wavelength path #3 is found, and thus we let $F(i, j) = 1$ for such (i, j) that satisfies $H(i, j) = 3$. Then, wavelength path #3 is assigned to User 3. The hash table and flag is updated as shown in Table 3. In this table, such box (i, j) is shaded that satisfies $F(i, j) = 1$.

Table 1: Hash-Table and Flags of Path Selection (Initial State)

Hash-Table for path selection		Choice of λ path			Assigned λ path $a(i)$
		1st	2nd	3rd	
user ID	1	1	2	3	
	2	2	3	1	
	3	3	1	2	
	4	1	3	2	

Table 2: Hash-Table and Flags of Path Selection (1st stage)

Hash-Table for path selection		Choice of λ path			Assigned λ path $a(i)$
		1st	2nd	3rd	
user ID	1	1	2	3	
	2	2	3	1	2
	3	3	1	2	
	4	1	3	2	

Table 3: Hash-Table and Flags of Path Selection (2nd stage)

Hash-Table for path selection		Choice of λ path			Assigned λ path $a(i)$
		1st	2nd	3rd	
user ID	1	1	2	3	
	2	2	3	1	2
	3	3	1	2	3
	4	1	3	2	

4. Performance Evaluation of the Hash-Based Path Selection Algorithm

In this section, we roughly estimate the performance of the hash-based path selection algorithm. The following notations are used.

N	Total number of wavelength paths.
T_s	The time resolution of the SLAMNet controller.
r	Total link utilization, $0 \le r \le 1$.
n	The number of currently occupied wavelength paths.
m	The number of idle wavelength paths, $m = N - n$.
k	The number of path setup requests arrived within T_S.

We assume that the order of path setup requests arrived within T_S is unknown by the limitation of time resolution of SLAMNet controller. Thus all permutations of k requests are assumed to be equally likely observed. When we apply the simple FCFS discipline, the path assignments in both two OPSWs are consistent if and only if the permutation of the requests becomes identical. The probability of keeping path consistency is given by the following equations.

$$c(k,m)=\begin{cases}\dfrac{1}{k!} & \text{if } k \le m,\\[2ex] \dfrac{m!(k-m)!}{k!}\dfrac{1}{m!} & \text{if } k > m.\end{cases}$$

On the other hand, when we use the hash-based path assignment algorithm, the assigned wavelength paths will be randomized if the hash table is ideal, and thus the probability of keeping path consistency is obtained as follows.

$$c(k,m)=\begin{cases}\dfrac{m!}{m^k(m-k)!} & \text{if } k \le m,\\[2ex] \dfrac{m!(k-m)!}{k!}\dfrac{m!}{m^m} & \text{if } k > m.\end{cases}$$

In order to estimate the average performance of the above two path assignment methods, we apply a simple Poisson approximation model, where the arrival process of additional path setup requests is Poissonean at the arrival rate l, holding time of the additional paths are exponentially distributed, and the number of users are much larger than *N*. Based on the Poisson approximation model, we can roughly estimate the distribution of occupied wavelength paths between OPSWs as an Erlang distribution written by

$$E_n = \frac{(Nr)^n}{n!} \Bigg/ \sum_{i=0}^{N} \frac{(Nr)^i}{i!} .$$

We now normalize the time by the average holding time of additional paths. Then we can estimate the distribution of k as a Poisson function given by

$$q_k = \frac{(lT_S)^k}{k!} e^{-l T_S} = \frac{(NrT_S)^k}{k!} e^{-NrT_S} .$$

Therefore the probability of path inconsistency P is given as

$$P = \sum_{n=0}^{N} \left[E_n \sum_{k=2}^{\infty} \left\{ q_k (1 - c(k, N-m) \right\} \right]$$

Figure 4 shows P as a function of T_S with $r = 0.7$, where solid lines correspond to the hash-based method and dashed line represent FCFS method. The hash-based method is about one order better than the FCFS method when N=50 or 100. The performance enhancement is enlarged as N is increased. Figure 5 shows P as a function of r with $T_S = 10^{-3}$. The performance is enhanced one or two orders as the offered traffic load is decreased. The performance enhancement due to the load reduction is attractive as the network scale N becomes large. Figure 6 shows P as a function of N with $T_S = 10^{-3}$. The performance difference between the hash-based algorithm and the FCFS method is increased as N. The slope is constant for FCFS method, while it is flattened in large N for the hash-based algorithm. Figure 7 shows P as a function of N with $NrT_S = 10^{-3}$. Note that NrT_S corresponds to the average number of path setup request arrived within T_S. By fixing the number of NrT_S, we clarify the dependency on the network scale factor N. For the FCFS method, the performance is insensitive to both N and r. On the other hand, P of the hash-based method is rapidly reduced as N become larger than 10, and the performance enhancement becomes significant as the offered load r decreases. From the above results, we can say that the hash-based algorithm is good especially for large N and small r, and the most significant factor of P is T_S. When the objective value of P is given and N and r are pre-determined, the value of T_S is graphically designed by Fig. 7.

Figure 8 shows the SLAMNet prototype test system [10]. In this proof-of-concept model, we implemented the hash-based wavelength path selection algorithms for contention resolution of additional path assignment. The system emulates the case where four router pairs share four or fewer wavelength paths as additional paths on a best-effort basis.

5. Conclusions

This paper proposed a hash-based path selection algorithm for the Statistical Lambda Multiplexing Network (SLAMNet). This algorithm facilitates to resolve the conflicts of wavelength path assignments due to the asynchronous and distributed control scheme of the SLAMNet. The performance analysis is presented and the applicability of the proposed algorithm is discussed. We described a strategy to design the system parameters, N, r, and T_S by fixing the product NrT_S to some extent. Since the ranges of N and r may be limited by the reality, T_S is the key parameter for system designer, and the acceleration of the clock speed of the SLAMNet control system is very important to enhance the total performance of the network. It should be noted that the proposed algorithm is advantageous in a large-scale DWDM network that multiplexes hundreds of wavelengths into an optical link.

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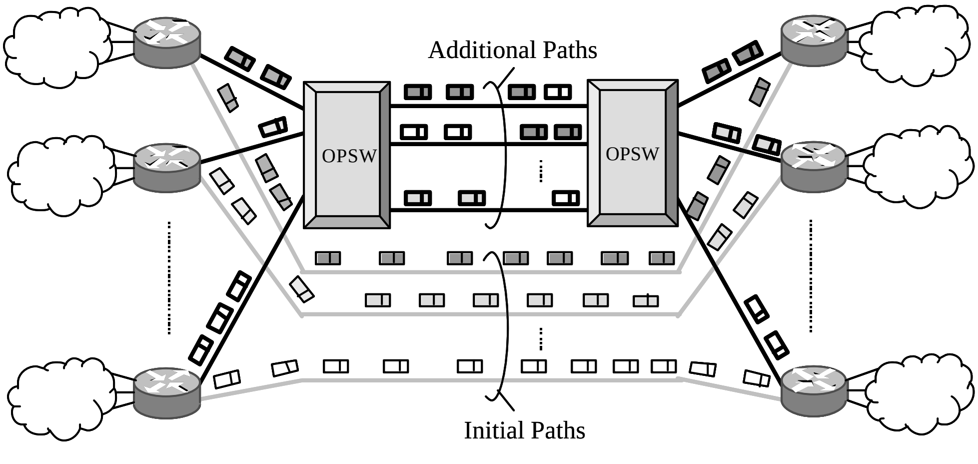

Fig. 1. Basic concept of SLAMNet.

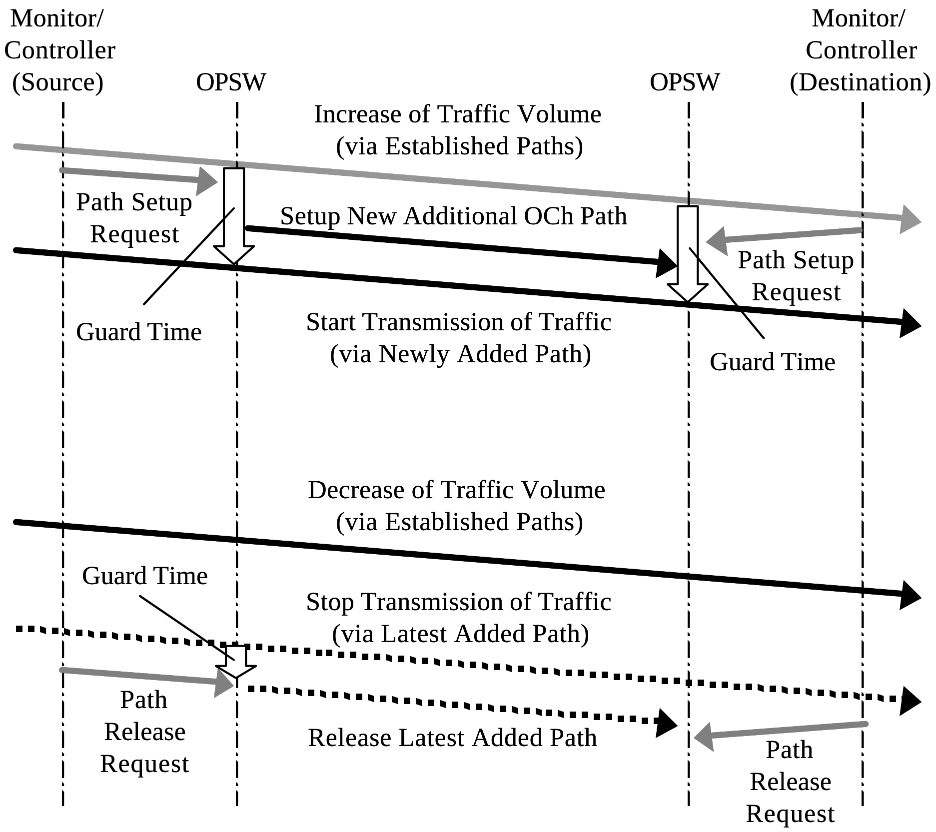

Fig. 2. Control sequence of the signaling-free path management.

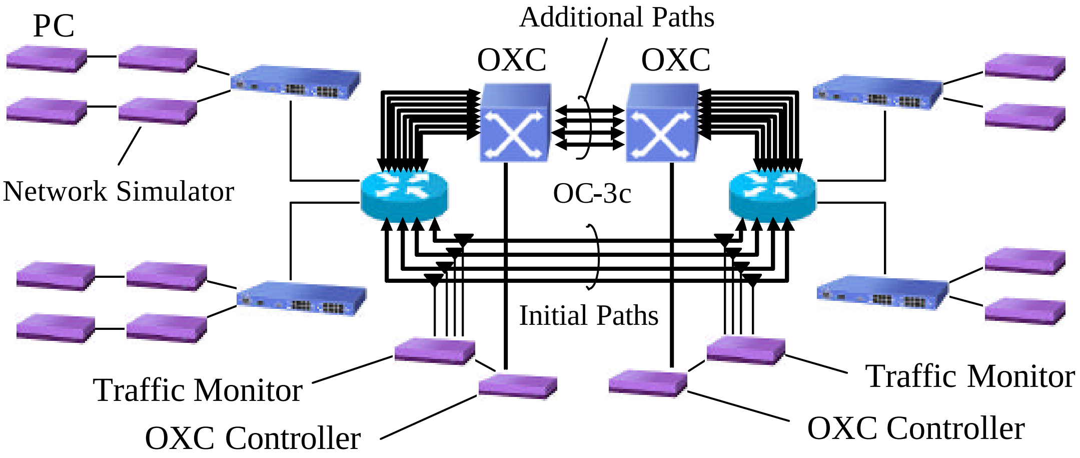

Fig. 3. Configuration of prototype system of SLAMNet.

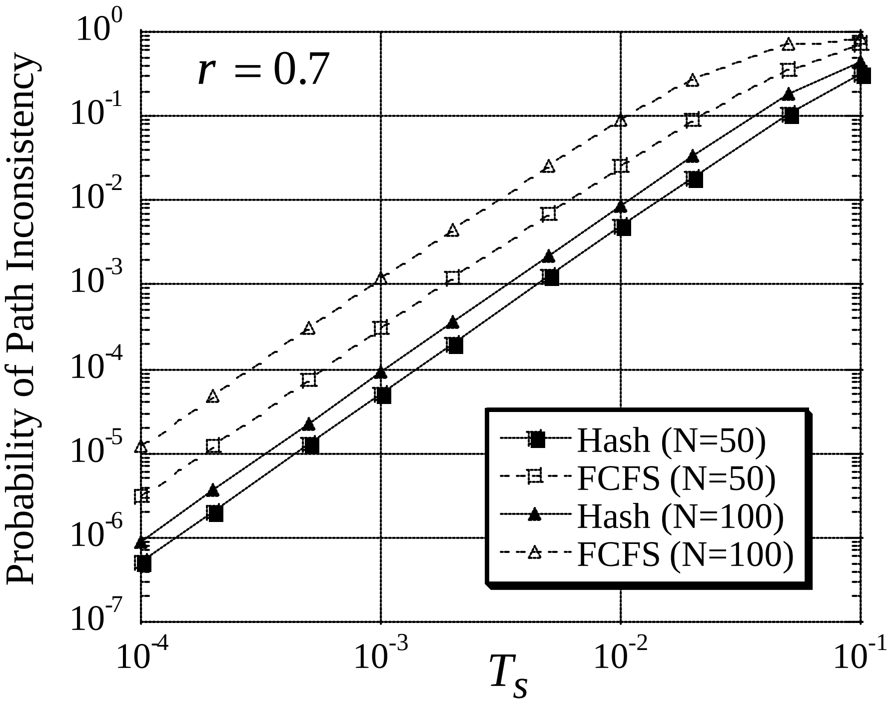

Fig. 4. Probability of path inconsistency vs. T_S with $r = 0.7$.

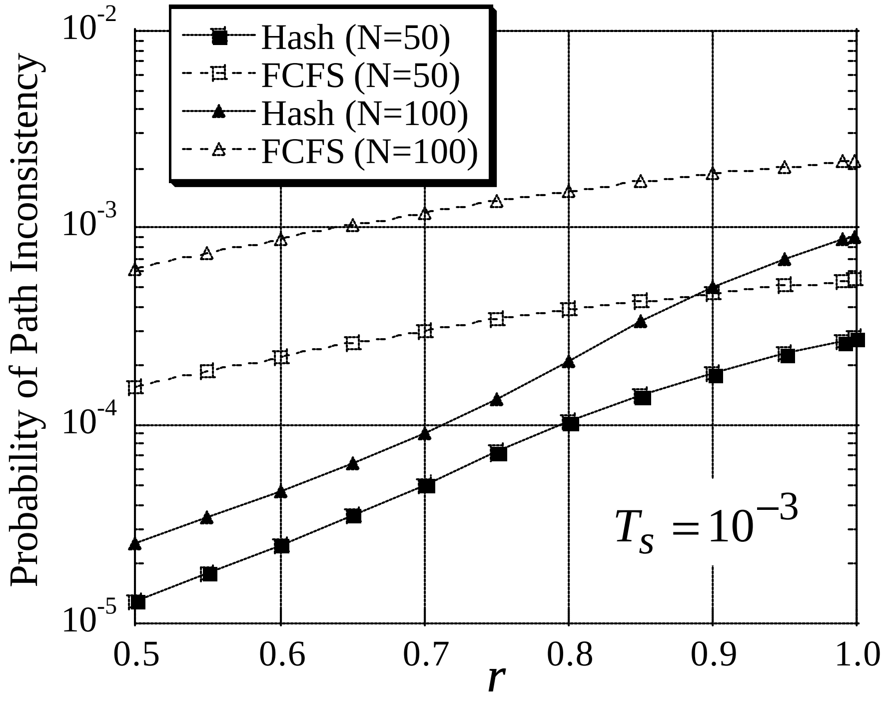

Fig. 5. Probability of path inconsistency vs. r with $T_S = 10^{-3}$.

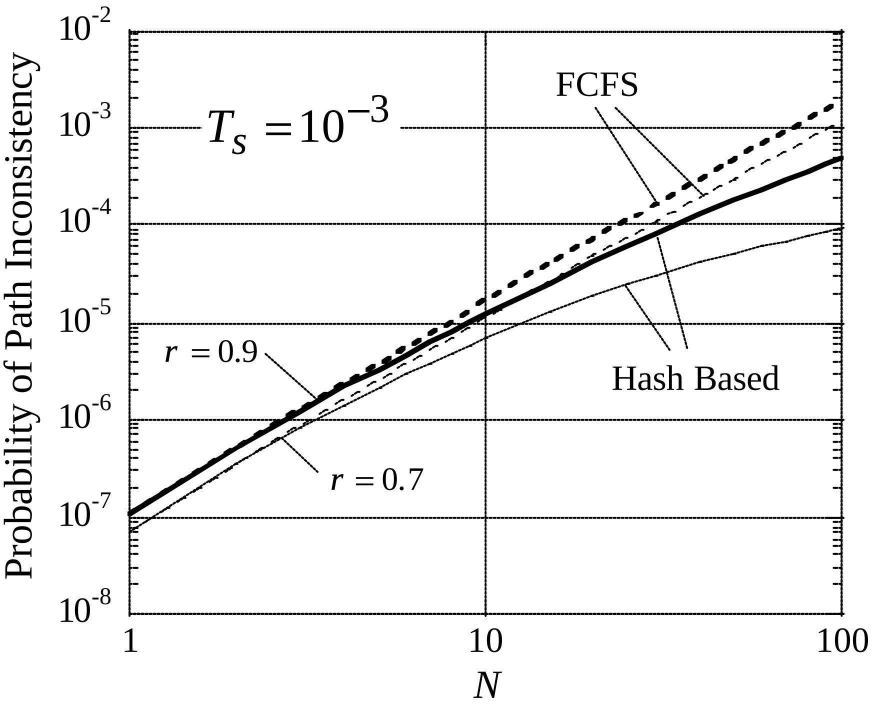

Fig. 6. Probability of path inconsistency vs. N with $T_s = 10^{-3}$.

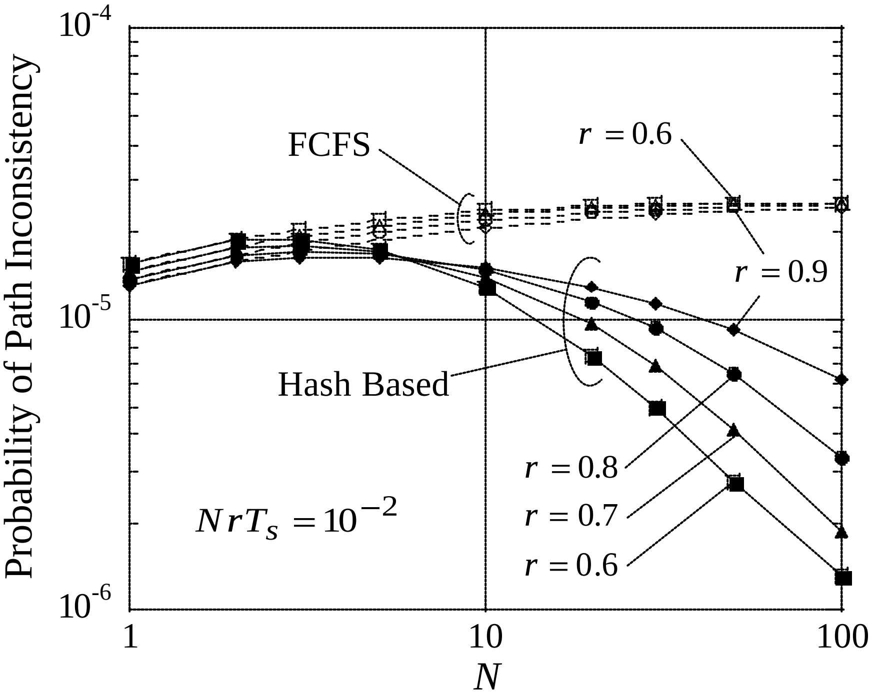

Fig. 7. Probability of path inconsistency with $NrT_s = 10^{-2}$.

Fig. 8. SLAMNet prototype system.